PEDOLOGICAL AND MANAGEMENT ASPECTS OF HARDENING AND SOFTENING OF LATERITES UNDER DIFFERENT LAND USE SYSTEMS

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I hereby declare that this thesis entitled **"Pedological and management aspects of hardening and softening of laterites under different land use systems"** is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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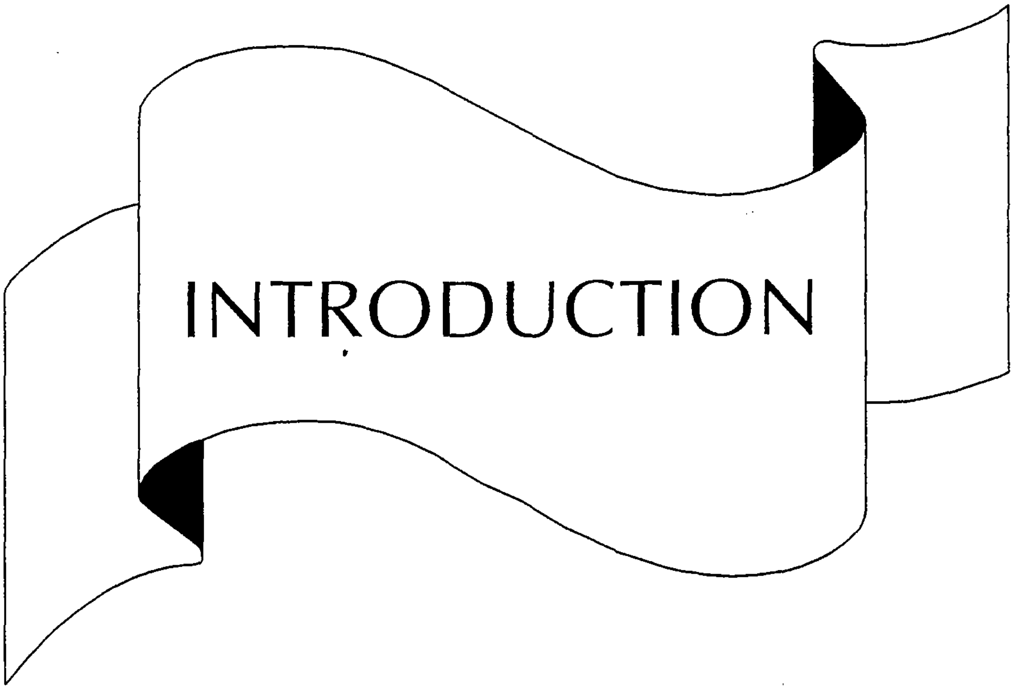
CONTENTS

Page No.

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES



INTRODUCTION

1. INTRODUCTION

Laterites and lateritic soils are considered as disastrous handicaps for agricultural development in humid tropical and subtropical regions of the world. Efforts are underway to prevent the lateral extension of these soils under the global environmental changes induced by human activities like deforestation and indiscriminate land use. In Kerala state which is located in south-west India, laterite and associated soils constitute about 60 per cent of the total area of the state.

Kerala, the southern most state of the Indian peninsula, lies between 8°18' and 12°48' North latitudes and 74°52' and 77°22' East longitudes. It is bound on the East by Western Ghats and on the West by the Lakshadweep Sea with a coast line of 580 km. It is a narrow strip of land, 32 to 130 km wide with a total geographic area of 38,863 sq.km, which is about 1.2 per cent of the total area of India. Climate is typically humid tropical with clear dry and wet seasons. Has an Isohyperthermic soil temperature regime and a ustic soil moisture regime in major part of the state.

Physiographically, Kerala is divided into three distinct regions :

1. Highlands of the eastern region consisting of mountains and forests of Western Ghats and foot hills

2. Midland region with undulating to rolling terrain intersected by rivers and valleys and

3. Coastal area consisting of fluvial plains and marine sands.

Though physiographically the state is divided into coastal area, midland and highland, 42 percent of the land area comes under midland which lies at an altitude ranging from 7.5 to 75 m above mean sea level. About 60 percent of the population out of 29 million live in this tract where laterite soils predominate.

Crop production on laterite and associated soils has been found to be low eventhough they are topographically and hydrologically suitable for annual food crops like cassava and perennial cash crops like rubber. There is considerable scope for improving the productivity of these acid soils through careful planning of land use.

Kerala state of India which is considered as the 'type locality' of laterite since the time of Francis (Hamilton) Buchanan, offers an ideal location for the study of pedological and management aspects of hardening and softening of laterites under different land use systems. There are numerous publications on ferruginous crust and hardening of soils related to laterite. It is agreed that iron plays a key role in the hardening process and in crust formation in the tropics. Many theories have been developed to explain the hardening of laterite in soils. The hard materials have a higher degree of crystallinity and a greater continuity of the crystalline phase than the soft material with which they are associated. Scanning electron microscopic studies show the formation of an interlocking network of goethite crystallites.

In highly laterised soils of Kerala, cassava and rubber form the major crops involving entirely different management systems. So far, no study has been conducted on the hardening and softening of laterites in different pedogenic environments of Kerala. Further, more than 10,000 ha of area in the districts of Malappuram, Kannur and Kasargod have been under the grip of intense laterisation and hard crust (cuirasse) formation making them unfit for normal cultivation. There are certain indigenous methods practised by local cultivators like addition of common salt in laterite pits to soften the indurated laterite. The impact of organic and inorganic ameliorants on the relative efficacy in softening the hardened material is yet to be investigated.

Hence this project was formulated to study the pedological and management aspects of hardening and softening of laterites under different land use systems, with the following objectives :

1. To study the pedogenic environments of the selected sites where laterite soils predominate
2. To study the macromorphology of the pedons
3. To study the physico-chemical characteristics related to hardening and softening of laterites and the inter-relationships among various laterisation indices

4. To study the soil acidity parameters and their inter-relationships to assess the soil acidification due to laterisation under different land uses

5. To study the relationships between different forms of free oxides of iron and aluminium in hard and soft laterites

6. To determine the relationships between the properties of the iron oxides present and the strength of hard and soft laterites in soils and

7. To evaluate the efficacy of different organic and inorganic ameliorants in softening of already hardened laterites.

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

The key soil characteristics that affect yield are nutrient content, water holding capacity, organic matter content, soil acidity, top soil depth and soil biomass. Soil quality is the inherent capacity of the soil to perform a range of productive, environmental and habitat functions. About two-third of all rainfed, cultivable area in developing countries is affected by one or other form of soil degradation. Chemical soil constraints are widespread : 36 percent of the tropical soils have low nutrient status; one-third have sufficiently acid conditions for soluble aluminium to be toxic for most crops; 22 percent are tropical clays that fix phosphorus and 5 percent have critically low cation exchange capacity (Lynden and Oldeman, 1997; Tengberg and Stocking, 1997 and Scherr, 1999).

There are probably few terms in soil science which have been so often defined, redefined and frequently misapplied as the term laterite. A number of research results are available on the morphological, physico-chemical, mineralogical, micromorphological and management aspects of laterites and associated soils. But, with regard to the pedological and management aspects of hardening and softening of laterites, not much work has been done so far. This chapter deals with the studies on laterites in general and a review of the work done on the various aspects of hardening and softening of laterites in order to have an insight into the present knowledge on the phenomena.

2.1. Classical studies on laterite soils

The term "laterite" was originally coined by Buchanan (1807) for a ferruginous, vesicular and soft material occurring in immense masses over the country rock of malabar in India. The freshly dug material, as described by Buchanan, was soft enough to be readily cut into blocks by an iron instrument, but upon exposure to air it quickly became as hard as brick and remarkably resistant to the action of air and water.

Since the time of Buchanan, a number of studies have been done on the various aspects of laterites and lateritic soils. Some of the important studies include that of Babington (1821), Harrassowitz (1926), Martin and Doyne (1927), Harrassowitz (1930), Fox (1936), Prescott and Pendleton (1952), Aubert (1954), Mohr and Van Baren (1954), Camargo and Bennema (1962), Kellogg (1949), Robinson (1949), Alexander and Cady (1962), Sivarajasingham *et al.* (1962), Maignien (1966), Sys (1968), Mc Farlane (!976), Schellmann (1981), Eswaran *et al.* (1990), Varghese and Byju (1993), Aleva (1994), Schellmann (1994) and Sehgal *et al.* (1998).

Studies on the genesis, morphology, physico-chemical characteristics, charge characteristics and fertility aspects of laterite soils of Kerala, India have been conducted by different workers including Sathyanarayana and Thomas (1962), Gopalaswami and Nair (1973), Gowaikar (1976), Venugopal (1980), Varghese (1981), Usha and Jose (1983), Byju and Varghese (1990), Rajendran (1992) and Jose *et al.* (1998).

2.2. Genesis

Laterite is a product of intense subaerial weathering and laterisation is a soil forming process occurring in humid tropics where alternate wet and dry seasons prevail. It can be defined in a general sense as the leaching out and elimination of silica, alkali and alkaline earths under alkaline hydrolysis and the accumulation of hydrated oxides of iron and aluminium, the latter being partly combined with silica.

Invariably all the rock types under these conditions give rise to laterite which looks similar in appearance. However, there will be marked change in mineralogy and migration of elements in laterite profiles. The available data on laterite profiles of Kerala developed over crystalline rocks indicate two stages in the genesis of laterite, first stage is marked by sudden depletion of silica, alkali and alkaline earths with enrichment of iron, aluminium and titanium. The second stage is marked by a gradual depletion of silica, alkali and alkaline earths with enrichment of iron, aluminium and titanium. However, the laterite developed over sedimentary formation and anorthosite show three stages in their genesis, first stage marked by rapid depletion of SiO_2, Al_2O_3 and TiO_2, in the second stage gradual depletion of silica, alkali and alkaline earths with enrichment of iron, aluminium and titanium and in the third stage rapid depletion of silica and partial removal of ferric iron with residual enrichment of alumina (Subramonian and Mani, 1978 ; Mallikarjuna *et al*, 1981; Nair and Mathai, 1981; Soman, 1982 and Narayanaswamy, 1986).

Benjamin (1976) has given a detailed account on the genesis of laterite in general. Kerala region constitute an important segment of western passive continental margin of the Indian shield and is bounded by Western Ghats on the east and the Arabian sea on the west. The rock types found in this region can be grouped into 1. The pre-cambrian, 2. The tertiary formations and 3. The recent to sub-recent sediments. The precambrian crystalline rocks dominate (70 per cent) over the other formations and comprise rock types like charnockite, khondalite, Sargur and Dharwar groups, migmatites, granite, syenite and basic to ultra basic rocks intruded by quartz veins, pigmatites and basic dykes (Soman, 1980 and Devaraju and Khanadali, 1993).

The tertiary sedimentary sequences unconformably overlie the precambrian and these are exposed towards the western part. The sequence comprises of fossiliferous shell limestone alternating with thick beds of sandy clays, calcareous clays and sandstones of Quilon formation and the current-bedded friable variegated sandstone with lignite seems and clays of beach sand deposits, limeshell deposits, teri sands and alluvium. The rocks of Archaen and Tertiary formations show extensive laterisation.

2.3. Morphology of *Laterite*

The most important and visible feature of laterite is the accumulation, form, colour and consistency of the iron oxides and hydroxides which impart the yellow, pink, brown and red colouration to the ground matrix and earthy clay. The term *'plinthite'* was introduced in the early 1960s as a substitute for the term laterite and to depict a diagnostic feature in these soils. The term originates from the Greek word *plinthos,* meaning brick. A working definition of plinthite given by Daniels *et al.* (1978) and modified by Eswaran *et al.* (1990) is given here.

Plinthite is an iron-rich, humus-poor mixture of clay with quartz and other minerals. It commonly occurs as dark red redox concentrations that usually form platy, polygonal or reticulate patterns. Plinthite changes irreversibly to an ironstone hardpan or to irregular aggregates on exposure to repeated wetting and drying, especially if it is also exposed to heat from the sun. The lower boundary of a zone in which plinthite occurs generally is diffuse or gradual, but it may be abrupt at a lithological discontinuity.

Generally, laterite forms in a horizon that is saturated with water for some time during the year. Initially, iron is normally segregated in the form of soft, more or less clayey, red or dark red redox concentrations. These redox concentrations, however, are not considered laterite unless there has been enough segregation of iron to permit their irreversible hardening on exposure to repeated wetting and drying. Laterite in the soil is usually firm or very firm when the soil moisture content is below the wilting point. Laterite doesn't harden irreversibly as a result of a single cycle of drying and rewetting; after a single drying, it will remoisten and can be dispersed in large part by shaking in water with a dispersing agent (Soil Survey Staff, 1998).

With regard to colour, *laterites* vary considerably and the shades most frequently encountered are pink, ochre, red and brown, but some occurrences are mottled and streaked with violet, and others exhibit green marbling (Maignien,1966). The different colours are due to the oxides of iron in various degrees of hydration and sometimes to manganese. Compounds of iron impart a grey-black colour and compounds of manganese, a velvety black in a reducing medium, while under conditions of oxidation, iron gives ochre, red or black, and manganese violet.

Alumina is white in pure state, but is often found mixed with iron in hardpans where it gives rise to the characteristic rose tints. Silica, which is ordinarily whitish and impregnated with the hydroxides of iron, may yield a red or rust colour. Kaolinites fix iron on their surface and become deep red (7.5YR to 10YR). It is the mixture of these differently coloured constituents which produces the extremely varied colouration of laterites (Varghese and Byju,1993).

Each zone of the laterite profile has its own distinctive character which is highlighted by varying morphological characters. Most of the laterite profiles in Kerala are composite and contain both detrital and residual components. Although the general pattern of the laterite profile development is similar in most of the areas, the development of the individual units of the profile is not however uniform. The synoptic laterite profile developed has the different units on a descending sequence as follows (Sinha Roy, 1979):

1. Humus zone
2. Loosely packed *laterite* gravel
3. Partly indurated *laterite* gravel with occasional lateritic clay
4. Vermicular *laterite* on which kaolinite content increases downward
5. Mottled zone
6. Blocky laterite with kaolinite network and relict parent rock structures
7. Pallid zone (mainly kaolinite), often with ironstone layers towards top
8. Partially altered parent rock
9. Fresh parent rock

Humus zone comprises of top soil rich in organic material. The laterite gravel comprises the detrital components of the laterite profile, and it also consists of ferruginous pebbles of various shapes and sizes that are loosely or closely packed. The vermicular laterite represents the top part of the residual laterite component. It contains tubular cavities of various sizes that are usually filled by kaolinitic clay. The vermicular laterite is underlain by the mottled zone. The most significant unit of weathering profile is the blocky laterite which in fact is the strongly weathered zone of the parent rock where relict structures are common. This unit is ubiquitous and is characterised by a kaolinitic network. Pallid zone is associated with blocky laterite and comprises of kaolinitic clay in pockets and bands. The thickness of this zone is highly variable. The pallid zone in most of the profiles merges with partially kaolinised rock at the base. Aleva (1983) gave some suggestions for the systematic structural and textural description of laterite soils.

2.4. Hardening of Laterite

It was long thought that the induration of laterites is due to the development of constituent sesquioxides, precipitated, concentrated and crystallised as a result of desiccation. The analytical facts show that a mere concentration of these materials would not in itself create the conditions for induration. Many laterite soils do not contain indurated horizon containing large amounts of iron or alumina or both, while other hardened soils may contain much smaller quantities of these materials (Aleva, 1994).

It does seem, however, that iron plays a key part in the induration processes (Maignien, 1966 and Eswaran *et al.*, 1990). Hardening and cementation must be distinguished from aggregation and growth by accretion . Aggregation is due to formation of strong chemical bonds between free hydroxides with a positive charge and negatively charged clay minerals or organic matter.

The origin of the cementation is not clearly established. Chadwick and Nettleton (1988) suggested that cementation in soils generally may be due to two different chemical processes : (1) crystalline cements held together by ionic chemical bonds within the compounds which occurs in petrogypsic and petrocalcic horizons; (2). cements composed of elements that form covalent bonds within the cementing agents and with other soil constituents. The latter occurs when the accumulating pedogenic compounds are composed of silicon, aluminium, iron and manganese, elements with intermediate electronegativity. Even in the crystalline form these compounds have outer surfaces composed of OH_2-OH groups, which can always be used to form covalent bonds with the same elements. This process would allow very close approach and therefore a high density of element.

Cementation and hardening result from a close packing of the crystals (Schwertmann, 1985). In most cases, some minimum amount of iron appears to be a primary requirement for hardening, that amount ranging widely among different materials and under different environments.

According to Sivarajasingham *et al.* (1962), the iron bearing parts of a hardened laterite have a higher degree of crystallinity and a greater continuity of the crystalline phase than the soft materials with which they are associated. Thin section studies of these materials showed that the crystalline phase of iron oxide minerals in the hard material occurs in a framework having a high degree of continuity within the mass, though the exact form may vary widely from specimen to specimen. It would appear that conditions that permit segregation and crystallisation of iron in a pattern that will provide a rigid framework are essential to the hardening process of most laterites. This implies conditions favourable to the movement of iron, at least locally, and favourable not only for development of crystallinity, but also for development of a significant degree of continuity of the crystalline phase.

Many studies suggest that chemical, mineralogical and micromorphological differences between the soft and the hard material are not great. A decrease in kaolin is associated with an increase in crystallinity and continuity of goethite, which is believed to be the primary cause of the change from soft to hard material (Maignien, 1966; Sivarajasingham *et al*, 1962; Schellmann, 1983 and Aleva, 1994). This implies the presence of environmental conditions such as to stimulate at least local movements of the iron, promote the development of crystallinity and permit the development of some degree of continuity of the crystalline phase.

Kaolinite possesses marked properties of absorbing and immobilising iron (Eswaran *et al*, 1990; Tardy, 1992). Kaolinite, a common constituent in laterite loose materials, occurs isolated in pockets, imprisoned in the cortex of crystallised goethite at the time of induration. This type of induration cannot occur if the kaolinite is impregnated with ferruginous solutions before the goethite crystallises; in such a case, there would be no continuity of the crystallised phase and hence no induration. They also reported that in hardened materials the percentage of kaolin is almost always lower than in the loose subjacent material, although this is not an alternate rule. In many cases it seems that kaolin is altered and that the alteration is accompanied by a liberation of iron which crystallises into goethite. This disappearence of kaolinite would diminish the capacity of the whole to immobilise iron and would consequently make it more likely that the continuous phase of goethite would develop.

Electron microscopic studies show that the presence of kaolinite crystals with corroded edges produced alteration of the mineral with corresponding increase in the iron content. This is a case of relative accumulation. Conversely, the presence of well preserved pseudohexagons in a hardened medium would indicate absolute accumulation of iron from outside the profile under study (Wood and Perkins, 1976 and Herbillon and Nahon, 1985).

In the formation of petroplinthite nodules, the last stage is the formation of the iron crust. Scanning electron microscope studies of the crust of the nodules (Stoops, 1970; Eswaran and Raghumohan, 1973 and Eswaran *et al*, 1980) show the closely packed goethite crystals. The acicular crystals are aligned perpendicular to the surface, and this gives the crust its rigidity. In the core of the petroplinthite, however, the goethite crystals are lenticular in form. They occur as rosettes or clumps and are friable or easily crushed between the fingers. The crust with its closely packed acicular goethite crystals was never encountered in plinthite nodules. This explains why plinthic material is easily crushed between the fingers and why it stains the fingers.

The lamellar cement binding the petroplinthite nodules in the petroferric contact is also composed of closely packed goethite. Consequently, the cementing due to formation of closely packed macrocrystals is responsible for the hardening (Schwertmann, 1985).

The hardening also requires an alternate wetting and drying situation. It appears that drying should be to the extent that the moisture tension is close to 15 kPa. The hardening process normally is subsequent to geomorphic changes in the landscape. In areas with an ustic soil moisture regime, the hardening is accelerated. Uplift of the landmass or lowering of the ground water table results in drying up of the soil material. Uplift is always accompanied by erosion, which would eventually expose the sesquioxide accumulation zone. This is most evident at the edges of the uplifted zones. The hardened petroplinthite is resistant to further erosion and escarpments are formed at these edges. This hardened rims of the uplifted zones now control the hydrology of the zone and set the stage for petroferric contact to be formed in the soils within the zone.

On the older continents such as West Africa and India, uplift is followed by peneplanation. The petroplinthite is broken and transported as gravel and occurs in the soils of the peneplain as a layer a few cms to more than 1m thick. These petroplinthic gravels may have no pedogenetic relationship to the soil in which they occur and their behaviour and roles are similar to stones of quartz or granite in other alluvial or colluvial soils. After deposition, a new set of soil forming processes commences. If an aquic soil moisture regime prevails, recementation of the petroplinthite may commence again leading to a petroferric contact. The cycle repeats itself (Eswaran *et al.*, 1990).

2.5. Softening of laterite or laterite degradation

On the human time scale, laterite horizons do seem to be relatively stable, yet detailed studies show that ferruginous cements which usually constitute the internal skeleton of the crusts, can develop rapidly if environmental conditions permit. Vegetation can become established on the crusts and help to loosen the hardened materials to varying depths.

Studies of soil material over a disintegrating crust showed that coarse fractions retained the composition of the underlying laterite but that fine fractions contained more silica and bases, related at least in part to introduction of fresh material from outside sources (Sivarajasingham *et al.*, 1962).

Thin section studies and mineralogical analysis revealed an increase in porosity, removal of gibbsite near the pores and cavities, appearance of traces of kaolin, and conspicuous rearrangement of constituents in the softer specimens. Some parts were highly depleted of iron while others were very densely impregnated, suggesting that the softening was associated with a decrease in continuity of the impregnating material.

Studies suggest that laterites soften when processes comparable to reversal of the hardening mechanisms destroy the continuity of crystallinity (Stoops, 1970; Eswaran *et al.*, 1980 and Schwertmann, 1985). A decrease in amount, and especially in continuity of crystalline material is most striking. Silication of aluminium compounds to kaolin may occur. Loss of aluminium is evident, loss or redistribution of iron and increase in hydration of iron compounds seem to be involved. Maintenance of a moist condition and actively growing vegetation appear to be associated with the process where it has been reported, and it is possible that the complexing of iron by organic compounds is involved.

Prevention of hardening of laterite that is still soft is a more feasible enterprise. Use of land in a manner that prevents erosion of the protecting unconsolidated soil cover, which minimises exposure to high temperature and dehydration and provides the mechanical desruption of extensive root systems, is clearly helpful. In some cases, maintenance of such areas under forest vegetation appears to be the only feasible use; in others, carefully managed agriculture is possible.

Rosevear (1942) reported that under a teakwood plantation, decomposition of laterite happened in a short period of 16 years. Jose *et al.* (1998) suggested to use land in a manner that prevents erosion of the protecting unconsolidated soil cover to minimise exposure to high temperature and dehydration. They also suggested to maintain such areas under forest and to carefully select crop combination that maintains a good cover.

2.6. Laterisation process

To study the process of laterisation, different workers used different parameters or indices. One of the earliest attempts to characterise laterites was based on silica: sesquioxide molar ratios. Iron enrichment and desilicification can be expressed by silica : sesquioxide molar ratios, which lower as the silica content of the clay is reduced and iron and alumina are accumulated (Varghese, 1981; Byju and Varghese, 1990 and Varghese and Byju, 1993).

2.6.1. Chemistry of major elements involved

From the point of view of formation of laterite, the elements of interest are silicon, aluminium, iron and manganese. Silica as a cation , $Si^{4+}4H_2O$, constitutes a very strong acid ($_pKa = -1.2$) and is commonly present as a hydroxide, $Si(OH)_4$, with limited molecular solubility (Millot, 1964 and Charlot, 1966). When precipitated, it polymerises by splitting up H_2O molecules.

Aluminium, on the other hand, forms a hydrate, $Al^{3+}\ 6H_2O$, with intermediate acidity ($_pKa = 5$), and as a result, below pH of 4.2 it is rather soluble but at higher pH it precipitates as $Al(OH)_3$, which may crystallise as gibbsite (Hem and Roberson, 1967). The solubility of gibbsite is low (K_sp about 32) and so once it is precipitated, it is a rather stable mineral.

Iron and manganese are rather special elements, as they can be reduced or oxidised as shown by Krauskopf (1967). The reduced compounds form hydrates with low acidity ($_p$Ka 9.5 and 10.6 respectively) and the presence of the pure $Fe(OH)_2$ and $Mn(OH)_2$ has not been reported. Fe^{3+} , Mn^{3+} and Mn^{4+} constitute rather strong to very strong acids ($_p$Ka less than 3) and therefore are commonly present as insoluble hydroxides or dehydrated oxides at the normal pH range of soils (Eswaran *et al.*, 1990). These fundamental differences in chemical properties of the reduced and oxidised forms cause the solubility to depend on the environmental conditions. The most simple expressions of these differences are the following reactions:

$$Fe^{2+}\ 6H_2O \leftrightarrows Fe(OH)_3 + 3H^+ + 3H_2O \quad E_0 = +1.06V$$

$$Mn^{2+}\ 4H_2O \leftrightarrows Mn(OH)_4 + 4H^+ + 4H_2O \quad E_0 = +1.23V$$

Besides redox potential, the presence of H^+ in these reactions indicates the important role of pH in these equilibriums.

Due to its high solubility, silicon is easily leached out of the system. In the presence of Al^{3+} ions, the solubility of silicon is decreased as the entities coprecipitate as amorphous gels, which according to Millot (1964) may age to kaolinite. The solubility and mobility of aluminium are complex and, as shown by De Coninck (1980), are controlled by concentration and the presence or absence of organic matter. In the presence of organic matter, precipitation of gibbsite occurs.

2.6.2. Laterisation indices

Those who regarded the break down of kaolinite to free alumina as a measure of laterisation stressed the silica : alumina ratio (Martin and Doyne, 1927). The silica : alumina ratio of pure kaolin is theoretically 1.18, so if the ratio is less than 1.18 there is assumed to be free alumina (Hardy and Follet-Smith, 1931). However, this figure is rarely used as a measure of laterisation since there is evidence that appreciable quantities of free alumina may occur even when the ratio is higher. Martin and Doyne (1927) who introduced silica : alumina ratio as diagnostic of laterite, initially suggested that a clay with a ratio of less than 1.35 was to be considered laterite and with a ratio of 1.35 to 2.0 it was lateritic. Moorman and Panaboke (1961) used the ratio 2.0 to divide laterite and non-lateritic materials.

Amorphous and poorly crystalline iron and aluminium oxides are normally quantified by means of the oxalate extraction method; while dithionite - citrate - bicarbonate (DCB) method can be used in the determination of the total content of these oxides in soils (Mehra and Jackson, 1960; Schwertmann, 1964; Schwertmann and Taylor, 1989 and Borggaard, 1990). The difference between DCB - extractable iron (Fe_d) and oxalate extractable iron (Fe_o) corresponds to crystalline iron oxides, while the difference between DCB - extractable aluminium (Al_d) and oxalate extractable aluminium (Al_o) may be considered a measure of aluminium bound in iron oxides because of isomorphous substitition (Torrent, 1987; Borggaard, 1990; Fontes and Weed, 1991; Singh and Gilkes, 1991 and Bennoah *et al*, 1997).

A high value of Fe_o / Fe_d (active iron ratio) indicates their relative enrichment in amorphous oxides than crystalline ones. High values for Fe_o / Fe_d ratios are indicative of the inhibitory effect of organic matter in the crystallisation of iron oxides (Schwertmann, 1966; Varghese, 1981 and Hamdan and Burnham, 1997).

Laterite number is used to assess the climatic limits of laterite formation (Kerner - Marilaun, 1927). The method considers precipitation, seasonality of rainfall and temperature to be critical variables. Laterite number is expressed as :

$$L = R^{-1/4} (S - s) t_m 100^{-1} \quad \text{where}$$

L = laterite number
R = annual precipitation, mm
S = wet season semi annual precipitation, mm
s = dry season semi annual precipitation, mm
t_m = minimum monthly mean temperature, °C

A laterite number of 50 is considered critical. High L values, favourable for laterisation, would appear to be associated with a very high markedly seasonal rainfall and high temperature. However, by this formula, the requisite R value for laterite formation could never be achieved in a situation where the rainfall, however high, was evenly distributed throughout the year (Mc Farlane, 1976). In Kerala (India), this parameter was tested to evaluate the laterisation process by Varghese (1981) and the results were well in agreement with other parameters used to assess laterisation.

Silt : clay ratio (Van Wambeke, 1962) is considered to be both an index of weathering and index of the extent of laterisation. Considering the critical value as 0.25 (Buringh, 1970), Varghese (1981) recorded values as low as 0.02 in some laterite soil profiles in Kerala, India. A low value of silt : clay ratio in the diagnostic horizon indicates the high ferrallitic nature of the soil.

The amount of water dispersible clay is also considered as an index of laterisation (Varghese and Byju, 1993; Hamdan and Burnham, 1997). There are no reports that a single index can give a universal definition of laterites and associated soils, but a set of indices have to be satisfied to name the material as laterite.

2.7. Free oxides of iron and aluminium in hardening and softening of laterites

A number of studies have been done on ferruginous crust and hardening of laterite in soils. It is agreed that iron plays a key rôle in the hardening process and crust formation in the tropics (Sivarajasingham *et al*, 1962 and Maignien, 1966). Many theories have been developed to explain the hardening of laterites in soils (Mc Farlane, 1976). The most popular hypothesis is that the hard materials in the crust have a higher degree of crystallinity and a greater continuity of the crystalline phase than the soft material with which they are associated. Eswaran and

Raghumohan (1973) indicated the formation of an interlocking network of goethite crystallites by scanning electron microscopic studies. Ahmed and Jones (1969) found with x-ray diffraction, an increase in crystalline iron compounds in the harder materials and Gamble and Daniels (1972) measured low Fe-oxalate / dithionite ratios (Fe_o / Fe_d) in the harder materials. Aluminium for iron substitution in the iron oxides of the crust has also been reported (Nahon *et al*, 1977), however, and from other studies such substitution appeared to decrease the crystallinity and the particle size of iron oxides (Norrish and Taylor, 1961 and Schwertmann *et al.*, 1977).

The reactivity of the aluminium and iron oxides are determined by the conditions under which the soil has formed. Thus, under cold, humid and nutrient poor conditions which result in organic matter accumulation, poorly crystalline oxides of small particle size are favoured, while under well aerated tropical conditions larger, more well developed crystals are formed (Schwertmann and Taylor, 1989 and Borggaard, 1990). Since the reactivity depends on the specific surface area, the amorphous and poorly crystalline oxides with the smallest particle size will be the most reactive.

Different observations are given on the types of iron oxides that are concentrated in the hard materials. Humbert (1948), Gallaher *et al.* (1974a, b) and Wood and Perkins (1976) found a predominance of haematite in the harder materials, and Eswaran *et al.* (1980) indicated the predomonance of goethite as responsible for hardening and that haematite is considered an accessory mineral. The formation of haematite from goethite by dehydration has been proposed by Sivarajasingham *et al.* (1962), Van Schuylenborgh (1971), Gallaher *et al.* (1974 a, b), Mc Farlane (1976) and Nahon *et al* (1977). Schwertmann (1971), Davy *et al.* (1975), Nahon *et al.* (1977) and Bigham *et al.* (1978) reported evidence for the transformation of haematite to goethite in soils.

Alexander and Cady (1962) indicated that the hard crust and the soft material below have the same bulk chemical composition. Soils that harden even with low amounts of iron are described by Fripiat and Gastuche (1952), who indicated that a higher concentration of iron would not itself create the conditions for induration. According to Eswaran *et al.* (1981), the induration process requires a large supply of iron over short periods to form a rigid compact crust. Ahmed and Jones (1969) and Wood and Perkins (1976) reported a high increase in the concentration of Fe_2O_3 from the yellow matrix to the plinthic material. Gallaher *et al.* (1974a) found, with electron microprobe analysis, an increase in iron compounds in the plasma of nodules. All these studies show that no clear conclusions have been reached regarding characterising the hard and the soft materials and understanding the processes of hardening and softening of laterites in soils.

Studies by Shadfan *et al* (1985) indicate that the harder iron rich materials in laterite soils have different chemical and mineralogical compositions from the softer materials they are associated with. Kaolinite and in some cases quartz tend to be more abundant in the softer materials but iron oxides are more prevalent in the hard material. Goethite is the most common form of iron oxide in these materials. The study also showed a positive linear relationship between the strength of the materials and both the dithionite extractable iron and mean crystalline dimension (MCD) indicating that both amount of iron oxide and crystal size contribute to hardening of laterites. The relatively higher aluminium concentration in the softer materials leads to substitution of iron during the crystallisation of iron oxides and thereby prevents crystal growth in these minerals. This will keep the materials soft. Also, finer grained iron oxide is more prone to be transported in solution or as a colloid to sites of crystal growth.

Perkins and Lawrence (1982) observed an increase in iron and aluminium with depth due to weathering processes. Iron is found to segregate within the mottled horizons of the pedons. Iron : aluminium ratios and aluminium - clay relationships suggest that aluminium doesn't segregate, but appears to be part of the silicate clay minerals. Plinthite, petroplinthite and petroferric contact are related forms and each has its own pathway of formation. A very early stage is depicted by the formation of mottles in soil subject to a fluctuating water table. In the Fe^{2+} form, iron is mobile and is transported to points where accumulation takes place through accretion. Once a nucleus is formed, the nodule grows as the nucleus serves as a template for further deposition. If there is periodicity in the supply of iron, concretions with a concentric fabric result, if there is a continuous supply, nodules with a diffuse fabric result. The low chroma zones (chroma of 2 or less) become a permanent feature of the soils, and the morphology may persist even if the water table is lowered (Eswaran *et al.*, 1990).

For laterite hardening, studies suggest that a further supply of iron is necessary, and this usually comes from the weathering zone, which may be in a permanently reduced situation. The ground water table recharges the mottled zone (Gallaher *et al.*, 1974b) with iron, and this absolute accumulation of iron is responsible for the considerable enrichment that leads to laterite formation. The reticulate pattern is due to reduction and local movement of iron.

Chadwick and Nettleton (1988) suggested that hardening and cementation in soils generally may be due to two different chemical processes : 1. crystalline cements held together by ionic chemical bonds within the components, which occurs in petrogypsic and petrocalcic horizons; and 2. cements composed of elements that form covalent bonds within the cementing agents and with other soil constituents. The latter occurs when the accumulating pedogenetic compounds are composed of silicon, iron, aluminium, manganese etc., elements with intermediate electronegativity. Even in the crystalline form these compounds have outer surfaces composed of OH_2-OH groups, which can always be used to form covalent bonds with the same elements. This process would allow very close approach and therefore a high density of the element.

Many studies have shown that associated with the formation of plinthite is a particle size change. The plinthic material feels sandier and more brittle. Wood and Perkins (1976) analysed the pale soil matrix, mottles and plinthite and established that there was a decrease in measured clay which is probably related to aggregation of clay and silt to form silt and sand sized particles, which has been well established in iron rich soils. The marked changes are in the free iron content, which shows a 5 - 10 fold increase from the pale matrix to the plinthic materials. Also associated with the increase of iron is the presence of crystalline species of iron such as goethite and haematite.

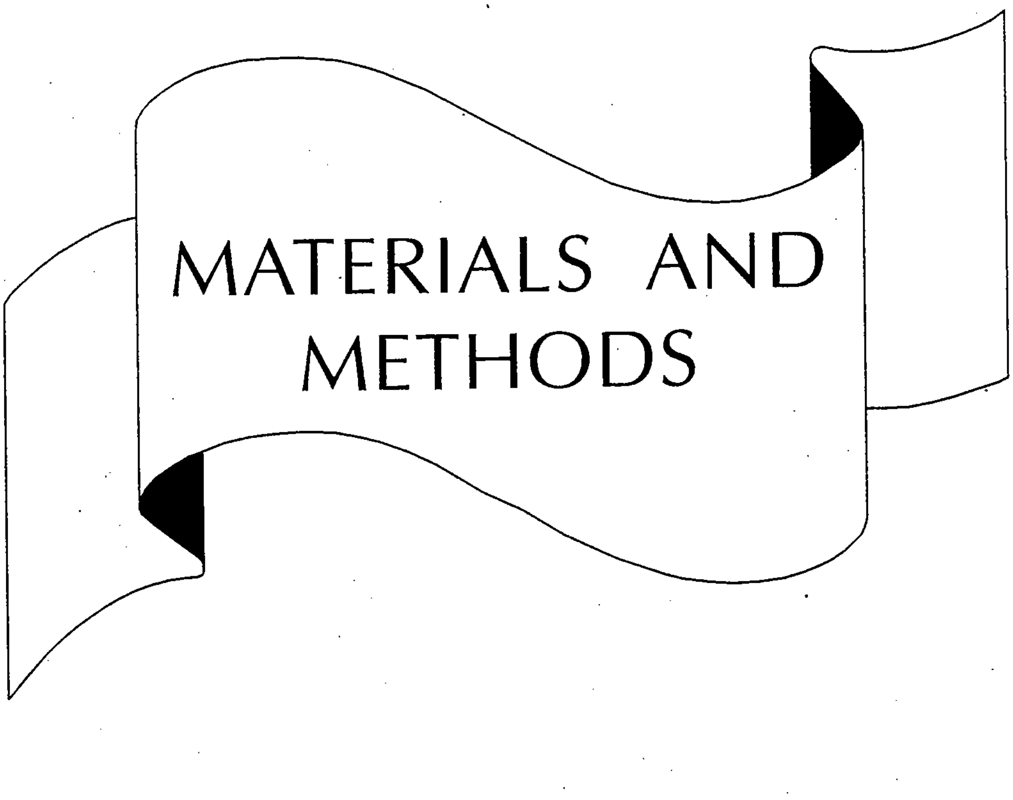
2.8. Organic and inorganic ameliorants in softening of laterites

Indurated laterites pose difficulties in their cultivation. Traditional farmers have been following certain practices like application of common salt in laterite pits dug for planting coconut in many regions, which, they say, will soften the hard laterites and help penetration of roots for initial establishment of the crop (Menon and Pandalai, 1958). Application of common salt at 2 kg/pit is recommended in lateritic areas (KAU, 1993).

Mineralisation or humification of fresh organic residues added to soil cause preferential dissolution and migration of ferric ion and aluminium. Fulvic acids and at pH above 6.5 humic acids can also attack and degrade minerals to form water soluble and water insoluble metal complexes. If metal / humic acid or metal / fulvic acid ratios are low, the complexes are water soluble, but if the ratios are high, the metal / fulvic acid or humic acid complexes become water insoluble (Schnitzer and Khan, 1972). Fulvic acid has been shown to be efficient for dissolving metals from goethite and gibbsite. Similarly strong solvent activity has been reported for humic acid and for hematite, pyrolusite, feldspar, biotite, enstatite, actinolite and epidote (Schnitzer and Khan, 1978).

The complexing of iron by humic materials appears to have an adverse effect on the structural stability of iron rich minerals as, along with iron, other elements such as aluminium, magnesium and potassium are also more readily released and brought into solution (Schnitzer and Khan, 1978).

Silicate application is reported to lower the zero point of charge (ZPC) of tropical soils and increase their cation exchange capacity. The degree of chemical weathering particularly the degree of desilication is indicated in the ZPC as highly leached ferruginous soils low in organic matter generally showed higher ZPC values (Khalid and Silva, 1978; Khalid *et al.*, 1978; Raman, 1986; Sreekala, 1993). These studies show the significance of silicates application on lowering the rate of pedogenic development and hardening of laterites in humid tropical regions.



MATERIALS AND METHODS

3. MATERIALS AND METHODS

The materials used and methodology followed to study the pedological and management aspects of hardening and softening of laterites under different land use systems are described in this chapter.

3.1. Study sites

Three land use systems, viz., cassava, rubber and uncultivated barren were selected from three agroclimatic zones of Kerala where laterite soils predomonate. The three land use systems lying adjacent and coming under the same soil series were selected from southern, central and northern agroclimatic zones of Kerala. The locations identified are Thiruvananthapuram, Angadipuram and Kannur.

3.2. Characterisation of the pedogenic environment

The pedogenic environments and land use systems selected were characterised by studying the geology, geomorphology, climate, relief, vegetation, age of the landscape and land use systems of the locations and the details are prepared following the procedure suggested by Ven *et al.* (1995).

3.3. Macromorphology of the pedons

At each location, pedons were selected in soils under cassava, rubber and uncultivated barren which were lying adjacent. Major geoclimatic and pedogenic parameters of the locations were studied in detail using standard methodology. From each land use system, pedons were studied to a depth of 2m. Site characteristics and soil profile descriptions were made following standard terminology (Ven *et al.*, 1995). Based on these studies and physico - chemical analyses, the pedons were classified according to Soil Taxonomy of USDA (Soil Survey Staff, 1998).

3.4. Collection and processing of soil samples and other soil materials

From each pedon genetic horizons were identified and marked and representative replicate soil samples were collected for various analysis described later in this chapter. To evaluate the efficacy of different ameliorants in softening of already indurated laterites, laterite blocks were collected from a laterite quarry near Bharathannur in Thiruvananthapuram. All blocks were collected from the same depth and used for the laboratory incubation experiment described in section 3.9.

The soil samples were air-dried and sieved through a 2 mm sieve to separate air-dry fine earth from gravel for various analyses. The gravel percent was also recorded. The processed samples were used for conducting various laboratory experiments described below.

3.5. Physico chemical properties related to hardening and softening of laterites

The soil samples collected from each horizon of the different pedons were subjected to various physico chemical analyses to assess the process of laterisation and to study the changes happening during hardening and softening of laterites.

Single value constants, viz., bulk density, particle density, porosity, maximum water holding capacity and volume expansion were studied following the procedure outlined by Wright (1939). Mechanical analysis was done by the International Pipette method (Klute, 1986) to estimate various soil separates which include coarse sand, fine sand, silt and clay. The quotient silt / clay (L/A value) was calculated since it is suggested as a means to measure the extent of laterisation and soil degradation. Water dispersible clay content was estimated following the International Pipette method described by Soil Survey Staff (1972). Loss on ignition was estimated by the method of Jackson (1962).

Organic carbon content of various horizons was estimated by the chromic acid digestion method of Walkley and Black (1934). Total amounts of N, P_2O_5, K_2O, CaO, MgO, SiO_2, Fe_2O_3 and Al_2O_3 were estimated following the procedures described by Hesse (1971). The molar ratios of silica : alumina, silica : iron and silica : sesquioxide were also calculated to assess the extent of laterisation.

At each location, the data on physico-chemical properties related to hardening and softening of laterites were statistically analysed for comparison using completely randomised design (CRD) with total number of horizons in each location as treatments and two replications. For significant parameters, the critical difference (CD) at 5 per cent level was computed to make the pair wise comparison.

$$CD = t\alpha \sqrt{\frac{2MSE}{r}}$$

where $t\alpha$ is the students' t table value at 5 per cent level corresponding to the error degree of freedom.

The common horizons under same land use from different locations were grouped as Ap/A, Bt_1 and Bt_2 layers and pooled analysis was done to compare the effect of land use on various properties studied. For significant parameters, the CD corresponding to land use x location was worked out to compare the means.

3.6. Soil acidity parameters

Soil pH was determined potentiometrically in water (1 : 2.5), 1M KCl (1 : 2.5), 0.01M $CaCl_2$ (1 : 2) and 1M NaF (1 : 50) (Black, 1965 and Page *et al.*, 1982). Exchangeable cations which include Ca, Mg, K and Na were determined in neutral 1N ammonium acetate extract. Calcium and magnesium were determined using Atomic Absorption Spectrophotometer (AAS) and potassium and sodium using Flame Photometer. Exchangeable acidity, exchangeable aluminium and exchangeable hydrogen were determined following the method of Hesse (1971). Extractable acidity was estimated using barium chloride - triethanol amine extract according to the method described by Hesse (1971).

Cation exchange capacity (CEC) of the various samples was determined by the neutral 1N ammonium acetate method (Page *et al.*, 1982) and by sum of cations method (Soil Survey Staff, 1998). CEC by sum of cations method is determined by adding sum of bases estimated by ammonium acetate method and barium chloride - triethanol amine extractable acidity. The effective cation exchange capacity (ECEC) was estimated by adding sum of bases extracted with neutral 1N ammonium acetate and 1N KCl extractable aluminium (Reeuwijk, 1993). The percent base saturation was estimated based on CEC values from ammonium acetate and sum of cations methods.

At each location, the various soil acidity parameters were statistically analysed for comparison using completely randomised design (CRD) with total number of horizons in each location as treatments and two replications. For significant parameters, the critical difference (CD) at five per cent level was computed to make the pair wise comparisons. The common horizons under same land use from different locations were grouped as Ap/A, Bt_1 and Bt_2 layers and pooled analysis was done to compare the effect of land use on various properties studied. For significant parameters, the CD corresponding to land use x location was worked out to compare the means.

3.7. Free oxides of iron and aluminium in pedons

Dithionite and oxalate extractable iron (Fe_d and Fe_0) and aluminium (Al_d and Al_0) were estimated by the procedure outlined by Mehra and Jackson (1960) modified by McKeague and Day (1966). Based on these four estimations, the following ratios / forms of free oxides of iron and aluminium were calculated based on standard references cited against each of them.

1. Active iron ratio, Fe_o / Fe_d (Mc Keague and Day, 1966)
2. Crystalline iron oxides, Fe_d - Fe_o (Bennoah *et al*, 1997)
3. Aluminium bound in iron oxides, Al_d - Al_o (Fontes and Weed, 1991)
4. Aluminium substitution in iron oxides,

$$\frac{(Al_d - Al_o)}{(Al_d - Al_o) + (Fe_d - Fe_o)} \times 100$$

(Shadfan *et al.*, 1985)

The data on the free oxides of iron and aluminium, active iron ratio, crystalline iron oxides, aluminium bound in iron oxides and aluminium substitution in iron oxides at each location were statistically analysed for comparison using completely randomised design (CRD) with total number of horizons in each location as treatments and two replications. For significant parameters, the critical difference (CD) at five per cent level was computed to make the pairwise comparisons. The common horizons under the same land use from different locations were grouped as Ap/A, Bt_1 and Bt_2 layers and pooled analysis was done to compare the effect of land use on various properties studied. For significant parameters, the CD corresponding to land use x location was worked out to compare the means.

3.8. Free oxides of iron and aluminium and strength of hard and soft laterites

From the indurated laterite blocks collected from the three study sites, harder and softer spots were carefully scraped and separated for analysis of oxalate and dithionite extractable iron and aluminium (Mc Keague and Day, 1966). Three replicate samples were collected for each treatment for statistical comparison. The Al - substitution in soils was calculated using the formula described earlier.

To measure the strength of the materials in laterite samples, a micropenetrometer attached to a single action hydraulic cylinder operated with a pump was used. The force needed for a 3 mm diameter flat tip to penetrate the surface of the samples to a depth of 2 mm was measured on an oil pressure gauge as pounds per square inch and then calculated as kg cm^{-2}. A flat tip was found to be more suitable for the penetration measurements than a pointed tip. To prevent the roughness of the bottom surface of the different samples from affecting their resistance to penetration pressure, laterite samples surrounded with the soil matrix were embedded in a high viscosity resin that hardened at room temperature. Samples were not completely immersed in resin. After hardening of the resin, the exposed portion of the sample was ground with medium-grit sand paper to obtain a flat surface for the penetration. The resin did not penetrate the pores in the samples, thereby preventing any change in the strength of the materials. The small penetrometer tip and the large size of the bulk sample also prevented any effect of the resin on the measurement. Penetration pressures were measured with the penetrometer at selected soft and hard spots in laterite. Samples were then scraped from the penetrated spots for chemical analysis.

3.9. Efficacy of organic and inorganic ameliorants in softening of indurated laterites

In order to study the efficacy of organic and inorganic ameliorants in softening of indurated laterites, a laboratory experiment was conducted in Completely Randomised Design (CRD) with 19 treatments and three replications. Different treatments used for the experiment are given below.

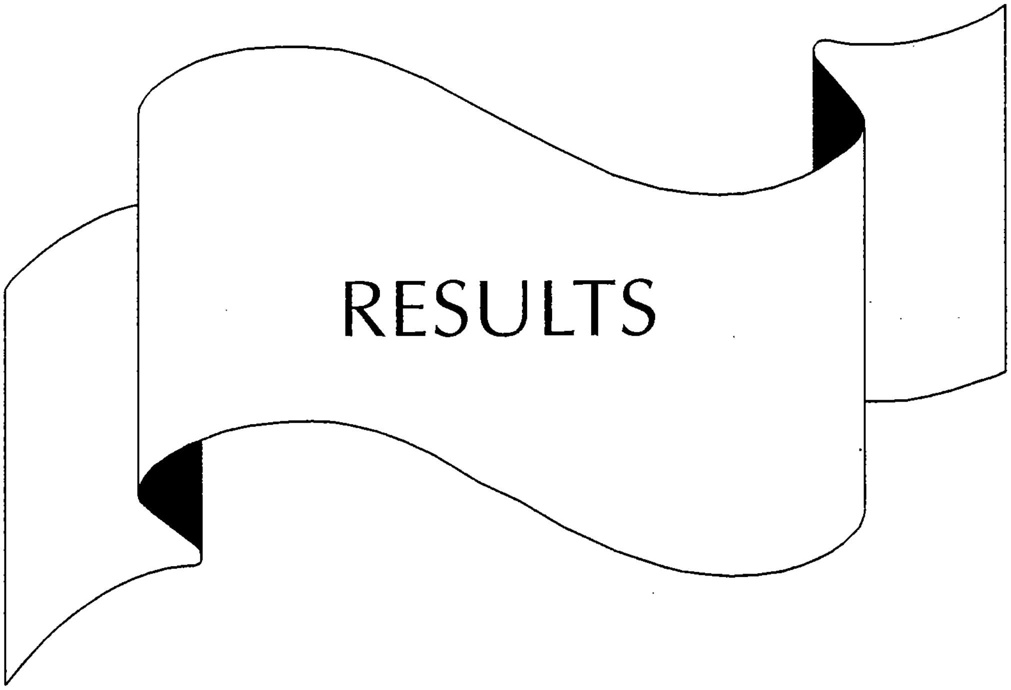
Various treatments of the laboratory experiment

Treatment No.	Treatment	
T1	Cowdung slurry	20 %
T2	Cowdung slurry	40 %
T3	Vermiwash	25 %
T4	Vermiwash	50%
T5	Green leaf extract *(Sesbania grandiflora)*	20 %
T6	Green leaf extract	40%
T7	NaCl	20%
T8	NaCl	40%
T9	$NaSiO_3$	20 %
T10	$NaSiO_3$	40%
T11	$CaCl_2$	20%
T12	$CaCl_2$	40%
T13	$Ca_2Si_3O_8$	20%
T14	$Ca_2Si_3O_8$	40%
T15	$MgCl_2$	20%
T16	$MgCl_2$	40%
T17	$Mg_2Si_3O_8$	20%
T18	$Mg_2Si_3O_8$	40%
T19	Distilled Water	

Hard laterite block cut from a laterite quarry in Thiruvananthapuram was cut into 57 uniform sized blocks. These blocks were immersed in the different treatments mentioned above for a period of one year. Analysis of the material laterite was done before the experiment and at intervals of 3, 6, 9 and 12 months. Analyses were done to estimate the contents of bases, sesquioxides, oxalate and dithionite extractable iron and aluminium substitution in iron oxides in laterite samples at different time intervals. Based on chemical analytical data and statistical analysis, treatments having maximum effect on reversal of hardening were selected for mineralogical and micromorphological study. Mineralogical analysis of the clay fraction of the selected laterite samples were done using X-ray diffraction technique.

X-ray diffraction was carried out on powder mounts using a Philips X-ray diffractometer with a Cu-Kα target X-ray tube operated at 40 kV and 20 mA (Whittig, 1965). The X-ray diffraction patterns were recorded at a speed of 2° 2θ/min for the selected samples. For iron oxides, 111 goethite and 110 haematite peaks were used for the measurement so as to minimise interference. Peak broadening were also studied to assess the change in crystallinity of important minerals. The width of the lines at half maximum intensity was used for assessing the crystallinity of the various minerals (Klug and Alexander, 1974). Minerals were identified from X-ray diffractograms using differentiating criteria compiled by Bayliss *et al.* (1980).

The strength of the laterite samples before and after treatments with selected ameliorants was measured using a micropenetrometer attached to a single action hydraulic cylinder operated with a pump. The procedure followed was the same as described in the previous section (3.8). Micromorphological studies were also done on the laterite samples before and after treatments using a Petrological microscope (Ortholux 11 POL-BK) to study the changes that have occurred due to various treatments imposed on a hard laterite.



RESULTS

4. RESULTS

The results of the different experiments conducted to study the pedological and management aspects of hardening and softening of laterites under different land use systems of Kerala are described here.

4.1. Pedogenic environment of the study sites

Kerala state, located in south-west India as a narrow coastal strip bounded on the north-east by Karnataka, east by Tamil Nadu and on the west by Lakshadeep sea, is the study site of this project. Since Kerala is considered as the '*type locality*' of laterite from the time of Francis (Hamilton) Buchanan, it is the ideal place to study the intricate phenomena of hardening and softening of laterites under different land use systems.

Various climatic and pedogenic parameters of the three locations identified for the study are given in Table 1 and the study sites are shown in Fig. 1. In general, the climatic and other geoclimatic and pedogenic factors are conducive to the process of laterisation. The climate is humid tropical and prolonged bimodal rainfall

Table 1. Details of study sites

Parameters	Location		
	Thiruvananthapuram	Angadipuram	Kannur
Latitude (N)	8°19'	11°30'	11°50'
Longitude (E)	77°11'	76°40'	76°10'
Altitude (m)	130	50	75
Annual precipitation (mm)	1840	2907	3275
Period of dry spell (months)	3	4	5
Laterite number	35	68	85
Parent rock	Khondalites	Charnockites	Dharwar schists
Formation	Sedimentary	In-situ	In-situ
SMR[1]	Ustic	Ustic	Ustic
STR[2]	Isohyperthermic	Isohyperthermic	Isohyperthermic

[1]SMR - Soil moisture regime, [2]STR - Soil temperature regime

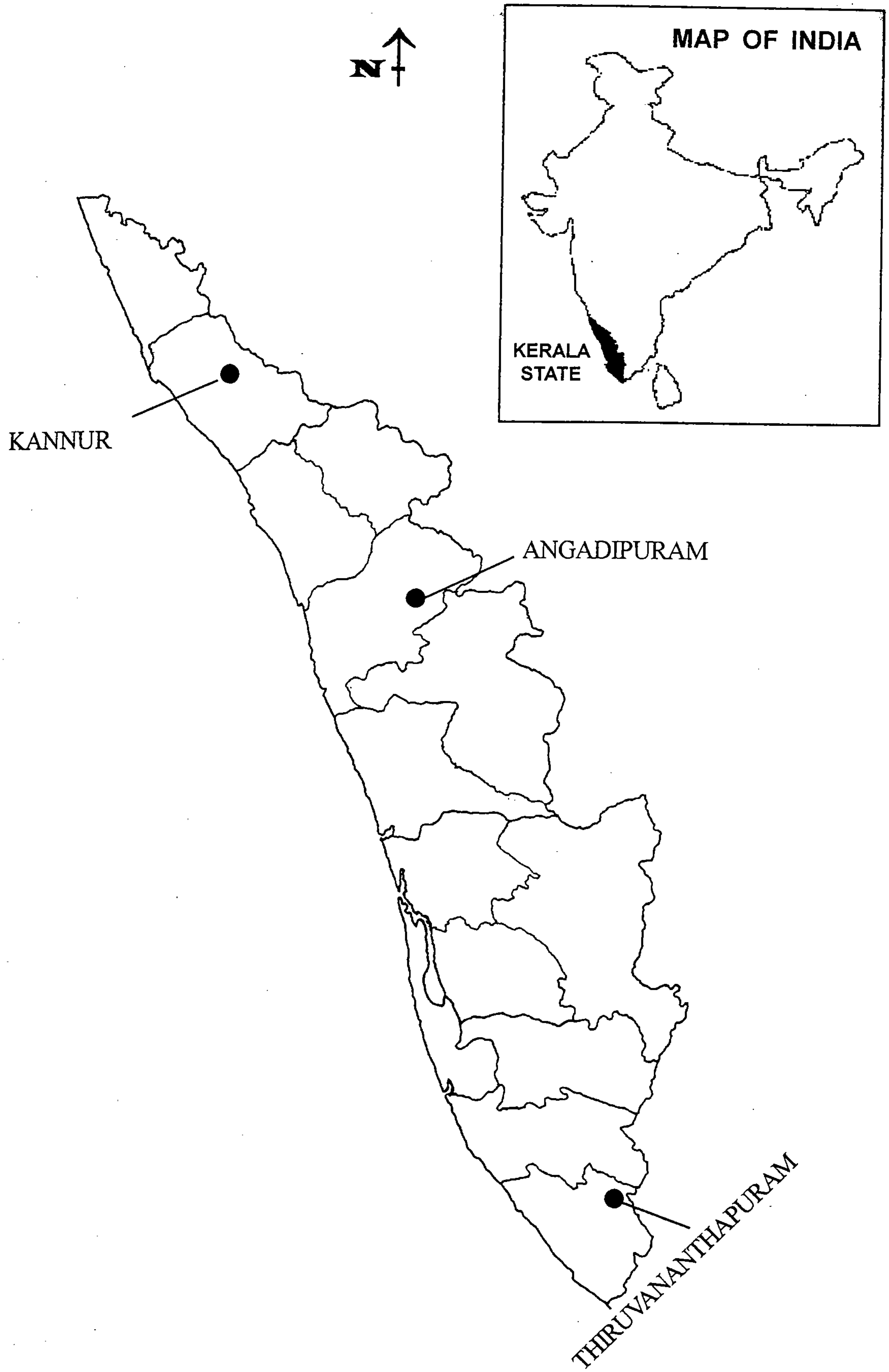


Fig. 1. Map showing the study sites

pattern and intermittent dry spells observed here are conducive to laterisation (Fig. 2). Out of the three locations selected for the study, Thiruvananthapuram has a laterite number of 35 while it is 68 for Angadipuram and a high value of 85 for Kannur. Annual precipitation and period of dry spell were lower in Thiruvananthapuram and progressively higher values could be observed for Angadipuram and Kannur, respectively.

The parent rocks over which the laterites developed also varied at the three locations as observed from Table 1. The soil moisture regime is ustic in all locations and with regard to soil temperature regime, all locations have an isohyperthermic soil temperature regime.

The study site, Kerala state, constitute an important segment of western passive continental margin of the Indian shield, and is bounded by Western Ghats on the east and the Arabian sea on the west. The precambrian crystalline rocks dominate over the other two formations viz., tertiary formation and the recent to subrecent sediments. The pre-cambrian rocks comprise rock types like Charnockites, Khondalites and Dharwar schists which are the parent rocks of our three locations.

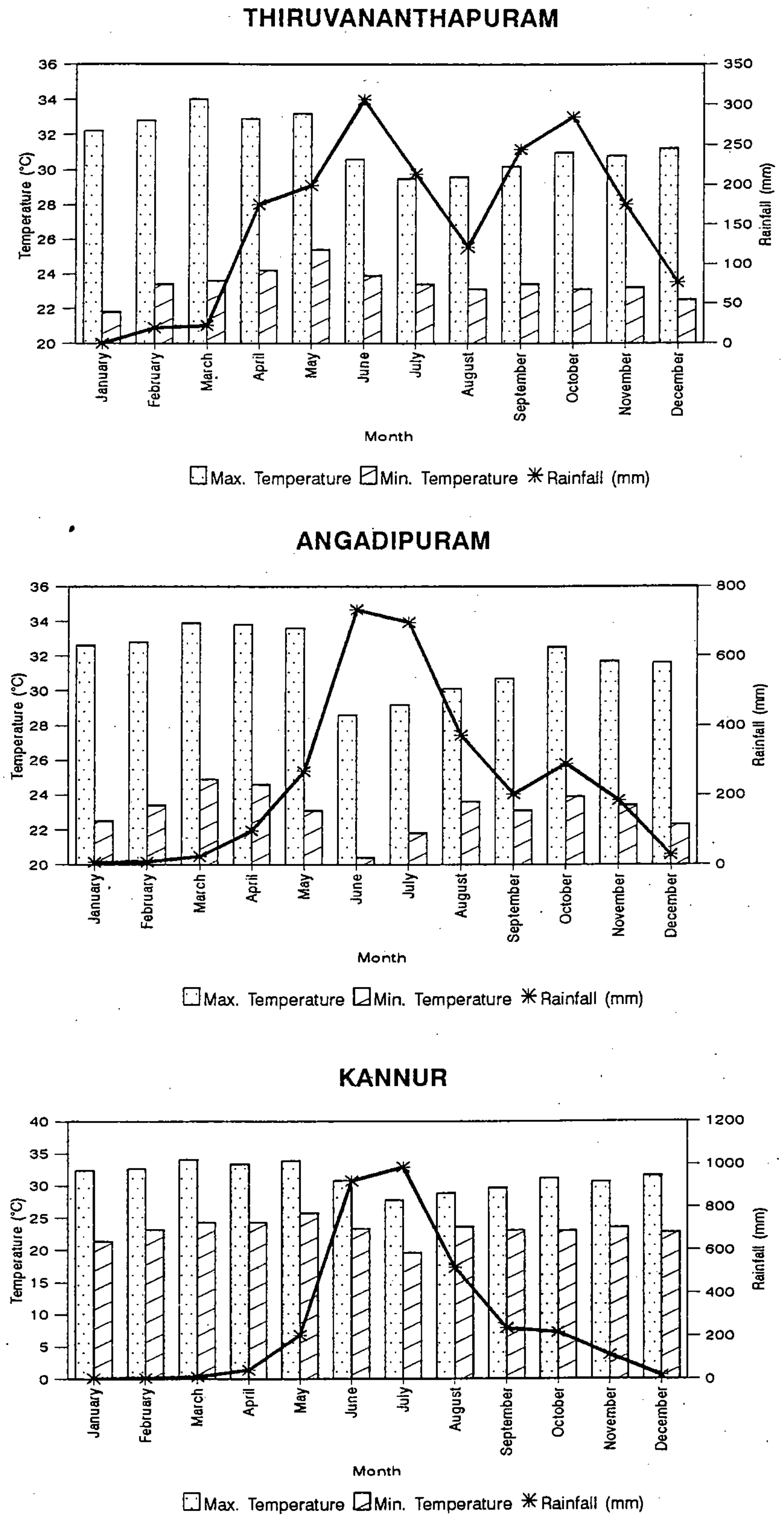


Fig. 2. Meteorological parameters of the study sites

4.2. Site characteristics and soil profile morphology

A detailed morphological description of the various profiles is given here.

Location I. Thiruvananthapuram

A General Information

1.	Soil name	:	Laterite soil
2.	Location	:	Vattakarikkakom near Bharathanoor in Thiruvananthapuram district
3.	Elevation	:	130 m
4.	Co-ordinates	:	8°19' N latitude an 77°11' E longitude
5.	General climate	:	Humid tropical. Annual precipitation : 1840mm Mean annual temperature : 27.5°C Period of dry spell : 3 months Laterite No : 35
6.	Soil climate	:	Isohyperthermic soil temperature regime Ustic soil moisture regime.
7.	Landform and topography	:	Undulating upland, sloping irregular.
8.	Land use and vegetation	:	Rainfed arable cultivation. Cassava and Rubber are the major cultivated crops.
9.	Parent material	:	Khondalite.
10	Surface characteristics	:	No rock outcrops. Very few surface coarse fragments. Slight sheet erosion
11.	Soil water relations	:	Moderately well drained. Never saturated. Slow run-off. Deep phreatic fresh ground water.

B. Soil Horizon Description

Profile 1. Cassava

Horizon	Depth (cm)	Description
Ap	0-28	Dark reddish brown, 5YR 3/2 moist and yellowish red, 5 YR 4/6 dry; sandy clay loam; strong, medium , angular blocky; slightly hard, firm, slightly sticky ; medium , few pores; hard ironstone nodules and concretions; medium, few roots, clear, smooth boundary; pH 5.1.
AB	28-63	Dark reddish brown, 5YR 3/4 moist and reddish brown. 5YR 4/4 dry; sandy clay loam; moderate, medium, angular blocky; slightly hard; friable, slightly sticky; medium, few pores; fine, very few roots; gradual, wavy boundary; pH 5.0.
Bt_1	63-97	Dark red, 2.5YR 3/6 moist and red, 2.5YR 4/6 dry; sandy clay; strong, coarse, angular blocky; slightly hard, firm, sticky ; medium, common pores; few clay cutans; gradual, wavy boundary; pH 5.2
Bt_2	97-200	Dark red, 2.5YR 3/6 moist and red, 2.5YR 5/6 dry; sandy clay loam; strong, coarse, angular blocky; hard, firm, very sticky; medium, common pores; hard ironstone concretions; clear, wavy boundary; pH 5.0.

Profile 2. Rubber

Horizon	Depth (cm)	Description
Ap	0-9	Very dusky red, 2.5YR 2.5/2 moist and dusky red, 2.5 YR 3/2 dry; sandy clay loam; moderate, medium, angular blocky; slightly hard, friable, slightly sticky; medium, common pores; hard ironstone nodules; fine, common roots, few earthworm channels; clear, smooth boundary; pH 5.2.
A1	9-20	Dark reddish brown, 2.5YR 3/4 moist and reddish brown. 2.5YR 4/4 dry; sandy clay loam; moderate, medium, granular; slightly sticky; medium, few pores; very few clay cutans; medium, few roots; clear, wavy boundary; pH 5.0.
A2	20-34	Dark red, 2.5YR 3/6 moist and red, 2.5YR 4/6 dry; sandy clay loam; moderate, medium, granular; slightly hard, firm, slightly sticky; coarse, common pores; very few clay cutans; few, fine roots; clear, wavy boundary; pH 4.9.
AB	34-43	Dark red, 2.5YR 3/6 moist and dark red, 2.5YR 3/6 dry; sandy clay; strong, coarse, angular blocky; slightly hard, firm, slightly sticky; medium, common pores; very few roots; gradual, wavy boundary; pH 5.3.
Bt_1	43-114	Red, 2.5YR 4/8 moist and light red, 2.5YR 6/8 dry; sandy clay; strong, coarse, angular blocky; slightly hard, firm, sticky; medium, common pores; few clay cutans; medium, few roots; clear, wavy boundary; pH 5.3.
Bt_2	114-200	Red, 2.5YR 4/8 moist and light red, 2.5YR 6/8 dry; sandy clay; strong, coarse, angular blocky; hard, firm ,very sticky; coarse, common pores; few clay cutans; ironstone gravels, clear, wavy boundary; pH 5.2.

Profile 3. Uncultivated Barren

Horizon	Depth (cm)	Description
A	0-34	Very dusky red , 2.5YR 2.5/2 moist and yellowish red, 2.5 YR 3/2 dry; sandy clay loam; moderate to strong, medium ,granular ; loose, very friable, slightly sticky ; medium , few pores; hard ironstone nodules and concretions; medium, few roots, clear, smooth boundary; pH 5.1.
Bt_1	34-89	Dark red, 2.5YR 3/6 moist and red ,2.5YR 4/8 dry; sandy clay loam; strong, coarse, angular blocky; slightly hard; firm, sticky; fine, common pores; very few, distinct clay cutans; presence of plinthite in more than half of the total volume; gradual, wavy boundary; pH 4.8.
Bt_2	89-200	Red, 2.5YR 4/8 moist and red, 2.5YR 4/8 dry; sandy clay ; strong, coarse, angular blocky; hard, firm, sticky ; medium, few pores; clear, wavy boundary; pH 4.9.

Location II Angadipuram

A. General Information

1. Soil name	:	Laterite soil
2. Location	:	Angadipuram near Perinthalmanna in Malappuram district
3. Elevation	:	50 m
4. Co-ordinates	:	11°30' N latitude an 76°40' E longitude
5. General climate	:	Humid tropical. Mean annual precipitation : 2907mm Mean annual temperature : 28.0°C Period of dry spell : 4 months Laterite No : 68
6. Soil climate	:	Isohyperthermic soil temperature regime Ustic soil moisture regime.
7. Landform and topography	:	Undulating upland, sloping irregular.
8. Land use and vegetation	:	Rainfed arable cultivation. Cassava and Rubber are the major cultivated crops.
9. Parent material	:	Charnockite.
10. Surface characteristics	:	Very few rock outcrops, few surface coarse fragments. Moderate sheet erosion and slight rill erosion.
11. Soil water relations	:	Well drained. Never saturated. Moderately rapid run - off. Extremely deep, phreatic , fresh ground water.

B. Soil Horizon Description

Profile 1. Cassava

Horizon	Depth (cm)	Description
Ap	0-21	Dark reddish brown, 5YR 2.5/2 moist and dark reddish gray, 5 YR 4/2 dry; sandy clay loam; moderate, medium , granular; slightly hard, very friable, slightly sticky ; medium , common pores; fine, common roots, abrupt, smooth boundary; pH 5.0.
EB	21-40	Dark reddish brown, 5YR 2.5/2 moist and reddish brown. 5YR 4/3 dry; sandy clay loam; moderate, medium, granular; slightly hard; firm, slightly sticky; medium, common pores; hard ironstone gravels and nodules; fine, few roots; clear , smooth boundary; pH 4.9.
B	40-108	Dark reddish brown, 5YR 3/4 moist and yellowish red, 5YR 5/6 dry; sandy clay loam;strong, coarse, angular blocky; hard, firm, sticky ; medium, few pores; ironstone nodules and concretions; fine, very few roots; clear, smooth boundary; pH 4.8
Bt_1	108-142	Reddish yellow, 5YR 6/8 moist and reddish yellow, 5YR 7/8 dry; sandy clay loam; strong, coarse, angular blocky; hard, firm, very sticky; fine, few pores; hard clay cutans; clear, wavy boundary; pH 5.0.
Bt_2	142-200	Reddish yellow, 5YR 7/8 moist and reddish yellow, 5YR 7/6 dry; sandy clay loam; strong, coarse, angular blocky; very hard, firm, sticky ; fine, few pores; very few clay cutans; clear, smooth boundary; pH 5.1

Profile 2. Rubber

Horizon	Depth (cm)	Description
Ap	0-13	Very dark gray, 5YR 3/1 moist and dark gray, 5 YR 4/1 dry; sandy clay loam; strong, medium, angular blocky; slightly hard, friable, slightly sticky; medium, many pores; hard ironstone nodules; fine, common roots, few earthworm channels; diffuse, wavy boundary; pH 5.2.
Eo	13-24	Dark reddish brown, 5YR 4/4 moist and reddish brown. 5YR 5/4 dry; sandy clay loam; moderate, medium, angular blocky; slightly hard, firm, slightly sticky; medium, common pores; few sesquioxide cutans; medium, common roots; clear, wavy boundary; pH 5.1.
B	24-42	Dark reddish brown, 5YR 3/3 moist and reddish brown, 5YR 4/3 dry; sandy clay loam; strong, coarse, angular blocky; slightly hard, firm, sticky; medium, common pores; hard ironstone concretions; medium, few roots; diffuse, smooth boundary; pH 5.
Bt_1	42-115	Dark reddish brown, 5YR 3/3 moist and reddish brown, 5YR 4/3 dry; sandy clay; moderate, medium, angular blocky; slightly hard, firm, sticky; fine, few pores; hard ironstone nodules and concretions; medium, very few roots; clear, smooth boundary; pH 5.4.
Bt_2	115-200	Red, 2.5YR 4/6 moist and red, 2.5YR 5/6 dry; sandy clay loam; moderate, medium, angular blocky; hard, firm, sticky; medium, few pores; hard ironstone gravels, medium, very few roots; clear, wavy boundary; pH 5.2.

Profile 3. Uncultivated Barren

Horizon	Depth (cm)	Description
A1	0-8	Dark reddish brown, 5YR 3/2 moist and yellowish gray, 5 YR 4/2 dry; sandy clay loam; moderate, medium, granular; loose, very friable, slightly sticky; medium, many pores; hard ironstone gravels; fine, very few roots, clear, smooth boundary; pH 4.9
A2	8-37	Dark reddish brown, 5YR 3/3 moist and reddish brown ,5YR 4/3 dry; sandy clay loam; strong, medium, granular; slightly hard; friable, slightly sticky; medium, many pores; clear, wavy boundary; pH 4.8.
E	37-74	Dark red, 2.5YR 4/6 moist and red, 2.5YR 5/8 dry; sandy clay loam ; strong, fine, angular blocky; slightly hard, firm, slightly sticky ; fine, common pores; hard ironstone nodules; abrupt, smooth boundary; pH 4.9.
Bt_1	74-108	Dark red, 2.5YR 3/6 moist and red, 2.5YR 4/8 dry; sandy clay loam ; strong, coarse, angular blocky; hard, firm, very sticky ; coarse, common pores; presence of plinthite in more than half of the volume; clear, smooth boundary; pH 5.3.
Bt_2	108-200	Red, 2.5YR 4/6 moist and red, 2.5YR 5/8 dry; sandy clay loam ; moderate, medium, angular blocky; very hard, firm, sticky ; medium, common pores; ironstone nodules and concretions, weakly cemented by clay-sesquioxides; clear, wavy boundary; pH 5.1.

Location III Kannur

A General Information

1.	Soil name	: Laterite soil
2.	Location	: Thaliparamba in Kannur district
3.	Elevation	: 75m
4.	Co-ordinates	: 11°50' N latitude an 76°10' E longitude
5.	General climate	: Humid tropical. Mean annual precipitation : 3275 mm Mean annual temperature : 28.5°C Period of dry spell : 5 months Laterite No :80
6.	Soil climate	: Isohyperthermic soil temperature regime Ustic soil moisture regime.
7.	Landform and topography	: Rolling terrain, upland landform, middle slope.
8.	Land use and vegetation	: Rainfed arable cultivation. Cassava and Rubber are the major cultivated crops.
9.	Parent material	: Dharwar schists.
10.	Surface characteristics	: Very few rock outcrops, few surface coarse fragments. Moderate sheet erosion and rill erosion.
11.	Soil water relations	: Well drained. Never saturated. Moderately rapid run-off. Extremely deep, phreatic , fresh ground water.

B Soil Horizon Description

Profile 1. Cassava

Horizon	Depth (cm)	Description
Ap	0-17	Dark reddish brown, 5YR 2.5/2 moist and dark reddish gray, 5 YR 4/2 dry; sandy clay loam; moderate, medium , granular; slightly hard, friable, slightly sticky ; medium , common pores; hard ironstone gravel;medium , common roots, abrupt, smooth boundary; pH 5.1.
B1	17-36	Dark reddish brown, 5YR 3/4 moist and reddish brown. 5YR 5/4 dry; sandy clay loam; moderate, medium, angular blocky; slightly hard; firm, slightly sticky; fine, common pores; fine, few roots; clear , smooth boundary; pH
B2	36-79	Dark reddish brown, 5YR 2.5/2 moist and reddish brown, 5YR 5/4 dry; sandy clay loam; strong, coarse, angular blocky; slightly hard, friable , slightly sticky ; fine, few pores; hard ironstone nodules ; fine, very few roots; abrupt, smooth boundary; pH 4.9
Bt_1	79-137	Dark reddish brown, 5YR 3/3 moist and reddish brown, 5YR 4/3 dry; sandy clay loam; strong, medium, angular blocky; hard, firm, sticky; fine, common pores; clear, wavy boundary; pH 5.2
Bt_2	137-200	Red, 2.5YR 4/6 moist and red, 2.5YR 5/6 dry; sandy clay loam; strong, coarse, angular blocky; hard, very firm, very sticky ; medium, common pores; ironstone nodules and concretions; clear, smooth boundary; pH 4.9

Profile 2. Rubber

Horizon	Depth (cm)	Description
Ap	0-17	Dark reddish brown, 5YR 2.5/2 moist and dark reddish gray, 5 YR 4/2 dry; sandy clay loam; strong, medium , angular blocky; slightly hard, friable, slightly sticky ; medium , common pores; ironstone gravels ; fine, few roots, few earthworm channels; clear smooth boundary; pH 4.9.
A1	17-39	Dark reddish brown, 5YR 2.5/2 moist and reddish brown. 5YR 4/3 dry; sandy clay loam; moderate, medium, angular blocky; slightly hard, firm, slightly sticky; medium, few pores; hard ironstone nodules; medium, very few roots; abrupt , smooth boundary; pH 4.8.
Eo	39-108	Dark reddish brown, 5YR 3/4 moist and yellowish red, 5YR 5/6 dry; sandy clay loam; strong, coarse, angular blocky ; slightly hard, firm, sticky ; fine, few pores;few sesquioxide cutans; medium ,very few roots; gradual, wavy boundary; pH 4.8.
Bt_1	108-141	Reddish yellow, 5YR 6/8 moist and reddish yellow , 5YR 7/8 dry; sandy clay; strong, coarse, angular blocky ; hard, firm, very sticky; fine, common pores; few clay cutans and concretions ; medium, very few roots; clear , wavy boundary; pH 5.2.
Bt_2	141-200	Reddish yellow, 5YR 6/8 moist and reddish yellow, 5YR 7/8 dry; sandy clay loam; strong , medium , angular blocky; very hard, firm , sticky; fine , common pores; very few roots; clear, wavy boundary; pH 5.0.

Profile 3. Uncultivated Barren

Horizon	Depth (cm)	Description
A	0-12	Dark reddish brown, 5YR 3/2 moist and dark reddish gray , 5 YR 4/2 dry; sandy clay loam; moderate, medium ,granular; slightly hard, very friable, slightly sticky; medium, few pores; ironstone gravel; fine, very few roots, clear, smooth boundary; pH 5.0.
E	12-27	Dark reddish brown, 5YR 3/4 moist and reddish brown ,5YR 4/3 dry; sandy clay loam; moderate, medium, angular blocky; hard; firm, sticky; fine , common pores; clear, wavy boundary; pH 4.9
EB	27-81	Dark red, 2.5YR 3/6 moist and red, 2.5YR 4/8 dry; sandy clay loam; strong, coarse, angular blocky; slightly hard, firm, slightly sticky; medium, few pores; clear , smooth boundary; pH 5.0.
Bt_1	81-139	Dark red, 2.5YR 3/6 moist and red, 2.5YR 4/8 dry; sandy clay loam ; strong, medium, angular blocky; hard, very firm, very sticky ; fine, common pores; clear , wavy boundary; pH 5.1.
Bt_2	139-200	Red, 2.5YR 4/6 moist and red, 2.5YR 5/8 dry; sandy clay loam; strong , coarse, angular blocky; medium , few pores; gradual , smooth boundary; pH 4.9.

4.2.1. Classification scheme of the pedons

Based on field observations and laboratory analyses given in later chapters, the pedons were classified under Soil Taxonomy (Soil Survey Staff, 1998) upto great group levels (Table 2). From the table, it is evident that all the pedons studied come under the soil order Ultisols and suborder Ustults.

4.3. Physico chemical characteristics related to hardening and softening of laterites

4.3.1. Single value constants

The single value constants studied are bulk density (BD), particle density (PD), porosity, maximum water holding capacity (MWHC) and volume expansion (Table 3). At Thiruvananthapuram, significant increase in bulk density could be observed down the profile from Ap/A to Bt_1 to Bt_2 layers in all the land use systems under study. Among the three different land use systems, the bulk density differed significantly in the Bt_1 layer, highest value of 1.25 Mg m^{-3} being recorded in soils under rubber and lowest value of 1.20 Mg m^{-3} recorded in uncultivated barren, which was on par with that of cassava. No significant difference in bulk density could be observed among Ap/A layers or among Bt_2 layers under different land use systems. In the case of particle density, no significant difference could be observed down the profiles or among profiles of different land uses.

Table 2. Classification scheme of the pedons

Location	Land use	Classification
Thiruvananthapuram	Cassava	Plinthic Haplustults
	Rubber	Typic Haplustults
	Uncultivated barren	Typic Plinthustults
Angadipuram	Cassava	Plinthic Haplustults
	Rubber	Kanhaplic Haplustults
	Uncultivated barren	Typic Rhodustults
Kannur	Cassava	Typic Haplustults
	Rubber	Typic Haplustults
	Uncultivated barren	Typic Plinthustults

Table 3. Single value constants of the pedons

Horizon	Depth (cm)	B.D Mg m^{-3}	P.D Mg m^{-3}	Porosity %	MWHC %	Volume expansion %
I. Thiruvananthapuram						
A. Cassava						
Ap	0-28	1.15	2.03	36.86	35.00	1.81
AB	28-63	1.19	2.19	40.86	32.70	1.61
Bt$_1$	63-97	1.22	2.47	40.51	33.90	1.40
Bt$_2$	97-200	1.24	2.56	41.51	32.40	1.44
B. Rubber						
Ap	0-9	1.16	2.04	38.17	36.00	1.87
A1	9-20	1.19	2.16	41.00	33.20	1.66
A2	20-34	1.21	2.20	40.65	33.70	1.63
AB	34-43	1.20	2.27	41.53	35.20	1.41
Bt$_1$	43-114	1.25	2.52	41.40	34.80	1.39
Bt$_2$	114-200	1.26	2.60	40.78	34.70	1.44
C. Uncultivated barren						
A	0-34	1.17	2.04	37.39	33.80	1.78
Bt$_1$	34-89	1.20	2.49	39.56	30.40	1.42
Bt$_2$	89-200	1.25	2.59	37.78	32.10	1.39
CD		0.02	NS	1.36	1.10	0.28
II. Angadipuram						
A. Cassava						
Ap	0-21	0.99	2.59	51.75	41.10	1.31
EB	21-40	1.04	2.63	49.37	38.90	1.34
B	40-108	1.10	2.68	50.67	40.00	1.29
Bt$_1$	108-142	1.12	2.65	53.34	44.30	1.49
Bt$_2$	142.200	1.15	2.67	54.22	39.65	1.36
B. Rubber						
Ap	0-13	0.99	2.62	52.05	44.15	1.34
Eo	13-24	1.03	2.69	50.69	40.75	1.39
B	24-42	1.10	2.76	50.26	41.20	1.34
Bt$_1$	42-115	1.09	2.67	54.85	45.35	1.55
Bt$_2$	115-200	1.14	2.66	56.67	38.30	1.40

Table 3. (Contd....)

Horizon	Depth (cm)	B.D	P.D	Porosity %	MWHC %	Volume expansion %
		Mg m^{-3}				
C. Unculivated barren						
A1	0-8	1.04	2.59	50.68	40.30	1.28
A2	8-37	1.07	2.63	48.65	39.00	1.31
E	37-74	1.11	2.68	50.41	39.55	1.29
Bt$_1$	74-108	1.13	2.65	53.94	43.65	1.46
Bt$_2$	108-200	1.17	2.67	53.54	38.90	1.39
CD		0.03	0.03	NS	1.10	0.03
III. Kannur						
A. Cassava						
Ap	0-17	1.23	2.46	54.24	38.15	1.64
B1	17-36	1.23	2.52	52.10	36.00	1.39
B2	36-79	1.24	2.56	49.94	36.05	1.39
Bt$_1$	79-137	1.30	2.51	52.62	39.25	1.51
Bt$_2$	137-200	1.32	2.59	52.14	36.00	1.39
B. Rubber						
Ap	0-17	1.20	2.42	55.02	40.05	1.67
A1	17-39	1.23	2.51	52.10	36.80	1.40
E0	39-108	1.24	2.56	48.74	36.00	1.41
Bt$_1$	108-141	1.30	2.53	53.40	39.95	1.52
Bt$_2$	141-200	1.33	2.60	52.74	35.95	1.38
C. Uncultivated barren						
A	0-12	1.25	2.45	53.81	36.70	1.61
E	12-27	1.27	2.51	50.92	35.80	1.39
EB	27-81	1.28	2.54	51.20	35.90	1.41
Bt$_1$	81-139	1.27	2.50	52.68	38.70	1.52
Bt$_2$	139-200	1.30	2.56	52.10	35.45	1.43
CD		0.03	0.02	1.21	NS	0.04

Porosity of the surface horizons did not differ significantly while in Bt_1 layer of soils under rubber, significantly higher value, compared to that of uncultivated barren could be observed. The hard laterite layer (Bt_2) of soils under cassava and rubber recorded significantly higher porosity compared to that of uncultivated barren. The values for soils under cassava and rubber were on par.

Maximum water holding capacity of both surface and Bt_1 layers in soils under cassava and rubber was significantly higher compared to those of uncultivated barren. In the case of Bt_2 layer, soils under rubber had significantly higher value (34.7 per cent) compared to that of cassava and uncultivated barren (32.4 and 32.1 per cent respectively). Volume expansion of surface, Bt_1 or Bt_2 layers under different land uses didn't show any significant difference.

At Angadipuram, significantly lower bulk density was observed in surface layer of soils under cassava and rubber, which were on par, than that of uncultivated barren. Same trend was observed in Bt_1 layers too while no difference was observed among Bt_2 layers. No significant difference in particle density and porosity was observed in Ap/A, Bt_1 or Bt_2 layers of pedons under different land uses.

The maximum water holding capacity of epipedons as well as Bt_1 layers of soils under cassava and uncultivated barren was on par while that of rubber was significantly higher. Highest values could be observed in Bt_1 layer in all pedons. Significantly higher volume expansion (1.34

per cent) could be observed in epipedon of soils under rubber compared to that of uncultivated barren (1.28 per cent). Epipedon of soils under cassava recorded a value of 1.31 per cent which is on par with that of uncultivated barren.

At Kannur, among different pedons, the epipedon of soils under uncultivated barren had significantly higher bulk density (1.25 Mg m^{-3}) than that of rubber (1.20 Mg m^{-3}). The bulk density of epipedon of soils under cassava was on par with that of other two land uses. No difference could be noted among Bt_2 layers of different land uses.

With regard to particle density, epipedon of uncultivated barren recorded significantly higher value (2.45 Mg m^{-3}) compared to that of rubber (2.42 Mg m^{-3}). Though the value for soils under cassava (2.46 Mg m^{-3}) was on par with that of uncultivated barren, it was significantly higher than that of rubber. Porosity of the epipedon under different land uses didn't differ significantly. Similar trend could be observed in lower layers too. No significant difference could be observed in the case of maximum water holding capacity values.

Epipedon of soils under rubber had a significantly higher volume expansion (1.67 per cent) compared to that of uncultivated barren (1.61 per cent) which was on par with that of cassava (1.64 per cent). Significantly lower values could be observed in Bt_2 layers of soils under both cassava and rubber compared to that of uncultivated barren. Within the pedons, Ap/A, Bt_1 and Bt_2 layers differed significantly in volume expansion.

The common layers under different land uses were grouped into epipedons (Ap/A horizons), Bt_1 horizons and Bt_2 horizons and results of the pooled analysis are given in Appendix 1. The single value constants are given in Appendix 1.1. There was a significant decrease in bulk density of the epipedons of soils under rubber (1.11 Mg m^{-3}) and cassava (1.12 Mg m^{-3}), which were on par, compared to that of uncultivated barren (1.15 Mg m^{-3}). The Bt_1 horizons or Bt_2 horizons showed no difference. In all the three land uses, the bulk density increased significantly down the profiles. The particle density didn't differ among similar horizons under different land uses. No significant change could be observed in porosity too.

The maximum water holding capacity of the epipedons as well as Bt_1 horizons of different land uses differed significantly as rubber > cassava > uncultivated barren. In the case of Bt_2 horizons, a significantly lower value was observed in soils under uncultivated barren than that of rubber and the Bt_2 layer of soils under cassava recorded a value which was on par with the other two. In the case of volume expansion, epipedon of soils under rubber had significantly higher value compared to that of uncultivated barren and soils under cassava had a value on par with that of uncultivated barren.

4.3.2. Particle size analysis of the pedons

The results of the particle size analysis of the different pedons are summarised in Table 4. At Thiruvananthapuram, no significant difference could be observed in gravel content of the pedons. One major

Table 4. Mechanical composition of the profiles

Horizon	Depth (cm)	Gravel (%)	Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	Silt/ clay
I. Thiruvananthapuram							
A. Cassava							
Ap	0-28	35.70	38.95	25.86	5.59	29.60	0.19
AB	28-63	34.60	32.90	25.40	7.51	34.20	0.22
Bt_1	63-97	31.90	25.30	25.42	8.54	40.75	0.20
Bt_2	97-200	32.15	23.42	33.62	7.47	35.50	0.21
B. Rubber							
Ap	0-9	34.20	38.58	23.82	5.78	31.82	0.18
A1	9-20	35.00	33.95	26.38	6.48	33.20	0.20
A2	20-34	33.00	30.94	29.03	7.49	32.55	0.23
AB	34-43	37.65	26.85	25.79	8.82	38.55	0.23
Bt_1	43-114	36.65	23.90	22.97	9.19	43.95	0.21
Bt_2	114-200	39.60	23.92	32.87	7.17	36.05	0.20
C. Uncultivated barren							
A	0-34	36.95	38.54	21.53	6.34	33.60	0.18
Bt_1	34-89	31.30	21.69	34.04	7.38	36.90	0.20
Bt_2	89-200	32.60	31.43	32.89	6.19	29.50	0.21
CD		NS	2.82	3.60	0.54	NS	0.02
II. Angadipuram							
A. Cassava							
Ap	0-21	36.55	42.19	32.96	4.31	20.55	0.21
EB	21-40	40.25	39.43	31.10	5.13	24.35	0.21
B	40-108	41.95	36.39	31.68	5.78	26.15	0.22
Bt_1	108-142	34.75	30.45	30.07	6.29	33.20	0.19
Bt_2	142-200	35.95	30.31	36.49	5.06	28.15	0.18
B. Rubber							
Ap	0-13	39.50	41.63	32.35	4.32	21.70	0.20
E	13-24	43.20	37.16	31.52	5.43	25.90	0.21
B	24-42	45.55	32.27	32.30	6.39	29.05	0.22
Bt_1	42-115	32.95	31.49	27.28	6.14	35.10	0.19
Bt_2	115-200	36.05	30.54	32.43	5.94	31.10	0.19

(Table 4 Contd...)

Horizon	Depth (cm)	Gravel (%)	Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	Silt/ clay
C. Uncultivated barren							
A1	0-8	40.15	44.27	31.63	4.21	19.90	0.21
A2	8-37	42.45	40.66	29.84	4.91	24.60	0.20
E	37-74	44.50	35.21	32.95	5.49	26.35	0.20
Bt$_1$	74-108	34.40	32.17	30.53	5.95	31.35	0.19
Bt$_2$	108-200	36.50	30.59	37.02	4.70	27.70	0.17
CD		2.24	12.15	3.43	0.39	2.21	0.01
III. Kannur							
A. Cassava							
Ap	0-17	35.15	41.72	26.69	5.70	25.90	0.22
B1	17-36	37.05	38.13	26.74	5.73	29.30	0.19
B2	36-79	38.35	31.24	31.34	6.52	30.90	0.21
Bt$_1$	79-137	32.45	28.92	28.58	6.51	36.00	0.18
Bt$_2$	137-200	35.30	27.73	32.94	5.73	33.60	0.17
B. Rubber							
Ap	0-17	31.40	39.51	26.61	7.08	26.80	0.21
A1	17-39	36.55	35.80	29.38	5.73	29.10	0.19
E0	39-108	39.15	33.47	29.41	6.22	30.90	0.20
Bt$_1$	108-141	35.20	29.56	25.23	6.10	39.10	0.16
Bt$_2$	141-200	34.50	28.31	31.41	5.58	34.70	0.16
C. Uncultivated barren							
A	0-12	36.35	41.27	28.00	5.53	25.20	0.22
E	12-27	37.50	37.87	29.63	5.20	27.30	0.19
EB	27-81	40.30	34.59	30.52	5.60	29.30	0.19
Bt$_1$	81-139	34.50	25.89	34.33	5.78	34.00	0.17
Bt$_2$	139-200	32.75	25.29	37.64	4.57	32.50	0.14
CD		2.87	2.57	NS	NS	2.06	0.03

observation with regard to coarse sand was the significantly higher value in Bt_1 layers of soils under cassava compared to that of uncultivated barren. The fine sand fraction was significantly lower in epipedon of uncultivated barren (21.53 per cent) than that of cassava (25.86 per cent). Epipedon of soils under rubber (23.82 per cent) recorded a value which was on par with that of uncultivated barren. The Bt_1 layer of soils under cassava and rubber recorded significantly lower value than that of uncultivated barren.

With respect to silt content, the epipedon of uncultivated barren had significantly higher content (6.34 per cent) than that of cassava (5.59 per cent) and rubber (5.78 per cent), which were on par. In the case of Bt_1 layer, soils under uncultivated barren recorded lowest value (7.38 per cent) followed by cassava (8.54 per cent) and rubber (9.19 per cent). All differed significantly. A significantly lower value could be observed, among Bt_2 layers, in uncultivated barren compared to that of other two land uses. The clay content within the profile and among similar layers of different pedons did not differ significantly.

At Angadipuram, gravel content in the epipedon of soils under cassava was significantly lower than that of uncultivated barren and rubber, which were on par. Within the profile, significant variation in gravel could be observed among surface, Bt_1 and Bt_2 layers in the pedon under rubber. In the case of coarse sand, the surface, Bt_1 and Bt_2 layers of the pedons under the three land use systems did not vary significantly. With regard to fine sand content, the Bt_2 layer of soils under uncultivated barren had significantly higher value as compared to that of rubber. The value for soils under cassava was on par with that of barren land.

The silt content varied significantly only in the Bt_2 layer of uncultivated barren (4.70 per cent) and that of rubber (5.94 per cent) while that of cassava (5.06 per cent) was on par with that of uncultivated barren though it differed significantly from that of rubber. Other layers didn't show much variation due to different land uses.

One important result in clay content of the different pedons is the significant difference in clay content between the overlying and textural B (Bt_1-layer) horizons in all pedons except those at Thiruvananthapuram. Maximum increase in clay content could be observed in soils under rubber followed by cassava and least increase is noted in barren land. Similarly, the Bt_2 layers recorded significantly lower clay content compared to their corresponding Bt_1 layers. Among the different pedons, the clay content of Bt_1 layer in soils under rubber (35.10 per cent) was significantly higher than that of uncultivated barren (31.35 per cent), which was on par with that of cassava (33.20 per cent). Similar trend could be observed in Bt_2 layers too.

At Kannur, gravel content varied significantly only among the epipedons. Significantly lower value was recorded in soils under rubber (31.40 per cent) compared to that of uncultivated barren (36.35 per cent) which didn't differ from that of cassava (35.15 per cent). No variation could be observed in coarse sand content of epipedons while significantly lower value could be noted in Bt_1 layer of soils under uncultivated barren

(25.89 per cent) than that of cassava (28.92 per cent) and rubber (29.56 per cent), which were on par. In the Bt_2 layers, significantly lower coarse sand content could be observed in uncultivated barren (25.29 per cent) compared to that of rubber (28.31 per cent) which was on par with that of cassava (27.73 per cent). No variation could be recorded in the case of both fine sand and silt contents.

Clay content in the textural B horizon (Bt_1 layer) of soils under rubber was significantly higher (39.1 per cent) than that of uncultivated barren (34.0 per cent) and cassava (36.0 per cent), which were on par. The clay increase in Bt_1 layer from the above horizon was significant in all pedons though maximum increase was recorded in pedons under rubber followed by uncultivated barren and cassava. The Bt_1 and Bt_2 layers of all pedons differed significantly in clay content and among different pedons, significantly higher clay could be noted in Bt_2 layer of pedon under rubber (34.70 per cent) than that of uncultivated barren (32.50 per cent) which was on par with that of cassava (33.60 per cent).

Results of the pooled analysis are given in Appendix 1.2. The gravel as well as coarse sand fractions showed no difference among similar horizon groupings under different land uses. The fine sand content was significantly lower in epipedons of soils under uncultivated barren (22.60 per cent) compared to that of cassava (28.50 per cent). Epipedons of soils under rubber had a value (27.10 per cent) on par with that of other two. The fine sand fraction of Bt_1 horizon of soils under rubber (25.12 per cent) was significantly lower than that of uncultivated barren

(32.58 per cent). Soils under cassava had a value (28.04 per cent) on par with the other two. The Bt_2 horizons didn't show any difference in fine sand content. There was significant increase in fine sand content in Bt_2 layers compared to the overlying Bt_1 horizons in soils under cassava and rubber while they were on par in soils under uncultivated barren. The silt content of epipedons under different land uses showed no difference while in Bt_1 horizons as well as in Bt_2 horizons, significantly higher silt contents were observed in soils under cassava and rubber compared to that under uncultivated barren. The clay content showed no significant difference among similar horizons under different land uses.

The silt / clay ratio is given in Table 4. At Thiruvananthapuram, the silt / clay ratio increased significantly from Ap/A layer to Bt_1 layer in soils under both rubber and uncultivated barren. But at Angadipuram, the silt / clay ratio showed a decreasing trend down the profiles. The epipedons and Bt_1 layers under different land uses didn't show any difference in silt / clay ratio. In the case of Bt_2 horizons, significantly lower ratio was observed in soils under uncultivated barren than that of rubber, while that of cassava had a value on par with the other two.

At Kannur, no difference in silt / clay ratio could be observed among similar horizons under different land uses. Down the profiles, there was a decreasing trend in silt / clay ratio as at Angadipuram. The Bt_2 horizons had a significantly lower ratio compared to that of epipedons under all land use systems. Pooled analysis showed no difference in silt / clay ratio due to different land uses (Appendix 1.2.).

4.3.3. Organic carbon and organic matter

The changes in organic carbon (OC) and organic matter (OM) contents in the pedons are given in Tables 5 and 6. At all the three locations, the organic carbon content down the profiles decreased significantly. At Thiruvananthapuram, the organic carbon and organic matter contents in the epipedons of soils didn't differ significantly. At Angadipuram, there was significant reduction in organic carbon content in soils under uncultivated barren (2.01 per cent) compared to that of cassava (2.13 per cent) and rubber (2.14 per cent). At Kannur, the organic carbon content in the epipedons as well as in other similar subsurface horizons were on par. In the case of organic matter content in pedons at Angadipuram and Kannur, no significant variation could be observed between Ap/A, Bt_1 or Bt_2 layers.

When the organic matter content is expressed as kg m^{-2} to a depth of 1 m, it could be observed that soils under cassava at Thiruvananthapuram had 25.36 kg m^{-2} organic matter while that of rubber contained 22.40 kg m^{-2} and uncultivated barren, 20.48 kg m^{-2}. At Angadipuram, highest values could be noted in soils under rubber (25.62 kg m^{-2}) followed by soils under cassava (20.45 kg m^{-2}) and uncultivated barren (16.95 kg m^{-2}). At Kannur, very close values of 27.94, 26.78 and 25.75 kg m^{-2} to a depth in 1m could be recorded in soils under rubber, cassava and uncultivated barren.

Table 5. Organic carbon and organic matter content

Horizon	Depth (cm)	Organic carbon (%)	Organic matter (%)
I. Thiruvananthapuram			
A. Cassava			
Ap	0-28	1.96	3.38
AB	28-63	1.47	2.53
Bt$_1$	63-97	0.52	0.90
Bt$_2$	97-200	0.33	0.56
B. Rubber			
Ap	0-9	1.93	3.32
A1	9-20	1.48	2.55
A2	20-34	1.34	2.30
AB	34-43	1.07	1.85
Bt$_1$	43-114	0.79	1.36
Bt$_2$	97-200	0.36	0.62
C. Uncultivated barren			
A	0-34	1.88	3.23
Bt$_1$	34-89	0.61	1.05
Bt$_2$	89-200	0.30	0.51
CD		0.10	0.16
II. Angadipuram			
A. Cassava			
Ap	0-21	2.13	3.68
EB	21-40	1.49	2.57
B	40-108	0.68	1.17
Bt$_1$	108-142	0.51	0.88
Bt$_2$	142-200	0.34	0.58
B. Rubber			
Ap	0-13	2.14	3.68
E0	13-24	1.76	3.03
B	24-42	1.44	2.49
Bt$_1$	42-115	1.08	1.86
Bt$_2$	115-200	0.45	0.78

(Table 5. Contd...)

Horizon	Depth (cm)	Organic carbon (%)	Organic matter (%)
C. Uncultivated barren			
A1	0-8	2.01	3.56
A2	8-37	1.21	2.09
E	37-74	0.63	1.08
Bt_1	74-108	0.60	1.04
Bt_2	108-200	0.03	0.52
CD		0.11	0.98
III. Kannur			
A. Cassava			
Ap	0-17	1.95	3.35
B1	17-36	1.49	2.57
B2	36-79	1.18	2.04
Bt_1	79-137	0.62	1.06
Bt_2	137-200	0.36	0.61
B. Rubber			
Ap	0-17	1.96	3.38
A1	17-39	1.40	2.41
Eo	39-108	1.11	1.92
Bt_1	108-141	0.67	1.16
Bt_2	141-200	0.43	0.74
C. Uncultivated barren			
A	0-12	1.93	3.33
E	12-27	1.42	2.44
EB	27-81	1.10	1.90
Bt_1	81-139	0.72	1.23
Bt_2	139-200	0.43	0.75
CD		0.10	0.17

Table 6. Organic matter content expressed as kg m^{-2} to a depth of 1 m

Location / Landuse	Organic matter (kg m^{-2} to 1 m depth)
1. Thiruvananthapuram	
Cassava	25.36
Rubber	22.40
Uncultivated barren	20.48
2. Angadipuram	
Cassava	20.45
Rubber	25.62
Uncultivated barren	16.95
3. Kannur	
Cassava	26.78
Rubber	27.94
Uncultivated barren	25.75

Appendix 1.3 gives the results of the pooled analysis. Significantly higher organic carbon and organic matter contents were recorded in epipedons of soils under cassava and rubber than under uncultivated barren. In the case of Bt_1 as well as Bt_2 horizons, the organic carbon and organic matter were higher in soils under rubber followed by uncultivated barren and cassava.

4.3.4. Water dispersible clay and loss on ignition

The water dispersible clay (WDC) content and loss on ignition (LOI) of the various horizons of the pedons under study are given in Table 7. The water dispersible clay content showed a decreasing trend down the profile in all the studied pedons. At Thiruvananthapuram, the water dispersible clay content in Bt_2 layers of soils under uncultivated barren and cassava (1.65 per cent) was significantly higher than that under rubber (1.45 per cent). In all the three land uses, there were significant decrease in water dispersible clay from Ap/A to Bt_1 layer. In soils under rubber, the water dispersible clay of Bt_2 layer was significantly lower than that of Bt_1 layer above. In other two land uses, no variation could be noted between these two adjacent horizons.

At Angadipuram, the epipedon of soils under rubber had significantly higher water dispersible clay (2.40 per cent) than that of cassava. The Bt_1 layers didn't show any difference among the land uses. In the hard laterite Bt_2 layer of soils under rubber, a lowest value of 1.25 per cent could be observed which was significantly lower than those of

Table 7. Water dispersible clay and loss on ignition

Horizon	Depth (cm)	Water dispersible clay (%)	Loss on ignition (%)
I. Thiruvananthapuram			
A. Cassava			
Ap	0-28	2.50	6.42
AB	28-63	1.85	3.54
Bt$_1$	63-97	1.65	3.05
Bt$_2$	97-200	1.65	1.25
B. Rubber			
Ap	0-9	2.60	7.39
A1	9-20	2.05	5.62
A2	20-34	1.80	4.62
AB	34-43	1.75	3.13
Bt$_1$	43-114	1.70	2.50
Bt$_2$	114-200	1.45	1.94
C. Uncultivated barren			
A	0-34	2.55	4.99
Bt$_1$	34-89	1.70	3.04
Bt$_2$	89-200	1.65	1.24
CD		0.17	0.87
II. Angadipuram			
A. Cassava			
Ap	0-21	2.25	8.42
EB	21-40	1.95	6.89
B	40-108	1.90	5.04
Bt$_1$	108-142	1.80	4.76
Bt$_2$	142.200	1.55	2.03
B. Rubber			
Ap	0-13	2.40	10.25
Eo	13-24	2.00	7.70
B	24-42	1.95	6.05
Bt$_1$	42-115	1.75	4.18
Bt$_2$	115-200	1.25	2.41

(Table 7. Contd...)

Horizon	Depth (cm)	Water dispersible clay (%)	Loss of ignition (%)
C. Uncultivated barren			
A1	0-8	2.30	8.56
A2	8-37	1.95	6.38
E	37-74	1.80	5.26
Bt_1	74-108	1.80	3.65
Bt_2	108-200	1.55	1.55
CD		0.11	0.99
III. Kannur			
A. Cassava			
Ap	0-17	2.95	9.39
B1	17-36	2.45	7.39
B2	36-79	2.25	5.65
Bt_1	79-137	2.15	5.00
Bt_2	137-200	1.90	2.12
B. Rubber			
Ap	0-17	3.00	10.46
A1	17-39	2.50	7.94
E0	39-108	2.05	5.25
Bt_1	108-141	2.00	4.15
Bt_2	141-200	1.60	3.00
C. Uncultivated barren			
A	0-12	3.00	9.64
E	12-27	2.55	6.96
EB	27-81	2.30	6.27
Bt_1	81-139	2.15	5.15
Bt_2	139-200	1.95	2.31
CD		NS	2.22

cassava and uncultivated barren (1.55 per cent). Down the profiles, the water dispersible clay decreased significantly from Ap/A layer to Bt_1 layer to Bt_2 layer.

At Kannur, the water dispersible clay didn't show any significant variation either down the profiles or between similar layers of pedons under different land uses.

The loss on ignition also showed a decreasing trend downward in all pedons. At Thiruvananthapuram, loss on ignition in epipedon of soils under uncultivated barren (4.99 per cent) was significantly lower than that of cassava (6.42 per cent), which in turn was significantly lower than that of rubber (7.39 per cent). No significant difference could be noted among Bt_1 layers or among Bt_2 layers of soils under different land uses.

At Angadipuram, the loss on ignition of epipedon of soils under rubber (10.25 per cent) was significantly higher than those of uncultivated baren (8.56 per cent) and cassava (8.42 per cent) which were on par. Down the profile, there was significant decrease in loss on ignition from Ap/A layer to Bt_1 layer to the hard laterite, Bt_2 layer.

At Kannur, the loss on ignition didn't vary significantly between similar horizons of soils under different land uses. There was a decrease in loss on ignition down the pedons which differed significantly except between Bt_1 and Bt_2 layers of soils under rubber.

Results of the pooled analysis (Appendix 1.4) show that the water dispersible clay content of the epipedons of soils under cassava (2.57 per cent) was significantly lower than that of rubber (2.67 per cent) and uncultivated barren had a value (2.62 per cent) on par with the other two. When the Bt_1 horizons showed no difference in water dispersible clay, significantly lower content was noted in Bt_2 layers of soils under rubber (1.43 per cent) than that of cassava (1.70 per cent) and uncultivated barren (1.72 per cent). There was a significant lowering of water dispersible clay content down the profiles under all the land uses.

In the case of loss on ignition (Appendix 1.4), the epipedons of soils under rubber (9.37 per cent) had significantly higher value than that of cassava (8.08 per cent) and uncultivated barren (7.73 per cent) which were on par. The Bt_2 horizons showed significant difference in loss on ignition and they followed the order rubber > cassava > uncultivated barren.

4.3.5. Total elemental analysis

The total elemental analysis of the pedons with respect to elements related to laterisation is given in Table 8.

4.3.5.1. Nitrogen and phosphorus

At Thiruvananthapuram, the nitrogen content in the epipedons of soils under cassava and rubber differed significantly, a higher value (0.200 per cent) being recorded in soils under rubber. The uncultivated barren

Table 8. Total elemental analysis of the pedons (%)

Horizon	Depth (cm)	N	P_2O_5	K_2O	CaO	MgO	SiO_2	Fe_2O_3	Al_2O_3
I. Thiruvananthapuram									
A. Cassava									
Ap	0-28	0.172	0.081	0.141	0.029	0.044	37.50	19.00	22.20
AB	28-63	0.086	0.053	0.183	0.017	0.034	40.40	27.30	15.25
Bt_1	63-97	0.056	0.038	0.183	0.029	0.054	33.30	25.00	21.35
Bt_2	97-200	0.021	0.020	0.202	0.027	0.051	30.10	34.20	14.55
B. Rubber									
Ap	0-9	0.200	0.078	0.165	0.027	0.050	35.80	21.70	25.55
A1	9-20	0.094	0.064	0.156	0.017	0.046	43.20	33.10	14.85
A2	20-34	0.060	0.039	0.172	0.010	0.036	40.10	35.70	16.70
AB	34-43	0.038	0.033	0.194	0.009	0.040	42.80	27.70	19.70
Bt_1	43-114	0.029	0.021	0.204	0.026	0.054	30.00	26.60	20.75
Bt_2	114-200	0.018	0.023	0.223	0.023	0.048	29.10	34.00	14.05
C. Uncultivated barren									
A	0-34	0.178	0.045	0.132	0.026	0.041	33.10	19.30	24.00
Bt_1	34-89	0.082	0.032	0.154	0.014	0.037	31.40	24.80	16.20
Bt_2	89-200	0.026	0.021	0.181	0.027	0.042	31.40	31.10	13.40
CD		0.027	0.023	0.039	0.005	0.003	2.83	1.59	7.38

Table 8. (Contd...)

Horizon	Depth (cm)	N	P_2O_5	K_2O	CaO	MgO	SiO_2	Fe_2O_3	Al_2O_3
II. Angadipuram									
A. Cassava									
Ap	0-21	0.211	0.079	0.131	0.040	0.017	32.40	22.40	18.95
EB	21-40	0.075	0.039	0.112	0.023	0.016	31.60	21.10	21.85
B	40-108	0.074	0.023	0.138	0.023	0.017	36.30	23.20	27.80
Bt_1	108-142	0.039	0.022	0.185	0.031	0.029	27.10	20.90	24.10
Bt_2	142.200	0.024	0.016	0.171	0.029	0.027	24.60	36.30	23.05
B. Rubber									
Ap	0-13	0.206	0.053	0.136	0.044	0.016	38.80	23.50	20.70
Eo	13-24	0.085	0.057	0.131	0.025	0.030	35.60	22.78	21.20
B	24-42	0.048	0.038	0.147	0.020	0.028	34.20	22.10	26.10
Bt_1	42-115	0.033	0.024	0.203	0.025	0.031	22.50	25.90	25.65
Bt_2	115-200	0.018	0.019	0.208	0.023	0.027	23.00	38.50	24.90
C. Uncultivated barren									
A1	0-8	0.187	0.042	0.089	0.037	0.014	35.30	23.90	19.35
A2	8-37	0.060	0.035	0.111	0.024	0.012	32.10	22.90	21.65
E	37-74	0.052	0.025	0.114	0.023	0.010	34.40	21.50	27.00
Bt_1	74-108	0.034	0.027	0.179	0.029	0.018	27.20	26.10	24.80
Bt_2	108-200	0.025	0.014	0.174	0.027	0.019	23.00	34.90	21.00
CD		0.024	0.009	0.004	0.004	0.003	NS	1.48	1.71

Table 8. (Contd...)

Horizon	Depth (cm)	N	P_2O_5	K_2O	CaO	MgO	SiO_2	Fe_2O_3	Al_2O_3
III. Kannur									
A. Cassava									
Ap	0-17	0.183	0.052	0.142	0.036	0.030	19.60	24.30	24.15
B1	17-36	0.081	0.035	0.154	0.029	0.036	28.80	35.40	17.20
B2	36-79	0.038	0.029	0.170	0.030	0.044	33.00	41.90	22.10
Bt_1	79-137	0.035	0.025	0.192	0.035	0.046	34.30	36.60	22.95
Bt_2	137-200	0.023	0.016	0.174	0.031	0.030	28.60	40.30	15.30
B. Rubber									
Ap	0-17	0.191	0.078	0.147	0.038	0.031	24.60	19.80	25.35
A1	17-39	0.086	0.058	0.166	0.030	0.043	28.30	31.90	17.80
E0	39-108	0.049	0.041	0.166	0.023	0.047	37.00	32.70	21.20
Bt_1	108-141	0.043	0.025	0.191	0.039	0.050	36.70	32.20	20.85
Bt_2	141-200	0.014	0.020	0.193	0.036	0.036	37.20	36.40	16.10
C. Uncultivated barren									
A	0-12	0.173	0.062	0.126	0.038	0.027	21.20	25.20	23.60
E	12-27	0.078	0.044	0.144	0.027	0.037	29.80	34.30	16.90
EB	27-81	0.038	0.029	0.144	0.030	0.039	33.80	37.10	22.35
Bt_1	81-139	0.029	0.021	0.192	0.037	0.049	34.70	36.30	22.70
Bt_2	139-200	0.023	0.020	0.190	0.034	0.040	32.40	43.10	16.15
CD		0.023	0.019	0.022	0.005	0.006	2.68	1.49	1.49

had a value of 0.178 per cent which was on par with those of cassava and rubber. Not much variation among similar horizons under different land use systems could be observed. Down the profiles from Ap/A to Bt_1 to Bt_2 layers, there were significant reduction in nitrogen content except from the Bt_1 to Bt_2 layer of soils under rubber.

At Angadipuram, there were significant reduction in nitrogen content from Ap/A layer to Bt_1 layer but it was on par between Bt_1 and Bt_2 layers under all three land uses. In the epipedon as well as in other similar endopedons, no significant variation in nitrogen content could be observed among different land uses. The observations with regard to nitrogen in soils under different land uses at Kannur were similar to that at Angadipuram except that there was significant difference between Bt_1 layer (0.043 per cent) and Bt_2 layer (0.014 per cent) of soils under rubber.

With regard to the phosphorus content in the pedons at Thiruvananthapuram, there was significant reduction in epipedon of soils under uncultivated barren (0.045 per cent) compared to that of cassava (0.081 per cent) and rubber (0.078 per cent), which were on par. No significant variation could be noted among similar endopedons. At Angadipuram, phosphorus content in epipedons decreased significantly as cassava > rubber > uncultivated barren. No significant variation could be noted among similar endopedons. At Kannur, phosphorus content in epipedon of soils under rubber (0.078 per cent) was significantly higher than that in cassava (0.052 per cent), but that of uncultivated barren (0.062

per cent) didn't show any significant variation. No significant difference could be observed among similar endopedons.

Results of the pooled analysis (Appendix 1.5) show that the total nitrogen content of the epipedons was significantly higher in soils under rubber (0.20 per cent) than that of uncultivated barren and epipedons of soils under cassava had a nitrogen content on par with that of the other two. In the case of total P_2O_5, epipedons of both cassava (0.07 per cent) and rubber (0.07 per cent) had significantly higher values than that of uncultivated barren. The endopedons showed no difference.

4.3.5.2. Basic cations

Potassium, calcium and magnesium are the major basic cations involved in the pedogenesis due to laterisation. With respect to potassium (Table 8), no significant difference could be observed among epipedons of three land uses at Thiruvananthapuram. In the Bt_1 layer of soils under rubber, there was significantly higher potassium (0.204 per cent) content compared to that of uncultivated barren (0.154 per cent) which was on par with that of cassava (0.183 per cent). Similar trend could be observed in Bt_2 layers too.

At Angadipuram, potassium content in epipedons as well as Bt_1 layer varied significantly and they followed the order:rubber > cassava > uncultivated barren. In the Bt_2 layer, significantly higher content could be seen in soils under rubber (0.208 per cent) compared to that of cassava (0.171 per cent) and uncultivated barren (0.174 per cent), which were on par.

At Kannur, similar layers under different land uses didn't show any variation in K_2O content.

The calcium content in epipedons didn't show any difference among similar horizons under different land uses at Thiruvananthapuram. In the Bt_1 layer of uncultivated barren, the calcium content (0.014 per cent) was significantly lower than that of cassava (0.029 per cent) and rubber (0.026 per cent). At Angadipuram, significantly higher content in epipedon could be noted in soils under rubber (0.044 per cent) compared to that of uncultivated barren (0.037 per cent). The value for soils under cassava (0.040 per cent) was on par with that of other two land uses. In the Bt_1 layer, significantly lower value was recorded in soils under rubber (0.025 per cent) compared to that of cassava (0.031 per cent). The layer in uncultivated barren recorded a value (0.029 per cent) which didn't differ significantly from that of other land uses. Similar trend could be recorded in Bt_2 layers too. At Kannur, similar horizons under different land uses didn't show any difference in calcium content. Another important observation is the significant increase in calcium content in the Bt_1 layer, compared to the overlying layer, in soils under rubber and uncultivated barren.

The magnesium content in the epipedon of soils under rubber at Thiruvananthapuram (0.050 per cent) was significantly higher than that of cassava (0.044 per cent) and uncultivated barren (0.041 per cent). In the case of Bt_1 layer in soils under uncultivated barren, the magnesium content was significantly lower than that of cassava and rubber. In soils under uncultivated barren, there was a significant increase in calcium from Bt_1 to Bt_2 layer and this was on par in other two land uses.

At Angadipuram, the magnesium content showed significant difference though the epipedons didn't show any difference in magnesium content under different land uses. But, both in Bt_1 and Bt_2 layers of soils under cassava and rubber, there was significantly higher content than those in uncultivated barren. Down the profiles, there was significant increase in magnesium content in Bt_1 layer compared to the overlying layer in soils under cassava and rubber but were on par in uncultivated barren.

The magnesium content in soils at Kannur differed significantly. The magnesium content in epipedons of soils under different land uses was on par. In the Bt_2 layer of soils under uncultivated barren, there was significantly higher content (0.040 per cent) compared to that of cassava (0.030 per cent). The value for soils under rubber (0.036 per cent) was on par with that of the other two land uses. The values for the hard laterite layers were significantly lower than the corresponding overlying Bt_1 layers.

Results of the pooled analysis (Appendix 1, Table 5) show no difference in contents of K_2O, CaO and MgO among similar selected horizons under different land uses.

4.3.5.3. Silica and sesquioxides

With regard to SiO_2 content, the epipedon of soils under uncultivated barren (33.10 per cent) had a significantly lower amount compared to that of cassava (37.50 per cent) at Thiruvananthapuram. The textural-B horizons or hard laterite layers under different land uses did not show any difference. There was a significant decrease from textural-B horizon (33.30 per cent) to hard laterite layer (30.10 per cent) in soils under cassava in Thiruvananthapuram while this could not be observed under other two land uses. At Angadipuram, no significant variation in silica content was observed.

At Kannur, the epipedon of soils under both uncultivated barren and cassava had significantly lower silica contents compared to that of rubber. Though the textural-B horizons did not show any significant difference, the silica content of hard laterite layer decreased significantly as rubber > uncultivated barren > cassava. Another important observation is the significant increase in silica content from epipedon (19.60 per cent) to textural-B horizon (34.30 per cent) and then a significant decrease to hard laterite layer (28.60 per cent), only in soils under cassava.

The Fe_2O_3 content in the epipedon of soils under rubber (21.70 per cent) was significantly higher than those of cassava (19.00 per cent) and uncultivated barren (19.30 per cent), which were on par, at Thiruvananthapuram. Significant increase was observed from Ap/A layer to Bt_1 to Bt_2 horizons in all land uses. At Angadipuram, the Bt_1 layers of soils under rubber and uncultivated barren had significantly higher iron, which were on par, compared to that of cassava. With regard to Bt_2 layers, the iron content decreased significantly as rubber (38.50 per cent) > cassava (36.30 per cent) = uncultivated barren (34.90 per cent).

At Kannur, significantly higher iron in epipedons was observed in soils under uncultivated barren (25.20 per cent) and cassava (24.30 per cent), which were on par, than that of rubber (19.80 per cent). Same trend was observed for Bt_1 layers too. In the case of hard laterite horizon, it decreased significantly as uncultivated barren > cassava > rubber. Under all land uses, the iron content increased significantly from epipedon to textural-B horizon to hard laterite layer.

With respect to aluminium content, similar horizons under different land uses at Thiruvananthapuram didn't vary. But at Angadipuram, the Al_2O_3 content in epipedons of soils under rubber was significantly higher (20.70 per cent) than that of cassava (18.95 per cent). An intermediate value of 19.35 per cent was noted in soils under uncultivated barren which was on par with other two. Also, a significantly higher content is observed in Bt_2 layer of soils under rubber (24.90 per cent) followed by cassava (23.05 per cent) and uncultivated barren (21.00 per cent). Bt_1 layers did not show any difference among land uses.

At Kannur, the epipedon of soils under rubber had a significantly higher alumina content (25.35 per cent) than that of uncultivated barren (23.60 per cent). An intermediate value of 24.15 per cent, which was on par with the other two, was recorded in soils under cassava. In the Bt_1 layer, significantly lower value was observed in soils under rubber (20.85 per cent) than that of cassava (22.95 per cent) and uncultivated barren (22.70 per cent). The Bt_2 layers didn't show any difference in alumina content.

Pooled analysis (Appendix 1.5) showed no significant difference in iron content in similar horizons under different land uses. Under all land uses, the iron content increased significantly from epidedon to Bt_1 horizon to Bt_2 horizon. The Al_2O_3 content was also higher in epipedon under rubber than that of cassava and uncultivated barren which were on par. The Bt_1 horizons showed no difference while in Bt_2 horizons, the Al_2O_3 content was significantly higher in soils under rubber (18.35 per cent) compared to that of uncultivated barren (16.85 per cent) while the layer under cassava had a value (17.63 per cent) on par with the other two. The SiO_2 content showed no difference among similar horizon groupings under different land uses.

4.3.5.4. Molar ratios of silica, alumina and iron in the pedons

Table 9 gives the silica : alumina (sa ratio), silica : iron (sf ratio) and silica : sesquioxide (ss ratio) of the horizons in various pedons studied. With regard to sa ratio of epipedons at Thiruvananthapuram, significantly lower values were recorded in soils under rubber (2.35) and uncultivated barren (2.32), which were on par, compared to that of cassava (2.83). The sa ratio of hard laterite layer decreased significantly as uncultivated barren > cassava > rubber.

At Angadipuram, the sa ratio did not vary significantly among epipedons. In the case of Bt_1 layer, it was significantly lower in soils under rubber (1.47) compared to that of cassava (1.89) and uncultivated barren (1.84), which were on par. The hard laterite layer didn't show any

Table 9. Molar ratios of silica, alumina and iron in the pedons

Horizon	Depth (cm)	sa ratio	sf ratio	ss ratio
I. Thiruvananthapuram				
A. Cassava				
Ap	0-28	2.83	5.19	1.83
AB	28-63	4.44	3.89	2.07
Bt_1	63-97	2.63	3.50	1.50
Bt_2	97-200	3.47	2.32	1.39
B. Rubber				
Ap	0-9	2.35	4.34	1.52
A1	9-20	4.88	3.44	2.02
A2	20-34	4.03	2.95	1.70
AB	34-43	3.65	4.08	1.93
Bt_1	43-114	2.42	2.96	1.33
Bt_2	114-200	2.56	2.25	1.20
C. Uncultivated barren				
A	0-34	2.32	4.50	1.53
Bt_1	34-89	2.89	3.34	1.55
Bt_2	89-200	3.95	2.65	1.59
CD		0.46	0.74	NS
II. Angadipuram				
A. Cassava				
Ap	0-21	2.87	3.81	1.64
EB	21-40	2.43	3.94	1.51
B	40-108	2.19	4.12	1.43
Bt_1	108-142	1.89	3.41	1.22
Bt_2	142.200	1.79	1.78	0.89
B. Rubber				
Ap	0-13	3.15	4.35	1.83
Eo	13-24	2.82	4.10	1.67
B	24-42	2.20	4.09	1.43
Bt_1	42-115	1.47	2.29	0.86
Bt_2	115-200	1.55	1.57	0.78

Table 9. (Contd...)

Horizon	Depth (cm)	sa ratio	sf ratio	ss ratio
C. Uncultivated barren				
A1	0-8	3.06	3.88	1.71
A2	8-37	2.50	3.70	1.49
E	37-74	2.14	4.20	1.42
Bt_1	74-108	1.84	2.75	1.10
Bt_2	108-200	1.84	1.73	0.89
CD		0.30	1.40	0.19
III. Kannur				
A. Cassava				
Ap	0-17	1.36	2.13	0.83
B1	17-36	2.73	2.14	1.20
B2	36-79	3.06	2.08	1.24
Bt_1	79-137	2.51	2.47	1.24
Bt_2	137-200	3.14	1.87	1.17
B. Rubber				
Ap	0-17	1.63	3.27	1.09
A1	17-39	2.66	2.33	1.24
E0	39-108	2.93	2.98	1.48
Bt_1	108-141	2.97	3.00	1.49
Bt_2	141-200	3.88	2.69	1.59
C. Uncultivated barren				
A	0-12	2.87	2.21	0.90
E	12-27	2.43	2.28	1.29
EB	27-81	2.19	2.40	1.24
Bt_1	81-139	1.89	2.52	1.27
Bt_2	139-200	1.79	1.98	1.25
CD		0.37	0.51	0.13

significant difference. The ratio was significantly lower in both Bt_1 and Bt_2 layers, which were on par, compared to that of corresponding epipedons.

At Kannur, the sa ratio of epipedons of soils under cassava (1.36) and rubber (1.63), which were on par, was significantly lower than that of uncultivated barren (2.87). The sa ratio of Bt_1 as well as Bt_2 horizons decreased significantly as rubber > cassava > uncultivated barren.

The silica : iron ratio (sf ratio) of epipedons was significantly lower in soils under rubber (4.34) than that of cassava (5.19) at Thiruvananthapuram. No significant difference could be observed among Bt_1 layers or among Bt_2 layers under different land uses. The value for epipedons was significantly higher than those of the respective Bt_1 and Bt_2 layers. From Bt_1 to Bt_2 layer, significant reduction in the value was noted only in soils under cassava.

At Angadipuram, though significant difference was observed among treatments, no significant difference was observed among identical horizons under different land uses. The ratio of epipedons of soils under rubber and uncultivated barren was significantly higher than the respective Bt_1 and Bt_2 layers which were on par. From Bt_1 to Bt_2 horizon, a significant decrease was observed only in soils under cassava.

The sf ratio of epipedons of soils under cassava (2.13) and uncultivated barren (2.21), which were on par, was significantly lower than that of rubber (3.27) at Kannur. In the case of Bt_1 and Bt_2 layers, soils under rubber recorded significantly higher values compared to the respective horizons under other land uses.

The silica : sesquioxide molar ratio (ss ratio) did not show any significant variation among different horizons within a profile or between similar horizons under different land uses at Thiruvananthapuram. At Angadipuram, epipedons didnot show any difference while in the case of Bt_1 layer, it was significantly lower in soils under rubber (0.86) than that of uncultivated barren (1.10) and cassava (1.22), which were on par. The Bt_2 layers did not show any significant change due to land uses. The value decreased significantly from Ap/A layer to Bt_1 layer to Bt_2 layer both in soils under cassava and uncultivated barren, while very low values, which were on par, were observed both in Bt_1 and Bt_2 layers in soils under rubber.

At Kannur, the ratio, among epipedons, was significantly lower in soils under cassava (0.83) and uncultivated barren (0.90), which were on par, than that of rubber (1.09). Same trend was observed in Bt_1 layers as well as Bt_2 layers too. Down the profile, it increased significantly from epipedon to Bt_1 layer, the values for which were on par with those of respective Bt_2 horizons.

Results of pooled analysis (Appendix 1.6) showed no significant difference in silica : alumina, silica : iron or silica : sesquioxide molar ratios among selected horizon groupings under different land uses.

4.4. Soil acidity parameters

Various soil acidity parameters used to study acidification process in soils are given in Tables 10-13.

4.4.1. pH measurements

The pH is measured in water, 1 M KCl, 0.01 M $CaCl_2$ and IM NaF (Table 10).

4.4.1.1. pH - H_2O

All the pedons studied are acidic in reaction as shown by the pH-water. At Thiruvananthapuram, significant difference in pH-water was observed between epipedons of soils under rubber (5.15) and uncultivated barren (4.95). Soils under cassava had a pH of 5.05 which was on par with other two epipedons. In the Bt_1 layer, significantly higher pH was observed in soils under rubber (5.30) compared to uncultivated barren (4.75). The value of soils under cassava (5.20) was on par with that of rubber. In the Bt_2 layer also, soils under rubber had a higher pH (5.20) compared to that of cassava (4.95) and uncultivated barren (4.90), which were on par.

At Angadipuram, the pH-water of the epipedon decreased in the order rubber > cassava > uncultivated barren. In the Bt_1 layer, significantly higher pH was observed in soils under rubber (5.35) compared to that of cassava (5.20). Uncultivated barren had a value of

Table 10. Soil pH determinations

Horizon	Depth (cm)	Soil pH			
		H_2O	KCl	$CaCl_2$	NaF
I. Thiruvananthapuram					
A. Cassava					
Ap	0-28	5.05	3.60	3.60	10.70
AB	28-63	5.00	3.55	3.45	10.35
Bt_1	63-97	5.20	3.45	3.15	10.55
Bt_2	97-200	4.95	3.35	3.15	9.75
B. Rubber					
Ap	0-9	5.15	3.50	3.65	10.70
A1	9-20	5.00	3.40	3.40	10.45
A2	20-34	4.90	3.05	3.35	10.45
AB	34-43	5.25	3.35	3.20	10.65
Bt_1	43-114	5.30	3.45	3.20	9.65
Bt_2	114-200	5.20	3.45	3.05	9.50
C. Uncultivated barren					
A	0-34	4.95	3.45	3.50	10.15
Bt_1	34-89	4.75	3.25	3.20	10.80
Bt_2	89-200	4.90	3.25	3.10	9.65
CD		0.10	0.13	NS	0.37
II. Angadipuram					
A. Cassava					
Ap	0-21	5.00	3.55	3.65	9.60
EB	21-40	4.85	3.50	3.40	9.80
B	40-108	4.80	3.25	3.15	9.95
Bt_1	108-142	5.20	3.60	3.30	9.95
Bt_2	142.200	5.05	3.50	3.20	9.50
B. Rubber					
Ap	0-13	5.15	3.60	3.55	9.10
Eo	13-24	5.05	3.65	3.40	9.35
B	24-42	5.00	3.15	3.25	9.45
Bt_1	42-115	5.35	3.50	3.40	9.45
Bt_2	115-200	5.20	3.55	3.15	9.60

Table 10. (Contd....)

Horizon	Depth (cm)	Soil pH			
		H_2O	KCl	$CaCl_2$	NaF
C. Uncultivated barren					
A1	0-8	4.85	3.45	3.50	9.30
A2	8-37	4.80	3.60	3.45	8.95
E	37-74	4.85	3.45	3.30	9.00
Bt_1	74-108	5.25	3.75	3.50	9.00
Bt_2	108-200	5.05	3.55	3.45	8.75
CD		0.14	0.19	0.15	NS
III. Kannur					
A. Cassava					
Ap	0-17	5.05	3.65	3.50	10.55
B1	17-36	4.95	3.50	3.35	10.45
B2	36-79	4.90	3.15	3.05	10.40
Bt_1	79-137	5.15	3.40	3.30	9.75
Bt_2	137-200	4.85	3.30	3.05	9.55
B. Rubber					
Ap	0-17	4.90	3.35	3.50	10.70
A1	17-39	4.80	3.30	3.25	10.45
E0	39-108	4.80	3.00	3.00	10.65
Bt_1	108-141	5.20	3.35	3.30	9.80
Bt_2	141-200	5.00	3.30	3.20	9.55
C. Uncultivated barren					
A	0-12	5.00	3.70	3.25	10.80
E	12-27	4.90	3.70	3.25	10.35
EB	27-81	4.95	3.30	3.00	10.25
Bt_1	81-139	5.05	3.45	3.20	9.80
Bt_2	139-200	4.85	3.15	3.00	9.70
CD		NS	0.20	0.24	0.24

5.25 which was on par with other two. In Bt_2 layer too, soils under rubber had a higher pH of 5.20 compared to those of cassava (5.05) and uncultivated barren (5.05). At Kannur, no significant difference in pH was noted either among different horizons within a profile or between similar horizons under different land uses.

4.4.1.2. pH - KCl

The pH-KCl of surface horizon of soils under uncultivated barren (3.45) at Thiruvananthapuram was significantly lower than that of cassava (3.60) which was on par with that of rubber (3.50). In the Bt_1 layer, soils under uncultivated barren had significantly lower pH-KCl (3.25) compared to those of cassava (3.45) and rubber (3.45). Similar trend is observed in Bt_2 layers too.

At Angadipuram, pH of surface horizon didn't show any difference. The Bt_1 layer of soils under rubber had a significantly lower value (3.50) compared to that of cassava (3.60) and uncultivated barren (3.75), which were on par. No difference could be observed in Bt_2 layers which had a pH-KCl value of less than 3.55.

The surface horizon of soils under rubber at Kannur had a lower pH of 3.35 compared to that of cassava (3.65) and uncultivated barren (3.70), which were on par. No difference could be observed either among Bt_1 layers or Bt_2 layers. The pH was less than 3.50 in these laterite layers under all the three land uses.

4.4.1.3. pH-$CaCl_2$

At Thiruvananthapuram, there was no significant difference in pH-$CaCl_2$ either among different horizons in a profile or among similar horizons under different land uses. The pH-$CaCl_2$ showed a decreasing trend down the profiles. At Angadipuram, pH-$CaCl_2$ differed significantly. The surface horizon of soils under different land uses did not show any difference with regard to pH-$CaCl_2$. But the Bt_1 layer of soils under uncultivated barren recorded a higher pH (3.50) compared to that of cassava (3.30) which was found to be on par with that of rubber (3.40). Similar trend could be observed in Bt_2 layers also.

The surface horizon of soils under cassava and rubber at Kannur recorded a pH-$CaCl_2$ of 3.50 each which was significantly higher than that of uncultivated barren (3.25). In the case of Bt_1 layers or Bt_2 layers no significant difference could be observed. In soils under cassava and uncultivated barren, there were a significant lowering of pH from Bt_1 to Bt_2 layer which could not be observed under rubber.

4.4.1.4. pH-NaF

The pH-NaF was more than 10.00 in the surface horizons of soils under all the three land uses at Thiruvananthapuram. The pH was significantly lower in uncultivated barren (10.15) than that of cassava (10.70) and rubber (10.70). Significantly lower pH was observed in Bt_1 layer of soils under rubber (9.65) compared to that of cassava (10.55) and uncultivated baren (10.80), which were on par. The Bt_2 layer didn't show any difference in pH-

NaF. There was no variation in pH either among different horizons within a profile or among similar horizons under different land uses at Angadipuram.

The pH-NaF of the epipedon of soils under cassava at Kannur was significantly lower (10.55) compared to that of uncultivated barren (10.80) which was on par with that of rubber (10.70). Either the Bt_1 layers or Bt_2 layers didn't show any variation in pH. In all land uses, the pH of epipedon was significantly higher than the respective Bt_1 layers. In soils under rubber, the pH of Bt_2 layer was lower than the overlying Bt_1 horizons.

Pooled analysis of selected horizon groupings under different land uses (Appendix 1.7) shows that only pH-$CaCl_2$ varied significantly among different land uses. The pH-$CaCl_2$ of the epipedon of soils under cassava (3.58) and rubber (3.57), which were on par, was significantly higher than that of uncultivated barren (3.42). Both Bt_1 horizons and Bt_2 horizons under different land uses showed no variation in pH-$CaCl_2$. Under all land uses, the pH-$CaCl_2$ decreased in the order Ap/A horizons > Bt_1 horizons > Bt_2 horizons.

4.4.2. Exchangeable and extractable acidity

4.4.2.1. Exchangeable acidity

With regard to exchangeable acidity (Table 11), epipedon of soils under rubber at Thiruvananthapuram had a significantly lower value compared to that of uncultivated barren. The Bt_1 layer of soils under rubber had a significantly higher exchangeable acidity (3.85 cmol kg^{-1})

Table 11. Exchangeable and extractable acidity of the pedons

Horizon	Depth (cm)	Exchangeable acidity	Exchangeable H	Exchangeable Al	Extractable acidity
		c mol kg^{-1}			
I. Thiruvananthapuram					
A. Cassava					
Ap	0-28	1.27	0.25	1.02	8.87
AB	28-63	1.84	0.30	1.54	7.14
Bt_1	63-97	3.58	0.25	3.33	8.03
Bt_2	97-200	3.70	0.10	3.60	3.65
B. Rubber					
Ap	0-9	0.86	0.15	0.71	8.56
A1	9-20	1.99	0.35	1.64	6.79
A2	20-34	2.62	0.20	2.42	6.97
AB	34-43	3.32	0.25	3.07	7.87
Bt_1	43-114	3.85	0.10	3.75	5.55
Bt_2	114-200	2.80	0.25	2.55	2.55
C. Uncultivated barren					
A	0-34	1.62	0.20	1.42	8.47
Bt_1	34-89	1.96	0.10	1.86	6.11
Bt_2	89-200	3.64	0.20	3.44	3.39
CD		0.45	0.13	0.67	0.89
II. Angadipuram					
A. Cassava					
Ap	0-21	2.74	0.30	2.44	6.59
EB	21-40	2.90	0.20	2.70	6.70
B	40-108	2.41	0.15	2.26	7.46
Bt_1	108-142	3.65	0.15	3.50	4.85
Bt_2	142-200	3.15	0.15	3.00	2.55
B. Rubber					
Ap	0-13	3.23	0.35	2.88	6.98
Eo	13-24	3.02	0.35	2.67	6.92
B	24-42	2.24	0.15	2.09	7.39
Bt_1	42-115	3.50	0.15	3.35	5.40
Bt_2	115-200	2.93	0.15	2.78	2.88

Table 11. (Contd....)

Horizon	Depth (cm)	Exchangeable acidity	Exchangeable H	Exchangeable Al	Extractable acidity
		c mol kg^{-1}			
C. Uncultivated barren					
A1	0-8	3.57	0.25	3.32	6.67
A2	8-37	2.96	0.15	2.81	6.31
E	37-74	2.57	0.25	2.32	6.72
Bt$_1$	74-108	3.51	0.15	3.36	4.76
Bt$_2$	108-200	3.67	0.25	3.42	2.57
CD		NS	NS	0.41	1.51
III. Kannur					
A. Cassava					
Ap	0-17	1.72	0.10	1.62	7.27
B1	17-36	2.48	0.25	2.23	5.48
B2	36-79	2.75	0.15	2.60	5.60
Bt$_1$	79-137	4.46	0.20	4.26	3.01
Bt$_2$	137-200	2.79	0.10	2.69	2.34
B. Rubber					
Ap	0-17	1.81	0.10	1.71	7.81
A1	17-39	2.67	0.25	2.42	6.22
E0	39-108	2.12	0.25	1.87	5.87
Bt$_1$	108-141	3.93	0.20	3.73	3.43
Bt$_2$	141-200	2.45	0.15	2.30	2.60
C. Uncultivated barren					
A	0-12	2.48	0.15	2.33	7.73
E	12-27	3.07	0.15	2.92	5.87
EB	27-81	2.56	0.25	2.31	5.46
Bt$_1$	81-139	4.26	0.15	4.11	3.11
Bt$_2$	139-200	2.61	0.10	2.51	2.46
CD		0.54	NS	0.97	1.76

compared to that of uncultivated barren (1.96 cmol kg^{-1}). The value for soils under cassava was on par with that of rubber. Significantly lower value of exchangeable acidity was recorded in Bt_2 layer of soils under rubber than that of other two land uses. No difference in exchangeable acidity could be observed at Angadipuram.

At Kannur, the exchangeable acidity of the surface horizon of soils under cassava (1.72 cmol kg^{-1}) and rubber (1.81 cmol kg^{-1}), which were on par, was significantly lower than that of uncultivated barren (2.48 cmol kg^{-1}). In the subsurface layers, no difference was noticed among similar horizons. In all land uses, there was an increase in exchangeable acidity from surface to Bt_1 layer and then a decrease to Bt_2 layer.

4.4.2.2. Exchangeable hydrogen and aluminium

Exchangeable hydrogen differed significantly among various horizons at Thiruvananthapuram. There was no significant difference in exchangeable hydrogen in the epipedons of soils under different land uses. But the value was significantly lower in Bt_1 layers of soils under rubber (0.10 cmol kg^{-1}) and uncultivated barren (0.10 cmol kg^{-1}) compared to that of cassava (0.25 cmol kg^{-1}). The Bt_2 layer of soils under rubber had a significantly higher exchangeable hydrogen content (0.25 cmol kg^{-1}) compared to that of cassava (0.10 cmol kg^{-1}) and uncultivated barren (0.20 cmol kg^{-1}), which were on par. Another important observation is the significant increase in exchangeable hydrogen from Bt_1 layer (0.10 cmol kg^{-1}) to Bt_2 layer (0.25 cmol kg^{-1}) of soils under rubber. At Angadipuram and Kannur, the exchangeable hydrogen content didn't show any difference.

The exchangeable aluminium contents in the pedons were very high compared to exchangeable hydrogen values. At Thiruvananthapuram, epipedon of soils under rubber had significantly lower value (0.71 cmol kg^{-1}) compared to that of cassava (1.02 cmol kg^{-1}) and uncultivated barren (1.42 cmol kg^{-1}), which were on par. In the case of Bt_1 layer, soils under uncultivated barren recorded a significantly lower value (1.86 cmol kg^{-1}) than that of cassava (3.33 cmol kg^{-1}) and rubber (3.75 Bt_2 cmol kg^{-1}), which were on par. But in hard laterite layer, exchangeable aluminium was significantly lower in soils under rubber than that of other two land uses, which were on par.

At Angadipuram, surface horizon of soils under cassava had significantly lower value (2.44 cmol kg^{-1}) followed by rubber (2.88 cmol kg^{-1}) and uncultivated barren (3.32 cmol kg^{-1}). The Bt_1 layer of soils showed no difference in exchangeable aluminium content. In the case of Bt_2 horizon, both soils under cassava and rubber had significantly lower exchangeable aluminium content, which were on par, than that of uncultivated barren.

At Kannur, exchangeable aluminium varied significantly among different horizons. But it was on par among similar horizons under different land uses. A significant increase could be observed from Ap/A layer to Bt_1 layer and a decrease from Bt_1 layer to Bt_2 layer below in all land uses under study.

4.4.2.3. Extractable acidity or potential acidity

At all three locations the extractable acidity showed significant difference. The extractable acidity of similar horizons among different land uses did not show any variation at Thiruvananthapuram (Table 11). But there was a significant decrease in extractable acidity in the Bt_2 layers compared to the above horizons. The extractable acidity of similar horizons under different land uses at Angadipuram too showed no difference though there was a significant reduction in extractable acidity down the profiles under all land uses. At Kannur, there were no difference in extractable acidity values among similar horizons under different land uses. But there was significant decrease down the profile from Ap/A to Bt_1 layer, while that of hard laterite layer was on par with that of the respective Bt_1 layer above.

The results of the pooled analysis (Appendix 1.8) show that the exchangeable acidity of surface horizons decreased significantly as uncultivated barren > cassava > rubber. The Bt_1 horizons of soils under cassava had a significantly higher amount of exchangeable acidity (3.90 cmol kg^{-1}) than that of rubber (3.76 cmol kg^{-1}) and uncultivated barren (3.24 cmol kg^{-1}). The exchangeable acidity of the Bt_2 horizons also followed the same trend as that of surface horizons. Exchangeable H and Al showed no difference among similar horizon groupings under different land uses.

The extractable acidity of surface horizons of soils under different land uses didn't vary significantly. In the case of Bt_1 horizons, soils under cassava had a significantly higher content than that of rubber and uncultivated barren which were on par. With regard to Bt_2 horizons, the exchangeable acidity was on par under all the three land uses.

4.4.3. CEC, ECEC and base saturation

4.4.3.1. Cation exchange capacity

The cation exchange capacity (CEC) (Table 12) of the various horizons of the pedons was determined both by neutral 1 N ammonium acetate method and by sum of cations method. Both showed significant difference at Thiruvananthapuram. Though the surface horizons did not show any difference in CEC (NH_4OAc) at Thiruvananthapuram, marked decrease in CEC was observed in Bt_1 and Bt_2 layers which followed the order cassava > uncultivated barren > rubber for Bt_1 layer and cassava > rubber > uncultivated barren for Bt_2 layer. Down the profiles, there was a decreasing trend from surface horizons to Bt_1 horizon to Bt_2 horizon. The CEC (sum of cations) of the surface horizons as well as Bt_1 layers differed significantly among different land uses. The CEC (sum of cations) of the Bt_2 layer of soils under rubber (3.05 cmol(p+) kg^{-1} was significantly lower than that of uncultivated barren (4.15 cmol(p+) kg^{-1}) and cassava (4.35 cmol(p+) kg^{-1}) which were on par.

At Angadipuram also, CEC (by both methods) differed significantly. But the CEC (NH_4OAc) of similar horizons did not vary. Down the profile, significant decrease in CEC from Ap/A layer to Bt_1 layer was observed only under uncultivated barren. The Bt_1 and Bt_2 layers were on par with respect to CEC (NH_4OAc) but there was significant decrease in CEC in the Bt_2 layers compared to their respective surface horizons. The CEC (sum of cations) of the surface horizon of soils under uncultivated barren (8.25 cmol(p+) kg^{-1}) was significantly lower compared

Table 12. Cation exchange capacity (CEC) and effective cation exchange capacity (ECEC) of the pedons

Horizon	Depth (cm)	CEC NH$_4$OAc method	CEC Sum of cations	ECEC
		c mol (p$^+$) kg^{-1}		
I. Thiruvananthapuram				
A. Cassava				
Ap	0-28	7.40	11.90	4.05
AB	28-63	6.05	8.70	3.10
Bt$_1$	63-97	6.40	9.35	4.65
Bt$_2$	97-200	3.00	4.35	4.30
B. Rubber				
Ap	0-9	7.65	11.45	3.60
A1	9-20	6.15	8.89	3.75
A2	20-34	6.05	8.85	4.30
AB	34-43	6.50	9.50	4.70
Bt$_1$	43-114	4.50	6.75	4.95
Bt$_2$	114-200	2.05	3.05	3.05
C. Uncultivated barren				
A	0-34	7.50	10.90	3.85
Bt$_1$	34-89	5.15	7.45	3.20
Bt$_2$	89-200	2.95	4.15	4.20
CD		0.29	0.24	0.40
II. Angadipuram				
A. Cassava				
Ap	0-21	6.15	8.85	4.70
EB	21-40	5.65	8.15	4.15
B	40-108	6.10	9.05	3.85
Bt$_1$	108-142	4.15	6.00	4.65
Bt$_2$	142.200	2.10	3.05	3.50
B. Rubber				
Ap	0-13	6.20	8.90	4.80
Eo	13-24	5.70	8.35	4.10
B	24-42	6.05	8.65	3.35
Bt$_1$	42-115	4.35	6.35	4.30
Bt$_2$	115-200	2.25	3.35	3.25

Table 12. (Contd....)

Horizon	Depth (cm)	CEC NH$_4$OAc method	CEC Sum of cations	ECEC
		c mol (p$^+$) kg^{-1}		
C. Uncultivated barren				
A1	0-8	5.85	8.25	4.90
A2	8-37	5.35	7.70	4.15
E	37-74	5.75	8.00	3.60
Bt$_1$	74-108	3.75	5.55	4.65
Bt$_2$	108-200	2.15	3.15	3.90
CD		2.46	0.20	NS
III. Kannur				
A. Cassava				
Ap	0-17	6.70	9.70	4.05
B1	17-36	5.15	7.20	3.95
B2	36-79	4.95	7.00	3.50
Bt$_1$	79-137	2.55	3.60	4.85
Bt$_2$	137-200	2.05	2.85	3.20
B. Rubber				
Ap	0-17	6.90	10.00	3.90
A1	17-39	5.35	7.70	3.90
E0	39-108	5.15	7.20	3.20
Bt$_1$	108-141	2.85	4.05	4.35
Bt$_2$	141-200	2.05	3.00	2.70
C. Uncultivated barren				
A	0-12	6.55	9.50	4.10
E	12-27	4.95	7.15	4.20
EB	27-81	4.80	6.80	3.65
Bt$_1$	81-139	2.65	3.75	4.75
Bt$_2$	139-200	2.05	2.95	3.00
CD		0.17	2.77	0.28

to that of cassava (8.85 cmol(p+) kg^{-1}) and rubber (8.90 cmol(p+) kg^{-1}). In the Bt_1 layer, soils under rubber had significantly higher CEC (6.35 cmol(p+) kg^{-1}) compared to that of cassava (6.00 cmol(p+) kg^{-1}) and uncultivated barren (5.55 cmol(p+) kg^{-1}). Similar trend was observed in Bt_2 layers too.

At Kannur, the CEC (NH_4OAc) of the surface horizon of soils under rubber (6.90 cmol(p+) kg^{-1}) was significantly higher than that of cassava (6.70 cmol(p+) kg^{-1}) and uncultivated barren (6.55 cmol(p+) kg^{-1}), which were on par. Similar trend was observed in Bt_1 layer too while there was no difference in CEC in the Bt_2 layers under different land uses. The CEC decreased significantly down the profiles from surface horizon to Bt_1 to Bt_2 layers under all land uses. The CEC (sum of cations) showed significant reduction from surface horizon to corresponding Bt_1 layer but were on par between Bt_1 and Bt_2 layers under all land uses.

The CEC (sum of cations) values in all the studied pedons were higher than CEC (NH_4OAc) values. Marked difference could be observed in the surface horizons.

4.4.3.2. Effective cation exchange capacity

The effective cation exchange capacity (ECEC) (Table 12) of the surface horizon of soils under rubber at Thiruvananthapuram (3.60 cmol(p+) kg^{-1}) was significantly lower than that of cassava (4.05 cmol(p+) kg^{-1}) which was on par with that of uncultivated barren (3.85 cmol(p+) kg^{-1}). The ECEC was significantly lower in soils under uncultivated barren in the case of Bt_1 layer (3.20 cmol(p+) kg^{-1}) compared to that of cassava (4.65 cmol(p+) kg^{-1}) and rubber (4.95 cmol(p+) kg^{-1}) which were on par. In the case of Bt_2 layer, lower value was observed in soils under rubber (3.05 cmol$^{(p+)}$ kg^{-1}) compared to that of cassava (4.30 cmol(p+) kg^{-1}) and uncultivated barren (4.20 cmol(p+) kg^{-1}), which were on par. The ECEC didn't show any difference in pedons at Angadipuram.

The ECEC values differed significantly in pedons at Kannur. The surface horizon of soils under different land uses showed no difference in ECEC values. But in the case of Bt_1 layer as well as Bt_2 layer, soils under rubber had significantly lower ECEC value compared to other two land uses, the values for which were found to be on par.

Results of the pooled analysis (Appendix 1.9) of CEC (NH_4OAc) show no difference among similar horizon groups. The CEC (sum of cations) of surface horizons of soils under cassava (10.15 cmol(p+) kg^{-1}) and rubber (10.12 cmol(p+) kg^{-1}), which were o par, was significantly higher than that of uncultivated barren (9.55 cmol(p+) kg^{-1}). The CEC (sum of cations) of Bt_1 horizons under different land uses differed significantly in the order cassava > rubber > uncultivated barren. The Bt_2 horizons of soils under rubber had a lower CEC (sum of cations) than that of cassava and uncultivated barren, which were on par.

The ECEC was significantly lower in the Bt_1 horizons under uncultivated barren than that of cassava and rubber. In the case of Bt_2 horizons, soils under rubber had a significantly lower ECEC (3.00

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cmol(p+) kg^{-1}) compared to that of cassava (3.67 cmol(p+) kg^{-1}) and uncultivated barren (3.70 cmol(p+) kg^{-1}).

4.4.3.3. Base saturation

The per cent base saturation (Table 13) of various horizons of the pedons was estimated based on CEC determined by NH_4OAc method and sum of cations method. The base saturation (NH_4OAc) of identical horizons under different land uses did not show any variation at Thiruvananthapuram. There was a significant lowering of base saturation (NH_4OAc) as we go down from surface horizon to Bt_1 layer in soils under cassava and rubber and not in uncultivated barren.

The base saturation (sum of cations) of identical horizons under different land uses also didn't show any difference at Thiruvananthapuram. There was a significant lowering of base saturation (sum of cations) also as we go down from surface horizon to Bt_1 layer in soils under cassava and rubber and not in uncultivated barren.

At Angadipuram, the base saturation (NH_4OAc) of surface horizon of soils under cassava (36.81 per cent) was significantly higher than that of rubber (30.99 per cent) and uncultivated barren (27.02 per cent). In the case of Bt_1 layer, though a significantly higher value could be recorded in soils under cassava (27.82 per cent) compared to that of rubber (21.84 per cent) and uncultivated barren (21.16 per cent), they were on par. The hard laterite layer didn't show any difference in base saturation (NH_4OAc) values.

Table 13. Sum of bases and per cent base saturation (PBS) of the pedons

Horizon	Depth (cm)	Sum of bases $cmol(p^+)kg^{-1}$	PBS (%)	
			NH_4OAc	Sum of cations
I. Thiruvananthapuram				
A. Cassava				
Ap	0-28	3.04	41.04	25.50
AB	28-63	1.56	25.77	17.92
Bt_1	63-97	1.33	20.67	14.16
Bt_2	97-200	0.71	23.46	16.19
B. Rubber				
Ap	0-9	2.90	37.78	25.33
A1	9-20	2.12	34.38	23.75
A2	20-34	1.89	31.15	21.31
AB	34-43	1.63	25.04	17.16
Bt_1	43-114	1.21	26.68	17.84
Bt_2	114-200	0.51	24.61	16.58
C. Uncultivated barren				
A	0-34	2.43	32.40	22.29
Bt_1	34-89	1.34	26.05	17.98
Bt_2	89-200	0.77	25.96	18.43
CD		1.62	6.17	5.13
II. Angadipuram				
A. Cassava				
Ap	0-21	2.27	36.81	25.60
EB	21-40	1.45	25.65	17.79
B	40-108	1.60	26.17	17.63
Bt_1	108-142	1.16	27.82	19.25
Bt_2	142.200	0.51	24.05	16.55
B. Rubber				
Ap	0-13	1.92	30.99	21.57
Eo	13-24	1.44	25.16	17.19
B	24-42	1.27	20.91	14.63
Bt_1	42-115	0.95	21.84	14.96
Bt_2	115-200	0.47	20.80	14.01

Table 13. (Contd....)

Horizon	Depth (cm)	Sum of bases cmol(p^+)kg^{-1}	PBS (%)	
			NH_4OAc	Sum of cations
C. Uncultivated barren				
A1	0-8	1.58	27.02	19.14
A2	8-37	1.39	25.97	18.05
E	37-74	1.28	22.28	16.02
Bt_1	74-108	0.80	21.16	14.32
Bt_2	108-200	0.49	22.54	15.89
CD		1.26	5.81	5.67
III. Kannur				
A. Cassava				
Ap	0-17	2.44	36.39	25.12
B1	17-36	1.72	33.42	23.89
B2	36-79	1.40	28.28	20.01
Bt_1	79-137	0.60	23.31	16.51
Bt_2	137-200	0.51	24.92	17.89
B. Rubber				
Ap	0-17	2.19	31.76	21.90
A1	17-39	1.49	27.74	19.27
E0	39-108	1.34	25.95	18.52
Bt_1	108-141	0.63	21.93	15.44
Bt_2	141-200	0.41	19.72	13.50
C. Uncultivated barren				
A	0-12	1.77	27.04	18.65
E	12-27	1.28	25.84	17.90
EB	27-81	1.34	27.92	19.71
Bt_1	81-139	0.64	24.12	17.05
Bt_2	139-200	0.49	23.90	16.61
CD		1.36	5.91	4.59

The base saturation (sum of cations) of surface horizons in soils under cassava (25.60 per cent) was significantly higher than that of uncultivated barren (19.14 per cent), which was on par with that of rubber (21.57 per cent). No significant difference could be observed among Bt_1 layers or among hard laterite layers under different land uses.

At Kannur, the base saturation (NH_4OAc) of the surface horizon of soils under cassava (36.39 per cent) was significantly higher than that of uncultivated barren (27.04 per cent), which was on par with that of rubber (31.76 per cent). But the Bt_1 layers as well as Bt_2 layers under different land uses didn't show any significant difference with regard to base saturation (NH_4OAc).

The base saturation (sum of cations) of the surface horizons also showed similar trend. In the case of Bt_1 layers as well as Bt_2 layers under different land uses, no significant difference could be observed.

One important observation with regard to base saturation values at all the three study sites is the lower base saturation (sum of cations) values compared to base saturation (NH_4OAc) values.

Results of pooled analysis (Appendix 1.10) show that base saturation (NH_4OAc) of surface horizon of soils under cassava (38.08 per cent) was significantly higher than that of uncultivated barren (28.82 per cent), which was on par with that of rubber (33.51 per cent). Both Bt_1 and Bt_2 layers under different land uses didn't show any significant difference. Same trend could be observed in the case of base saturation (sum of cations) also.

4.5. Free oxides of iron and aluminium and hardening and softening of laterites

The relationship between free oxides of iron and aluminium and hardening and softening of laterites is given in Tables 14-15.

4.5.1 Free oxides of iron

The oxalate and dithionite extractable iron in different pedons is given in Table 14. Oxalate extractable iron (Fe_o)in the epipedon of soils under rubber at Thiruvananthapuram (0.22 per cent) was significantly higher compared to that of cassava (0.19 per cent) and uncultivated barren (0.18 per cent), which were on par. The Bt_1 layers did not show any difference in Fe_o while the Bt_2 layer of soils under uncultivated barren had significantly higher Fe_o content (0.15 per cent) compared to that of cassava (0.11 per cent) and rubber (0.12 per cent). Under all land use systems, the Fe_o content in epipedon and Bt_1 layer did not vary while in Bt_2 layer, there was significant lowering of Fe_o content.

The dithionite extractable iron (Fe_d) in epipedons as well as Bt_1 layer did not show any difference under different land uses at Thiruvananthapuram. The hard laterite layer under uncultivated barren had significantly higher Fe_d content (6.09 per cent) compared to that of cassava (4.60 per cent) and rubber (4.76 per cent). There was no difference in Fe_d content between epidpedons and their respective Bt_1 layers under different land uses. But the Fe_d content increased significantly in the Bt_2 layers of soils under cassava and uncultivated barren compared to the overlying layers.

Table 14. Free oxides of Fe and Al in pedons (%)

Horizon	Depth (cm)	Fe_o	Fe_d	Al_o	Al_d
I. Thiruvananthapuram					
A. Cassava					
Ap	0-28	0.19	2.78	0.09	0.87
AB	28-63	0.17	3.16	0.07	0.73
Bt_1	63-97	0.19	3.17	0.08	0.62
Bt_2	97-200	0.11	4.60	0.08	0.64
B. Rubber					
Ap	0-9	0.22	2.87	0.09	0.96
A1	9-20	0.19	3.10	0.10	0.86
A2	20-34	0.18	3.31	0.10	0.42
AB	34-43	0.18	3.32	0.09	0.41
Bt_1	43-114	0.21	3.88	0.08	0.46
Bt_2	114-200	0.12	4.76	0.08	0.38
C. Uncultivated barren					
A	0-34	0.18	2.14	0.07	0.91
Bt_1	34-89	0.20	3.02	0.06	0.74
Bt_2	89-200	0.15	6.09	0.05	0.63
CD		0.02	1.22	0.01	0.06
II. Angadipuram					
A. Cassava					
Ap	0-21	0.17	2.73	0.14	0.62
EB	21-40	0.14	3.14	0.13	0.44
B	40-108	0.14	3.39	0.12	0.48
Bt_1	108-142	0.19	3.47	0.11	0.52
Bt_2	142.200	0.14	3.53	0.10	0.41
B. Rubber					
Ap	0-13	0.19	3.48	0.13	0.58
Eo	13-24	0.16	3.89	0.11	0.52
B	24-42	0.15	3.71	0.10	0.51
Bt_1	42-115	0.21	4.17	0.09	0.61
Bt_2	115-200	0.16	6.30	0.09	0.47

Table 14. (Contd...)

Horizon	Depth (cm)	Fe_o	Fe_d	Al_o	Al_d
C. Uncultivated barren					
A1	0-8	0.15	2.78	0.13	0.56
A2	8-37	0.12	2.73	0.11	0.52
E	37-74	0.12	2.71	0.09	0.43
Bt_1	74-108	0.17	3.04	0.09	0.46
Bt_2	108-200	0.12	6.94	0.08	0.38
CD		0.02	1.76	0.02	0.03
III. Kannur					
A. Cassava					
Ap	0-17	0.16	2.40	0.04	0.81
B1	17-36	0.13	2.80	0.05	0.84
B2	36-79	0.12	3.01	0.05	0.73
Bt_1	79-137	0.15	1.87	0.05	0.64
Bt_2	137-200	0.11	4.61	0.03	0.59
B. Rubber					
Ap	0-17	0.18	2.25	0.05	0.78
A1	17-39	0.14	2.83	0.05	0.70
E0	39-108	0.14	2.48	0.06	0.56
Bt_1	108-141	0.18	2.22	0.06	0.61
Bt_2	141-200	0.13	7.01	0.05	0.50
C. Uncultivated barren					
A	0-12	0.15	2.78	0.04	0.81
E	12-27	0.13	3.60	0.04	0.73
EB	27-81	0.12	3.50	0.05	0.70
Bt_1	81-139	0.14	2.23	0.05	0.73
Bt_2	139-200	0.12	6.05	0.04	0.61
CD		0.01	0.93	0.01	0.06

The Fe_o content in the surface horizons of soil under rubber at Angadipuram (0.19 per cent) was significantly higher than that of uncultivated barren (0.15 per cent). The value for soils under cassava was on par with the other two. In the Bt_1 layer, soils under rubber had significantly higher Fe_o content (0.21 per cent) than that of uncultivated barren (0.17 per cent). The value for soils under cassava (0.19 per cent) was on par with the other two. The hard laterite layer under uncultivated barren had a significantly lower Fe_o content (0.12 per cent) than that of rubber (0.16 per cent). Laterite layer of soils under cassava had an Fe_o content on par with the other two. Down the profile, there was a significant reduction in Fe_o content in Bt_2 layer compared to that of the overlying Ap/A layer and Bt_1 layer.

Significant difference could be observed in Fe_d values. The dithionite extractable iron content in the surface horizons as well as Bt_1 layers didn't vary among different land- uses. Significantly lower Fe_d content was observed in Bt_2 layer of soils under cassava (4.53 per cent) compared to that of rubber (6.30 per cent) and uncultivated barren (6.94 per cent), which were on par. A significantly higher Fe_d content was noted in the Bt_2 layers compared to the respective surface horizons and Bt_1 layers above.

At Kannur, the Fe_o content in the surface horizon of soils under rubber (0.18 per cent) was significantly higher than that of cassava (0.16 per cent) and uncultivated barren (0.15 per cent), which were on par. Same trend was observed in the Bt_1 as well as Bt_2 layers also. Down the profile, there was significant reduction in Fe_o content in the layer compared to the respective overlying Bt_1 layer and surface horizon under all land uses.

The Fe_d content of epipedons as well as Bt_1 layers under different land uses was on par. In the case of Bt_2 layer, a significantly lower value could be observed in soils under cassava (4.61 per cent) compared to that of rubber (7.01 per cent) and uncultivated barren (6.05 per cent), which were on par. Down the profile, there was a significant increase in Fe_d content in Bt_2 layer compared to the overlying Bt_1 layer and surface horizon.

Analysis of pooled data from the three locations (Appendix 1.11), shows that the Fe_0 content was significantly higher in epipedons of soils under rubber (0.19 per cent) than that of cassava (0.17 per cent) and uncultivated barren (0.16 per cent), which were on par. Similar trend was observed in Bt_1 horizons too. No difference could be observed among Bt_2 horizons. Under all land uses, there was a significant lowering of Fe_0 content in Bt_2 horizons compared to the overlying Bt_1 horizons. The Fe_d did not show any difference due to different land uses.

4.5.2 Free oxides of aluminium

The oxalate extractable aluminium (Al_0) (Table 14) in the epipedons of soils under cassava (0.09 per cent) and rubber (0.09 per cent) were significantly higher compared to that of uncultivated barren at Thiruvananthapuram. Similar results were also observed in Bt_1 and Bt_2 layers. The dithionite extractable aluminium (Al_d) in the epipedon of soils under rubber (0.96 per cent) was significantly higher compared to that of cassava (0.87 per cent) and uncultivated barren (0.91 per cent). In the Bt_1 layer, Al_d followed the order uncultivated barren > cassava >

rubber. The Al_d content was significantly lower in Bt_2 layer of soils under rubber (0.38 per cent) compared to that of cassava (0.64 per cent) and uncultivated barren (0.63 per cent).

At Angadipuram, though significant difference could be observed in Al_0 values, no significant difference in Al_0 content was observed among similar horizons under different land uses. But there was significantly lower Al_0 content in Bt_1 and Bt_2 layers compared to their respective epipedons. Significantly higher Al_d content was observed in epipedon of soils under cassava (0.62 per cent) compared to that of rubber (0.58 per cent) and uncultivated barren (0.56 per cent). The Bt_1 layer of soils under rubber had higher content of Al_d (0.61 per cent) than that of cassava (0.52 per cent) and uncultivated barren (0.46 per cent). In the Bt_2 layer too, soils under rubber had significantly higher Al_d content (0.47 per cent) than that of cassava (0.41 per cent) and uncultivated barren (0.38 per cent), which were on par.

At Kannur also the Al_0 content differed significantly. The Al_0 content in epipedons as well as Bt_1 layers did not show any variation among different land uses at Kannur. But in the case of Bt_2 layer, there was a significantly higher content in soils under rubber (0.05 per cent) compared to that of cassava (0.03 per cent) and uncultivated barren (0.04 per cent). Dithionite extractable aluminium content of the epipedons did not differ while in the Bt_1 layer of soils under uncultivated barren, there was a significantly higher content of Al_d compared to that of cassava (0.64 per cent) and rubber (0.61 per cent). The Bt_2 layers of soils under both cassava (0.59 per cent) and uncultivated barren (0.61 per cent), which were on par, had a significantly higher Al_d content than that of rubber (0.50 per cent).

Pooled analysis of results of free oxides of aluminium (Appendix 1.11) shows no difference in the case of Al_o due to different land uses. In the case of Al_d, surface horizons recorded similar values while a significantly higher content was recorded in Bt_1 horizons of soils under uncultivated barren (0.64 per cent) than that of cassava (0.59 per cent) and rubber (0.56 per cent), which were on par. The Al_d content was significantly higher in Bt_2 horizons of soils under cassava (0.54 per cent) and uncultivated barren (0.54 per cent) compared to that of rubber (0.45 per cent).

4.5.3 Relationship between free oxides of iron and aluminium in pedons

Active iron ratio (Fe_o/Fe_d) (Table 15) showed significant difference. The active iron ratio (Fe_o/Fe_d) of similar horizons under different land uses at Thiruvananthapuram did not vary significantly. But the Bt_2 layers of soils under all the three land uses had significantly lower active iron ratio compared to the overlying horizons, which were on par. The results were similar at Angadipuram also. At Kannur, the active iron ratio of surface horizon of soils under rubber (0.08) was significantly higher than that of uncultivated barren (0.06). Surface horizon of soils under cassava had an intermediate value of 0.07 which was on par with other two. The Bt_2 layers of soils under all three land uses had significantly lower ratio compared to the overlying Bt_1 layer and surface horizon, which were on par.

Table 15. Relationship between different forms of free oxides of Fe and Al

Horizon	Depth (cm)	$\frac{Fe_o}{Fe_d}$	Fe_d-Fe_o (%)	Al_d-Al_o (%)	Aluminium substitution (%)
I. Thiruvananthapuram					
A. Cassava					
Ap	0-28	0.07	2.59	0.78	23.15
AB	28-63	0.06	2.99	0.66	18.08
Bt_1	63-97	0.06	2.98	0.54	15.34
Bt_2	97-200	0.03	4.49	0.56	11.09
B. Rubber					
Ap	0-9	0.08	2.65	0.87	24.72
A1	9-20	0.06	2.91	0.76	20.71
A2	20-34	0.06	3.13	0.32	9.28
AB	34-43	0.06	3.14	0.32	9.25
Bt_1	43-114	0.06	3.67	0.38	9.38
Bt_2	114-200	0.03	4.64	0.30	6.07
C. Uncultivated barren					
A	0-34	0.09	1.96	0.84	30.00
Bt_1	34-89	0.07	2.82	0.68	19.43
Bt_2	89-200	0.03	5.94	0.58	8.90
CD		0.02	1.23	0.16	4.33
II. Angadipuram					
A. Cassava					
Ap	0-21	0.06	2.56	0.48	15.79
EB	21-40	0.05	3.00	0.31	9.37
B	40-108	0.04	3.25	0.36	9.97
Bt_1	108-142	0.06	3.28	0.41	11.11
Bt_2	142.200	0.03	4.39	0.31	6.60
B. Rubber					
Ap	0-13	0.06	3.29	0.45	12.03
Eo	13-24	0.04	3.73	0.41	9.90
B	24-42	0.04	3.56	0.41	10.33
Bt_1	42-115	0.05	3.96	0.52	11.61
Bt_2	115-200	0.03	6.14	0.38	5.83

Table 15. (Contd...)

Horizon	Depth (cm)	$\frac{Fe_o}{Fe_d}$	Fe_d-Fe_o (%)	Al_d-Al_o (%)	Aluminium substitution (%)
C. Uncultivated barren					
A1	0-8	0.06	2.63	0.43	14.05
A2	8-37	0.05	2.61	0.41	13.58
E	37-74	0.05	2.59	0.34	11.60
Bt_1	74-108	0.06	2.87	0.37	11.42
Bt_2	108-200	0.02	6.82	0.30	4.21
CD		0.02	1.38	0.07	5.76
III. Kannur					
A. Cassava					
Ap	0-17	0.07	2.24	0.77	25.58
B1	17-36	0.05	2.67	0.79	22.83
B2	36-79	0.04	2.89	0.68	19.32
Bt_1	79-137	0.08	1.75	0.59	25.21
Bt_2	137-200	0.03	4.50	0.56	11.07
B. Rubber					
Ap	0-17	0.08	2.07	0.73	26.07
A1	17-39	0.05	2.69	0.65	19.46
E0	39-108	0.06	2.34	0.50	17.60
Bt_1	108-141	0.08	2.04	0.55	21.24
Bt_2	141-200	0.02	6.88	0.45	6.14
C. Uncultivated barren					
A	0-12	0.06	2.63	0.77	22.65
E	12-27	0.04	3.47	0.69	16.59
EB	27-81	0.04	3.38	0.65	16.13
Bt_1	81-139	0.07	2.09	0.68	24.55
Bt_2	139-200	0.02	5.93	0.57	8.76
CD		0.01	1.27	NS	3.70

The content of crystalline iron oxides (Fe_d-Fe_o) did not show any difference either among surface horizons or among Bt_1 layers of soils under different land uses at Thiruvananthapuram. But there was a significantly higher crystalline iron oxide content in the Bt_2 layer of soils under uncultivated barren (5.94 per cent) compared to that of cassava (4.49 per cent) and rubber (4.64 per cent). Down the profiles, the content of crystalline iron oxides increased significantly from Bt_1 to Bt_2 layers of soils under all land uses.

At Angadipuram, no difference was observed in crystalline iron oxide content of either surface horizons or Bt_1 layers under all land uses. But the Bt_2 layer of soils under rubber (6.14 per cent) and uncultivated barren (6.82 per cent) had significantly higher crystalline iron oxides than that of cassava (4.39 per cent). Down the profiles, there was a significant increase in their content from Bt_1 to Bt_2 layers of soils under rubber and uncultivated barren, and not in soils under cassava.

The content of crystalline iron oxides in the surface horizons and Bt_1 layers of soils under different land uses at Kannur also did not vary significantly. But there was a significantly higher content in Bt_2 layer of soils under rubber (6.88 per cent) compared to that of cassava (4.50 per cent). The Bt_2 layer of soils under uncultivated barren had a value of 5.93 per cent which was on par with that of rubber. Under all the three land uses, the Bt_2 layer of pedons had a significantly higher free-iron oxide content than their respective overlying horizons, which were on par.

The aluminium bound in iron oxides because of isomorphous substitution is calculated as Al_d-Al_o. The Bt_1 layer of soils under uncultivated barren at Thiruvananthapuram had a significantly higher amount of Al bound in Fe oxides (0.68 per cent) than that of rubber (0.38 per cent). The corresponding horizon under cassava had a value of 0.54 per cent which was on par with the other two. In the case of Bt_2 horizon, soils under rubber had a significantly lower value (0.30 per cent) than that of cassava (0.56 per cent) and uncultivated barren (0.58 per cent), which were on par. The aluminium bound in iron oxides was significantly higher in surface horizons compared to the respective Bt_1 and Bt_2 layers, which were on par.

The amount of aluminium bound in iron oxides did not differ in surface horizons of soils under different land use at Angadipuram. But in the case of Bt_1 layers, soils under rubber had a significantly higher amount (0.52 per cent) than that of cassava (0.41 per cent) and uncultivated barren (0.37 per cent). Similar trend was also observed in Bt_2 layers. There was a significantly higher amount in Bt_1 layers than underlying Bt_2 layers of soils under rubber and uncultivated barren but were on par in soils under cassava. Surface horizon and Bt_2 layer differed significantly only in soils under cassava. No significant difference in the amount of aluminium bound in iron oxides was observed in soils under different land uses at Kannur.

The aluminium substitution in iron oxides in the surface horizons of soils under cassava and rubber at Thiruvananthapuram was significantly lower compared to that of uncultivated barren. In the case of Bt_1 layer, significantly lower amount was observed in soils under rubber (9.38 per cent) compared to that of cassava (15.34 per cent) and uncultivated barren (19.43 per cent), which were on par. The Bt_2 layer of soils under rubber had a lower amount of substitution than that of cassava (11.09 per cent). The layer under uncultivated barren had a value of 8.90 per cent which was on par with the other two. Down the profile, epipedon had a significantly higher level of substitution compared to Bt_1 or Bt_2 layers. The Bt_2 layers of soils under uncultivated barren had a significantly lower level of substitution than that of the overlying Bt_1 horizons. The other two land uses showed no difference.

The aluminium substitution in iron oxides in similar horizons of soils under different land uses at Angadipuram was on par. But there was a significantly lower level of substitution in the Bt_2 layers of soils under rubber (5.83 per cent) and uncultivated barren (4.21 per cent) compared to the respective Bt_1 layers (11.61 and 11.42 per cent respectively). The Bt_1 and Bt_2 layers of soils under cassava showed no difference. But in all pedons, the Bt_2 layers had a significantly lower level of substitution compared to the respective epipedons which had a very high level of substitution.

At Kannur, the Al substitution in Fe oxides in epipedons showed no difference. In the case of Bt_1 layer, a significantly lower value was noted in soils under rubber (21.24 per cent) than that of cassava (25.21 per cent). The hard laterite layer of soils under rubber (6.14 per cent) had significantly lower value than that of cassava (11.07 per cent).

Results of the pooled analysis (Appendix 1.12) showed no difference in active iron ratio (Fe_o/Fe_d) due to different land uses. The crystalline iron oxide content was significantly higher in Bt_1 horizons of soils under rubber compared to that of uncultivated barren, which was on par with that of cassava. In the case of Bt_2 horizons, soils under cassava had significantly lower content (4.46 per cent) than that of rubber (5.89 per cent) and uncultivated barren (6.23 per cent).

The amount of aluminium bound in iron oxides showed no difference among epipedons, but in Bt_1 horizons, soils under uncultivated barren had significantly higher amount than that of cassava and rubber. In the case of Bt_2 horizons, soils under rubber had significantly lower value (0.38 per cent) than that of cassava (0.48 per cent) and uncultivated barren (0.49 per cent). The aluminium substitution in iron oxides showed no difference due to different land uses.

4.6. Iron and aluminium oxides in hard and soft laterites

Table 16 gives the details of oxalate and dithionite extractable iron and aluminium and material strength of hard and soft spots separated and analysed for laterite blocks collected from different land uses.

The Fe_o content in harder spots were significantly lower than that in soft areas under all land uses. Even among hard spots, the Fe_o content was significantly lower in laterites under rubber (0.10 per cent) than that of cassava (0.13 per cent) and uncultivated barren (0.13 per cent). The

Table 16. Oxalate and dithionite extractable iron and aluminium and material strength of hard and soft laterites

Land use	Laterite material	Fe_o (%)	Fe_d (%)	Al_o (%)	Al_d (%)	Al substitution (%)	Penetration pressure (kg cm^{-2})
Cassava	Hard	0.13	5.23	0.19	0.90	12.22	6.68
	Soft	0.20	3.11	0.15	0.64	14.41	3.81
Rubber	Hard	0.10	8.67	0.17	0.82	6.31	8.81
	Soft	0.13	3.94	0.14	0.83	15.33	2.47
Uncultivated barren	Hard	0.13	4.99	0.21	0.74	8.02	5.97
	Soft	0.17	3.24	0.19	0.94	19.63	2.51
CD		0.02	0.38	0.01	0.16	1.65	1.12

Fe_o content in soft areas differed significantly under the three land uses and it followed the order cassava > uncultivated barren > rubber.

In the case of Fe_d, harder spots had significantly higher values compared to the corresponding soft areas under all land uses. The Fe_d content in the harder spots in laterites under rubber (8.67 per cent) was significantly higher than that of cassava (5.23 per cent) and uncultivated barren (4.99 per cent), which were on par. In the soft spots of laterites under rubber also, the Fe_d content was significantly higher (3.94 per cent) than that of cassava (3.11 per cent) and uncultivated barren (3.24 per cent), which were on par.

The harder spots in laterites under all land uses had a significantly higher Al_o content than the corresponding softer areas. Among different land uses, the Al_o content in harder spots differed significantly as uncultivated barren > cassava > rubber. In the case of soft areas in laterites, that under uncultivated barren had significantly higher content (0.19 per cent) than that under cassava (0.15 per cent) and rubber (0.14 per cent), which were on par.

The Al_d content in the harder spots in laterites under different land uses was on par. In the case of soft areas in laterites, the Al_d content was significantly lower in laterites under cassava (0.64 per cent) than that of rubber (0.83 per cent) and uncultivated barren (0.94 per cent), which were on par.

The calculated percentage of Al substitution in laterite showed appreciable amount of Al substitution, especially in the soft laterites. The Al substitution was significantly higher in the softer spots than that of harder areas under all land uses. Within harder spots under different land uses, significant decrease was observed as cassava > uncultivated barren > rubber. The soft area of laterites under uncultivated barren had significantly higher percentage of Al substitution (19.63 per cent) than that of cassava (14.41 per cent) and rubber (15.33 per cent).

The penetration pressure of hard laterites was significantly higher than that of soft laterites under all the three land uses. The penetration pressure of hard laterites under rubber was significantly higher (8.81 kg cm^{-2}) than that of cassava (6.68 kg cm^{-2}) and uncultivated barren (5.97 kg cm^{-2}), which were on par. In the case of soft laterites, significantly high penetration pressure was observed in laterites under cassava (3.81 kg cm^{-2}) than that under rubber (2.47 kg cm^{-2}) and uncultivated barren (2.51 kg cm^{-2}), which were on par.

4.7. Efficacy of organic and inorganic ameliorants in softening of indurated laterites

The results of the chemical, mineralogical and micromorphological studies conducted on the hard laterite blocks before and after treatment for a period of one year are given here.

4.7.1. Chemical changes in hard laterite due to treatment with different ameliorants

4.7.1.1 Total K_2O

The results of the different treatments on the chemical parameters related to laterisation are given in Tables 17-23. The effect of organic

Table 17. Effect of organic and inorganic ameliorants on total K_2O content in laterite (%)

Treatment No.	Time interval (months) 3	6	9	12	Mean
T_1	0.201	0.202	0.193	0.220	0.204
T_2	0.194	0.200	0.194	0.191	0.161
T_3	0.200	0.188	0.200	0.192	0.195
T_4	0.201	0.205	0.191	0.190	0.197
T_5	0.199	0.199	0.195	0.196	0.197
T_6	0.208	0.204	0.195	0.194	0.200
T_7	0.185	0.197	0.196	0.186	0.186
T_8	0.209	0.197	0.197	0.193	0.199
T_9	0.192	0.200	0.197	0.182	0.193
T_{10}	0.199	0.188	0.199	0.186	0.193
T_{11}	0.198	0.192	0.190	0.191	0.193
T_{12}	0.196	0.201	0.197	0.175	0.192
T_{13}	0.193	0.197	0.198	0.192	0.195
T_{14}	0.209	0.205	0.195	0.191	0.200
T_{15}	0.197	0.197	0.194	0.187	0.194
T_{16}	0.199	0.187	0.193	0.187	0.192
T_{17}	0.194	0.201	0.196	0.190	0.195
T_{18}	0.197	0.196	0.198	0.188	0.195
T_{19}	0.199	0.197	0.192	0.195	0.196

CD for treatments : NS
CD for treatment x time interval : 0.008

and inorganic ameliorants on total K_2O content is given in Table 17. The different treatments did not give any significant difference in total K_2O content. A significantly higher amount of K_2O was observed in laterite, twelve months after treatment of cowdung slurry at 20 per cent concentration compared to 3, 6 or 9 months after treatments. Cowdung slurry at 40 per cent concentration gave a reverse trend at 12 months compared to 6 months after treatments. In the case of vermiwash treatments, the lower concentration reduced the K_2O content initially from 3 to 6 months and then it increased at 9 months after treatment which was on par with the value at 12 months after treatment. In the case of higher concentration, upto 6 months, there was no change in K_2O content which decreased significantly afterwards. Green leaf extract at 40 per cent concentration resulted in a lowering of K_2O content after 9 months of treatments compared to the value of 3 months after treatment.

4.7.1.2 Total CaO

The effect of various organic and inorganic ameliorants on total CaO content in laterite is given in Table 18. Significantly higher CaO content was observed in the treatments of calcium chloride, calcium silicate, cowdung slurry, vermiwash and green leaf extracts. But no effect could be noted due to change in concentration of the above treatments. Lower and higher concentrations gave results which were on par. In the case of cowdung slurry, at 20 per cent concentration, the CaO content increased significantly from 3 to 6 months after treatments. The vermiwash, at lower concentration, increased CaO contents from 3 to 6

Table 18. Effect of organic and inorganic ameliorants on total CaO content in laterite (%)

Treatment No.	Time interval (months) 3	6	9	12	Mean
T_1	0.031	0.037	0.038	0.039	0.036
T_2	0.038	0.039	0.024	0.037	0.034
T_3	0.037	0.039	0.039	0.036	0.038
T_4	0.042	0.042	0.042	0.036	0.041
T_5	0.040	0.044	0.042	0.040	0.042
T_6	0.044	0.045	0.041	0.041	0.043
T_7	0.027	0.028	0.028	0.026	0.027
T_8	0.028	0.028	0.029	0.029	0.029
T_9	0.028	0.028	0.028	0.027	0.028
T_{10}	0.029	0.029	0.028	0.027	0.028
T_{11}	0.044	0.048	0.048	0.047	0.046
T_{12}	0.048	0.050	0.048	0.049	0.049
T_{13}	0.043	0.047	0.047	0.047	0.046
T_{14}	0.043	0.050	0.050	0.049	0.048
T_{15}	0.028	0.028	0.027	0.026	0.027
T_{16}	0.028	0.030	0.029	0.029	0.029
T_{17}	0.028	0.029	0.028	0.025	0.028
T_{18}	0.028	0.027	0.027	0.028	0.027
T_{19}	0.028	0.028	0.028	0.028	0.028

CD for treatments : 0.003
CD for treatment x time interval : 0.001

months after treatment and then it decreased at 12 months after treatments. At higher concentration, it remained steady till nine months and a significant decrease was observed 12 months after treatments. The green leaf extract, at lower concentration, first increased the CaO content till 6 months and then a significant decrease could be observed. But at higher concentration, the decrease in CaO content could be observed only at 9 months after treatments.

In the case of calcium chloride and calcium silicate treatments, the CaO content showed a significant increase from 3 months to 6 months after treatments and it remained steady afterwards.

4.7.1.3 Total MgO

Table 19 gives the total MgO content in laterite blocks after treatment with various amendments. All the organic ameliorants as well as magnesium chloride and magnesium silicate resulted in a significantly higher MgO content compared to the control. No difference could be noted between higher and lower levels of these treatments. The MgO content increased to more than double in the case of $MgC1_2$ at 20 per cent (0.069 per cent) and $Mg_2Si_3O_8$ at 20 per cent (0.069 per cent) than the control (0.030 per cent). Cowdung slurry, green leaf extract and vermiwash at lower concentrations resulted in a MgO content of 0.051, 0.053 and 0.037 per cent respectively. No significant difference in MgO content was observed between different time intervals for a particular treatment.

Table 19. Effect of organic and inorganic ameliorants on total MgO content in laterite (%)

Treatment No.	Time interval (months) 3	6	9	12	Mean
T_1	0.046	0.056	0.051	0.051	0.051
T_2	0.051	0.039	0.055	0.045	0.047
T_3	0.035	0.039	0.038	0.035	0.037
T_4	0.038	0.039	0.035	0.034	0.036
T_5	0.049	0.054	0.054	0.053	0.053
T_6	0.053	0.059	0.050	0.050	0.053
T_7	0.031	0.030	0.031	0.029	0.030
T_8	0.031	0.028	0.026	0.028	0.028
T_9	0.032	0.029	0.026	0.028	0.029
T_{10}	0.033	0.030	0.029	0.030	0.030
T_{11}	0.033	0.026	0.028	0.029	0.029
T_{12}	0.032	0.028	0.028	0.031	0.030
T_{13}	0.034	0.030	0.029	0.026	0.030
T_{14}	0.033	0.028	0.029	0.031	0.030
T_{15}	0.054	0.068	0.068	0.069	0.065
T_{16}	0.064	0.069	0.069	0.071	0.068
T_{17}	0.065	0.072	0.069	0.068	0.069
T_{18}	0.068	0.074	0.073	0.070	0.071
T_{19}	0.031	0.031	0.029	0.027	0.030

CD for treatments : 0.005
CD for treatment x time interval : NS

4.7.1.4 Total Na_2O

The effect of different organic and inorganic ameliorants on the Na_2O content in laterite is given in Table 20. The NaCl and $NaSiO_3$ treatments resulted in a significantly higher Na_2O content in laterite than control or other treatments, which were on par. But the lower and higher levels of these two treatments did not show any difference. Among these two treatments, $NaSiO_3$ at 20 per cent concentration, was found to be significantly superior to NaCl treatment. No difference could be observed in Na_2O content at different time intervals of treatments.

4.7.1.5 Total Fe_2O_3

Table 21 gives effect of various treatments on Fe_2O_3 content of laterites. The Fe_2O_3 content was found to be significantly lowered in treatments of green leaf extract, cowdung slurry at 20 per cent, sodium silicate at 20 per cent, calcium silicate and magnesium silicate treatments. Among these treatments, lowest Fe_2O_3 content was noted in the samples treated with calcium silicate (19.96 per cent) followed by green leaf extract (23.39 per cent) treatments.

In the case of green leaf extract, a significant reduction in Fe_2O_3 content could be observed from 3 to 6 months of treatment which remained almost steady afterwards without much change. In the case of cowdung slurry at 20 per cent concentration, the Fe_2O_3 content decreased significantly upto 9 months of treatment and then it increased significantly to 29.59 per cent.

Table 20. Effect of organic and inorganic ameliorants on total Na_2O content in laterite (%)

Treatment No.	Time interval (months) 3	6	9	12	Mean
T_1	0.022	0.019	0.020	0.021	0.021
T_2	0.014	0.019	0.020	0.012	0.016
T_3	0.022	0.019	0.015	0.017	0.018
T_4	0.023	0.018	0.018	0.019	0.020
T_5	0.022	0.018	0.018	0.020	0.020
T_6	0.024	0.018	0.018	0.018	0.019
T_7	0.026	0.033	0.035	0.034	0.032
T_8	0.029	0.035	0.038	0.034	0.034
T_9	0.031	0.050	0.051	0.049	0.045
T_{10}	0.036	0.057	0.055	0.057	0.051
T_{11}	0.018	0.017	0.017	0.017	0.017
T_{12}	0.019	0.018	0.022	0.018	0.019
T_{13}	0.021	0.021	0.019	0.018	0.020
T_{14}	0.020	0.020	0.017	0.018	0.019
T_{15}	0.018	0.019	0.019	0.019	0.019
T_{16}	0.017	0.017	0.018	0.016	0.017
T_{17}	0.019	0.020	0.019	0.022	0.020
T_{18}	0.018	0.018	0.020	0.020	0.019
T_{19}	0.018	0.018	0.018	0.018	0.018

CD for treatments : 0.006
CD for treatment x time interval : NS

Table 21. Effect of organic and inorganic ameliorants on total Fe_2O_3 content in laterite (%)

Treatment No.	Time interval (months) 3	6	9	12	Mean
T_1	34.52	29.50	18.75	29.59	28.09
T_2	34.22	29.50	29.20	29.29	30.55
T_3	35.31	33.80	33.11	31.30	33.38
T_4	34.40	33.62	33.11	33.32	33.62
T_5	32.12	21.16	20.38	19.87	23.39
T_6	32.21	27.27	26.40	27.69	28.38
T_7	34.83	34.31	35.01	34.62	34.71
T_8	34.52	34.40	33.62	32.90	33.86
T_9	33.62	29.41	27.39	27.00	29.35
T_{10}	33.80	29.89	28.90	28.90	30.37
T_{11}	33.92	36.03	35.13	31.51	34.13
T_{12}	35.01	34.92	32.51	32.30	33.68
T_{13}	22.27	18.75	19.35	19.35	19.96
T_{14}	21.46	18.45	18.87	19.05	19.47
T_{15}	33.92	34.62	34.71	34.62	34.46
T_{16}	33.41	34.65	35.43	35.91	34.89
T_{17}	29.11	25.07	24.59	24.89	25.92
T_{18}	27.39	24.38	25.07	25.19	25.52
T_{19}	31.82	35.82	34.62	34.52	34.19

CD for treatments : 4.83
CD for treatment x time interval : 1.75

The sodium silicate at 20 per cent concentration also resulted in a lowering of Fe_2O_3 content upto 9 months which remained unchanged afterwards. In the case of calcium silicate and magnesium silicate treatments, there was a significant lowering of Fe_2O_3 content from 6 months onwards compared to the value at 3 months after treatments. From 6 months upto 12 months, the Fe_2O_3 content of laterites, subjected to these treatments, remained unchanged.

4.7.1.6 Total Al_2O_3

The effect of different treatments on Al_2O_3 content of laterite is given in Table 22. Results show no significant difference in Al_2O_3 content between different treatments as well as at different time intervals for any treatment.

4.7.1.7 Total SiO_2

Table 23 gives the effect of organic and inorganic ameliorants on SiO_2 content in laterite. Results of the study showed no significant difference in SiO_2 content in laterite due to different treatments or at different time intervals for any treatment.

4.7.1.8. Active iron ratio

The effect of different organic and inorganic ameliorants on active iron ratio (Fe_o / Fe_d) in laterite is given in Table 24. A significant increase in active iron ratio could be observed in the treatments of calcium silicate, green leaf extract, sodium silicate and cowdung slurry. For all these treatments, significant increase could also be observed from the initial

Table 22. Effect of organic and inorganic ameliorants on total Al_2O_3 content in laterite (%)

Treatment No.	Time interval (months) 3	6	9	12	Mean
T_1	19.23	19.27	18.60	17.63	18.68
T_2	18.90	12.90	18.33	17.90	17.01
T_3	19.60	18.37	17.77	17.90	18.41
T_4	18.43	18.77	18.53	17.63	18.34
T_5	18.60	16.27	17.60	17.77	17.56
T_6	17.93	14.53	18.10	18.13	17.18
T_7	18.20	18.10	18.90	18.67	18.47
T_8	18.40	18.40	18.33	17.87	18.25
T_9	18.47	17.60	17.00	14.87	16.98
T_{10}	17.70	17.27	17.37	15.33	16.92
T_{11}	17.90	18.20	18.73	18.90	18.43
T_{12}	17.27	17.30	14.67	17.63	16.72
T_{13}	14.67	18.07	13.13	11.97	13.21
T_{14}	13.87	12.63	12.37	12.67	12.88
T_{15}	18.97	18.83	18.60	18.73	18.78
T_{16}	18.00	17.87	18.10	17.77	17.93
T_{17}	18.47	18.07	18.10	16.23	17.72
T_{18}	18.33	18.10	16.63	16.40	17.37
T_{19}	18.50	18.50	18.60	17.97	18.39

CD for treatments : NS
CD for treatment x time interval : NS

Table 23. Effect of organic and inorganic ameliorants on SiO_2 content in laterite (%)

Treatment No.	Time interval (months) 3	6	9	12	Mean
T_1	31.24	31.74	32.10	30.54	31.41
T_2	20.18	31.74	31.74	20.27	25.98
T_3	31.30	31.61	30.17	30.97	31.01
T_4	30.82	32.89	31.61	31.18	31.63
T_5	31.31	30.75	32.16	30.45	31.18
T_6	31.46	30.82	31.74	30.75	31.20
T_7	31.24	30.60	32.31	29.90	31.01
T_8	31.61	31.67	31.61	29.60	31.12
T_9	35.52	37.81	38.58	39.10	37.75
T_{10}	34.30	37.51	38.37	38.80	37.26
T_{11}	31.09	32.38	30.60	31.31	31.35
T_{12}	31.82	29.90	30.24	31.89	30.97
T_{13}	37.09	40.38	39.80	39.80	39.27
T_{14}	37.88	41.09	39.31	38.46	39.18
T_{15}	31.24	32.04	31.95	30.75	31.50
T_{16}	30.24	30.11	31.39	31.46	30.79
T_{17}	32.74	37.66	37.17	37.81	36.34
T_{18}	32.89	37.81	36.66	37.17	36.34
T_{19}	31.39	30.45	30.60	32.38	31.20

CD for treatments : NS
CD for treatment x time interval : NS

Table 24. Effect of organic and inorganic ameliorants on active iron ratio in laterite

Treatment No.	Time interval (months) 3	6	9	12	Mean
T_1	0.05	0.07	0.08	0.08	0.07
T_2	0.05	0.08	0.08	0.08	0.07
T_3	0.04	0.05	0.05	0.06	0.05
T_4	0.04	0.04	006	0.06	0.05
T_5	0.04	0.06	0.09	0.09	0.07
T_6	0.05	0.07	0.09	0.09	0.08
T_7	0.05	0.06	0.07	0.07	0.06
T_8	0.04	0.05	0.05	0.06	0.05
T_9	0.05	0.06	0.08	0.08	0.07
T_{10}	0.05	0.06	0.07	0.08	0.07
T_{11}	0.03	0.04	0.04	0.05	0.04
T_{12}	0.04	0.04	0.05	0.05	0.05
T_{13}	0.05	0.07	0.09	0.09	0.08
T_{14}	0.05	0.07	0.08	0.09	0.08
T_{15}	0.04	0.06	0.06	0.07	0.06
T_{16}	0.05	0.06	0.06	0.07	0.06
T_{17}	0.04	0.04	0.05	0.05	0.05
T_{18}	0.05	0.04	0.05	0.05	0.05
T_{19}	0.03	0.03	0.04	0.04	0.04

CD for treatments : 0.02
CD for treatment x time interval : 0.01

to final time interval. Highest active iron ratio resulted due to the treatments of calcium silicate (both lower and higher concentrations resulted in identical mean values) and green leaf extract at 40 per cent concentration. Calcium silicate (20 per cent) and green leaf extract (40 per cent) treatments resulted in a significant increase in active iron ratio from three months upto nine months of treatment, and afterwards it did not show any variation. Sodium silicate (both levels), cowdung slurry (both levels) and green leaf extract (20 per cent) treatments also resulted in a significant increase in active iron ratio though it was slightly lower than that of the above treatments. The lower and higher concentrations of the treatments of green leaf extract and sodium silicate resulted in identical mean values of active iron ratio after a period of one year.

In the case of cowdung slurry, both levels resulted in a significant increase of active iron ratio only upto six months after treatments and no significant change could be observed afterwards. The green leaf extract (20 per cent) treatment caused an increase of Fe_o / Fe_d ratio upto nine months of treatment which remained steady afterwards. With regard to sodium silicate (20 per cent), a significant increase could be recorded only at nine months of treatment and no change could be observed due to different time intervals of sodium silicate (40 per cent) treatment.

4.7.1.9. Aluminium substitution in iron oxides

Table 25 gives the per cent aluminium substitution in iron oxides due to different treatments of organic and inorganic ameliorants. A significantly higher per cent of aluminium substitution in iron oxides

Table 25. Effect of organic and inorganic ameliorants on aluminium substitution in iron oxides in laterite (%)

Treatment No.	Time interval (months) 3	6	9	12	Mean
T_1	7.95	9.68	11.43	12.69	10.44
T_2	8.31	9.89	11.63	13.15	10.75
T_3	6.42	6.89	5.93	6.98	6.56
T_4	6.53	7.21	7.15	7.38	7.07
T_5	8.78	11.63	13.48	15.56	12.36
T_6	9.34	12.41	14.63	15.88	13.07
T_7	7.95	10.32	11.45	11.97	10.42
T_8	8.21	10.63	12.12	12.63	10.90
T_9	7.49	8.68	9.53	9.87	8.89
T_{10}	7.78	7.95	8.89	9.53	8.54
T_{11}	6.41	7.12	6.93	7.83	7.07
T_{12}	6.59	7.31	7.55	7.95	7.85
T_{13}	9.65	11.34	14.68	15.93	12.90
T_{14}	9.89	10.97	14.95	14.99	12.70
T_{15}	7.15	8.63	9.15	9.89	8.71
T_{16}	6.66	6.97	7.16	7.63	7.11
T_{17}	6.73	7.25	8.15	7.93	7.52
T_{18}	7.13	6.95	8.23	8.39	7.68
T_{19}	5.34	5.97	6.13	6.15	5.90

CD for treatments : 4.11

CD for treatment x time interval : 1.95

could be observed for the treatments green leaf extract (both levels), calcium silicate (both levels), cowdung slurry and sodium chloride though they were on par. The highest amount of substitution (13.07 per cent) was observed for green leaf extract (40 per cent) treatment followed by calcium silicate treatments (12.90 and 12.70 per cent respectively for lower and higher levels). The per cent aluminium substitution in iron oxides increased significantly upto nine months of treatment which did not show any significant difference afterwards. In the case of calcium silicate (both levels) treatments, a significant increase in aluminium substitution could be noted only from six months to nine months of treatments.

4.7.2. Mineralogical and micromorphological changes in hard laterite due to treatment with different ameliorants

The X-ray diffraction patterns of the clay materials of hard laterite block before treatment and after treatment with selected organic and inorganic ameliorants are given in Table 26-31. A summary of the relative abundance of the important minerals involved in hardening and softening of laterites is given in Table 32.

The results show that the sample before treatment had a higher content of highly crystallised kaolinite as evidenced by the width of the peaks (0.080 deg.) given in Table 33. A broadening of the kaolinite peaks could be observed in all the five treatments and a maximum value of 0.240 degree was observed in cowdung slurry (20 per cent) treatment.

Table 26. X-ray diffraction (XRD) patterns of clay materials from laterite before treatment

d-value (Ang)	Width (deg)	Peak (cts)	I / I_{max}	Significance
2.84	0.140	488	100.00	7.44
7.16	0.080	266	54.40	2.35
1.99	0.120	234	47.93	1.25
4.17	0.080	213	43.64	1.76
3.09	0.100	202	41.28	2.46
2.51	0.120	94	19.26	1.11
2.06	0.080	88	18.09	0.86
7.50	0.080	79	16.22	2.47
2.97	0.120	77	15.86	1.23
3.36	0.160	69	14.10	1.28
3.28	0.160	69	14.10	0.96
2.84	0.120	66	13.43	1.25
2.38	0.080	66	13.43	2.30
3.20	0.080	64	13.10	0.79
1.87	0.080	62	12.78	1.66
6.25	0.120	45	9.19	1.12
2.45	0.080	44	9.01	0.75

Table 27. X-ray diffraction (XRD) patterns of clay materials from laterite after treatment with sodium silicate (20 percent)

d-value (Ang)	Width (deg)	Peak (cts)	I / I_{max}	Significance
7.16	0.120	213	100.00	2.73
4.20	0.100	196	91.95	2.77
3.06	0.160	139	65.32	1.48
2.06	0.080	88	41.45	0.85
9.86	0.120	88	41.45	1.20
2.57	0.140	86	40.58	2.87
2.97	0.240	77	36.33	1.13
10.80	0.120	69	32.32	1.61
2.18	0.120	66	30.78	1.17
9.20	0.120	58	27.10	1.85
2.84	0.120	53	25.00	1.00
3.36	0.120	42	19.82	1.24
3.67	0.120	37	17.46	2.18
2.51	0.120	30	14.08	1.00
2.45	0.640	22	10.33	2.08
4.83	0.480	12	5.63	0.89

Table 28. X-ray diffraction (XRD) patterns of clay materials from laterite after treatment with magnesium silicate (20 percent)

d-value (Ang)	Width (deg)	Peak (cts)	I / I_{max}	Significance
4.15	0.080	199	100.00	2.70
3.06	0.120	190	95.79	2.14
7.16	0.120	128	64.23	1.93
1.99	0.080	123	61.97	1.73
2.97	0.240	123	61.97	1.38
3.35	0.120	102	51.31	1.62
3.36	0.160	102	51.31	1.43
3.16	0.120	81	40.74	1.94
3.28	0.120	77	38.95	0.88
6.32	0.080	67	33.82	2.03
1.87	0.120	58	29.05	0.97
2.34	0.120	56	28.29	1.02
2.56	0.120	50	25.36	1.16
2.51	0.120	38	19.10	0.80
2.45	0.120	20	10.05	1.48
4.83	0.200	18	9.30	0.79

Table 29. X-ray diffraction (XRD) patterns of clay materials from laterite after treatment with calcium silicate (20 percent)

d-value (Ang)	Width (deg)	Peak (cts)	I / I_{max}	Significance
2.97	0.080	117	63.06	3.92
1.99	0.080	86	33.74	1.32
2.84	0.080	74	39.99	0.96
3.06	0.080	71	38.15	0.75
2.29	0.080	71	38.15	2.57
3.28	0.200	66	35.47	0.83
4.29	0.080	66	35.47	0.86
3.16	0.240	61	32.89	1.11
4.34	0.120	53	28.81	0.97
3.57	0.080	50	27.25	1.35
4.15	0.120	49	26.49	2.42
4.83	0.120	45	24.27	2.92
7.16	0.120	38	20.78	2.55
3.67	0.400	36	19.46	1.67
2.51	0.240	27	14.61	1.08
2.45	0.080	12	6.97	0.83

Table 30. X-ray diffraction (XRD) patterns of clay materials from laterite after treatment with green leaf extract (20 percent)

d-value (Ang)	Width (deg)	Peak (cts)	I / I_{max}	Significance
4.21	0.080	149	100.00	1.16
6.25	0.080	92	61.92	1.46
3.30	0.120	81	54.42	1.25
4.45	0.080	74	49.69	2.19
3.28	0.120	72	48.54	1.04
3.56	0.240	69	45.28	1.02
7.16	0.120	67	45.18	0.82
3.84	0.120	62	41.93	2.52
3.16	0.080	59	39.83	1.36
2.97	0.160	59	39.83	1.06
6.39	0.080	59	39.83	1.57
4.83	0.160	37	25.00	1.04
2.51	0.320	28	18.79	1.74
2.45	0.400	14	9.40	0.78

Table 31. X-ray diffraction (XRD) patterns of clay materials from laterite after treatment with cowdung slurry (20 percent)

d-value (Ang)	Width (deg)	Peak (cts)	I / I_{max}	Significance
4.20	0.080	172	100.00	1.31
3.06	0.120	114	66.72	0.95
7.16	0.240	106	61.82	2.14
9.89	0.080	90	52.59	2.30
4.46	0.120	83	48.25	0.88
2.97	0.160	81	47.20	1.14
1.86	0.080	72	42.10	2.25
2.52	0.120	67	39.18	2.45
3.36	0.240	62	36.37	0.77
3.30	0.120	61	35.45	1.83
3.57	0.480	56	32.78	1.67
1.98	0.120	58	33.66	1.13
1.83	0.080	58	33.66	2.14
3.28	0.080	49	28.55	0.83
4.83	0.120	37	21.68	1.36
2.51	0.120	28	16.49	1.68
2.45	0.400	14	8.20	0.80

Table 32. Relative abundance of major minerals in the clay materials before and after treatments

I of d(hkl)	Peak value (cts)					
	Before treatment	Sodium silicate (20%)	Magnesium silicate (20%)	Calcium silicate (20%)	Green leaf extract (20%)	Cowdung slurry (20%)
Kaolinite (7.16A)	266	213	128	38	67	106
Gibbsite (4.83A)	—	12	18	45	37	37
Goethite (2.45A)	44	22	20	12	14	14
Haematite (2.51A)	94	30	38	27	28	28
Magnetite (2.97A)	77	77	123	117	59	81
Lepidocrocite (3.28 A)	69	—	77	66	72	49

Table 33. Width at half height (WHH) of the XRD peaks of major minerals in the clay materials before and after treatments

I of d(hkl)	Width (deg)					
	Before treatment	Sodium silicate (20%)	Magnesium silicate (20%)	Calcium silicate (20%)	Green leaf extract (20%)	Cowdung slurry (20%)
Kaolinite (7.16A)	0.080	0.120	0.120	0.120	0.120	0.240
Gibbsite (4.83A)	—	0.480	0.200	0.120	0.160	0.120
Goethite (2.45A)	0.080	0.640	0.120	0.080	0.400	0.400
Haematite (2.51A)	0.120	0.120	0.120	0.240	0.320	0.120
Magnetite (2.97A)	0.120	0.240	0.240	0.240	0.160	0.160
Lepidocrocite (3.28 A)	0.160	—	0.120	0.200	0.120	0.080

In the case of gibbsite, no appreciable amount could be noted in the hard laterite before treatment while a maximum abundance of 45 cts was observed after treatment with calcium silicate (20 per cent) followed by green leaf extract 20 per cent (37 cts) and cowdung slurry 20 per cent (37 cts). Least value of 12 cts was observed for sodium silicate (20 per cent) treatment and magnesium silicate (20 per cent) treatment resulted in a value of 18 cts.

The iron oxide mineral goethite was maximum in the hard laterite before treatment and least value was noted in the sample after treatment with calcium silicate (12 cts). The treatment of green leaf extract and cowdung slurry resulted in a value of 14 cts.

In the case of haematite, the hard laterite before treatment had the highest value of 94 cts and least value could be observed in the laterite block after treatment with calcium silicate (27 cts) followed by green leaf extract and cowdung slurry treatments (28 cts each).

The iron oxide mineral magnetite was 77 cts in the hard laterite sample before treatment which increased to 123 and 117 cts respectively after treatment with magnesium silicate (20 per cent) and calcium silicate (20 per cent). Lowest value of 59 cts was observed in the sample after treatment with green leaf extract.

In the case of lepidocrocite, not much variation could be observed in the hard laterite before treatment and after treatment with different ameliorants. In the case of the sample after treatment with sodium silicate (20 per cent) no appreciable quantity of lepidocrocite could be observed.

Grains and large patches of oriented aggregates of kaolin are prominent in all the micromorphological slides (Plates 1-6). The hard laterite block before treatment had highly crystallised kaolinite seen as submicroscopic plates. The optical density within the matrix is found to be altered due to various treatments. The continuity of the crystalline phase of the impregnating iron is found to be broken after treatment with calcium silicate (20 per cent) (Plate 4), cowdung slurry (20 per cent) (Plate 5) and green leaf extract (20 per cent) (Plate 6). The yellow and orange red colour of the matrix is due to the presence of goethite and the opaque portions are due to the presence of haematite.

Tiny nodular spherical bodies are found in the hard laterite block before treatment (Plate 1) and are found to have a film of orange red colour on the surface or as concentric shells within the body. A grid like network as oriented materials are found in the matrix. Concretionary and pisolitic nodular form of goethite and haematite are more conspicuous in this slide. Haematite is found as pore linings as bands and discrete masses.

Pisolitic forms of gibbsite are found in Plates 4, 5 and 6. Gibbsite pseudomorphs and goethite pseudomorphs are also found in these slides on microscopic examination. In these slides, gibbsite is found mostly as fillings in pores and cracks of both matrix and nodules. Pores

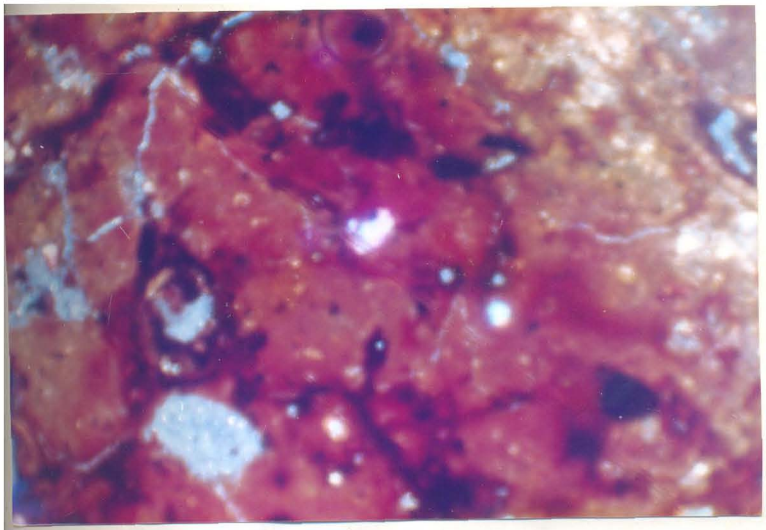


Plate 1. Thin section micrograph of laterite before treatment

Plate 2. Thin section micrograph of laterite after treatment with sodium silicate (20 per cent)

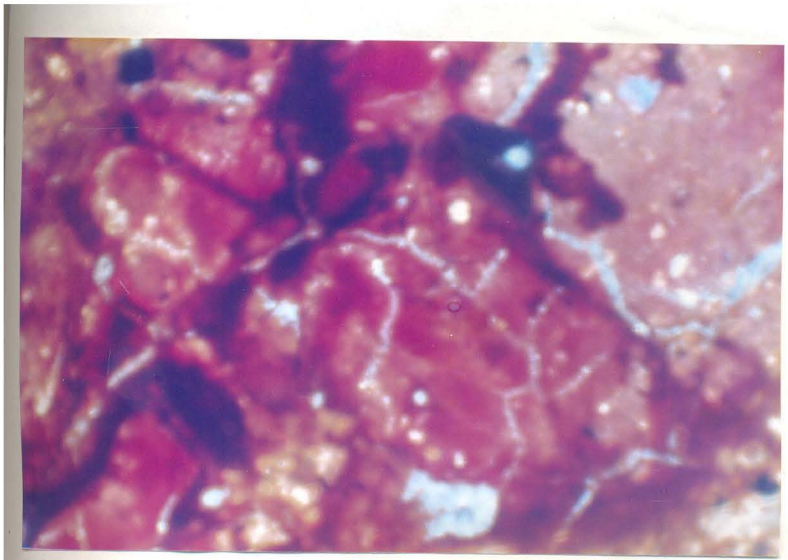


Plate 3. Thin section micrograph of laterite after treatment with magnesium silicate (20 per cent)

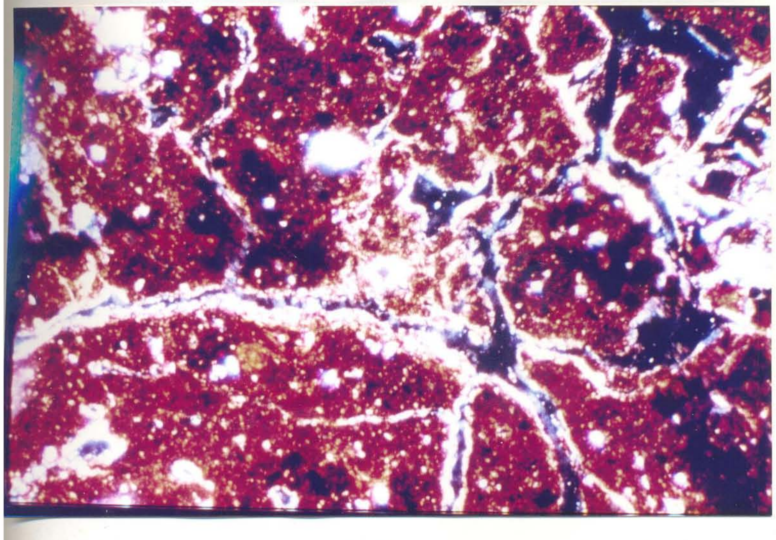


Plate 4. Thin section micrograph of laterite after treatment with calcium silicate (20 per cent)

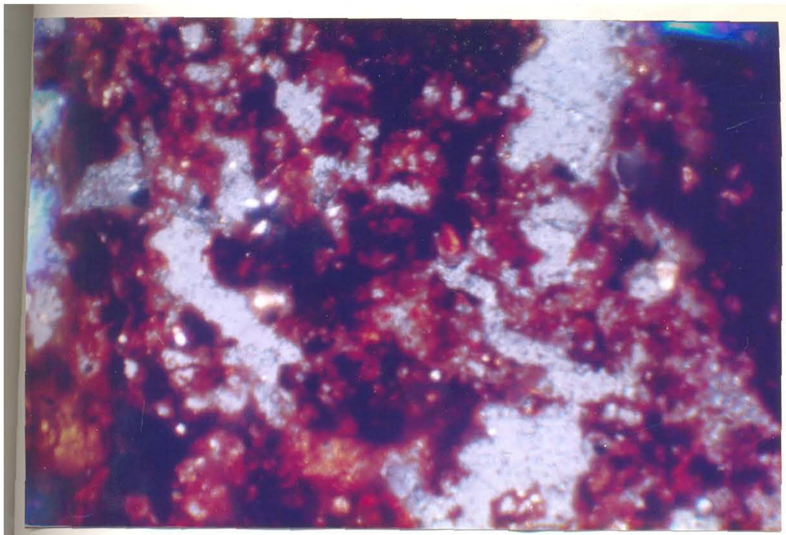


Plate 5. Thin section micrograph of laterite after treatment with green leaf extract (20 per cent)

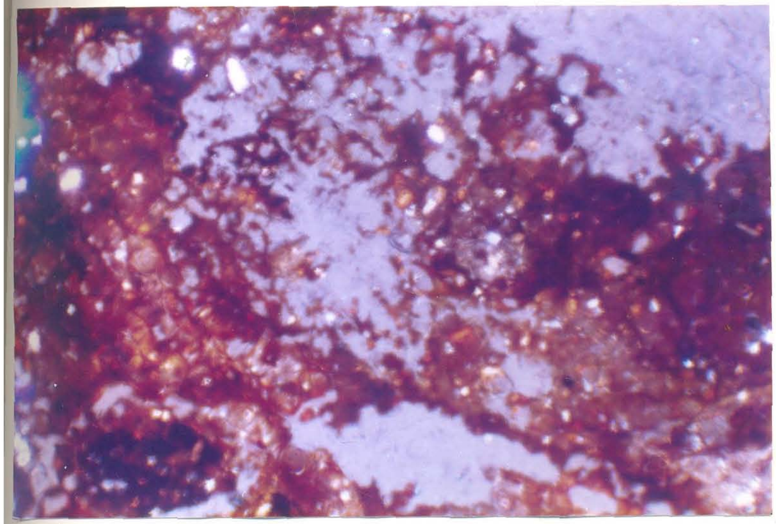
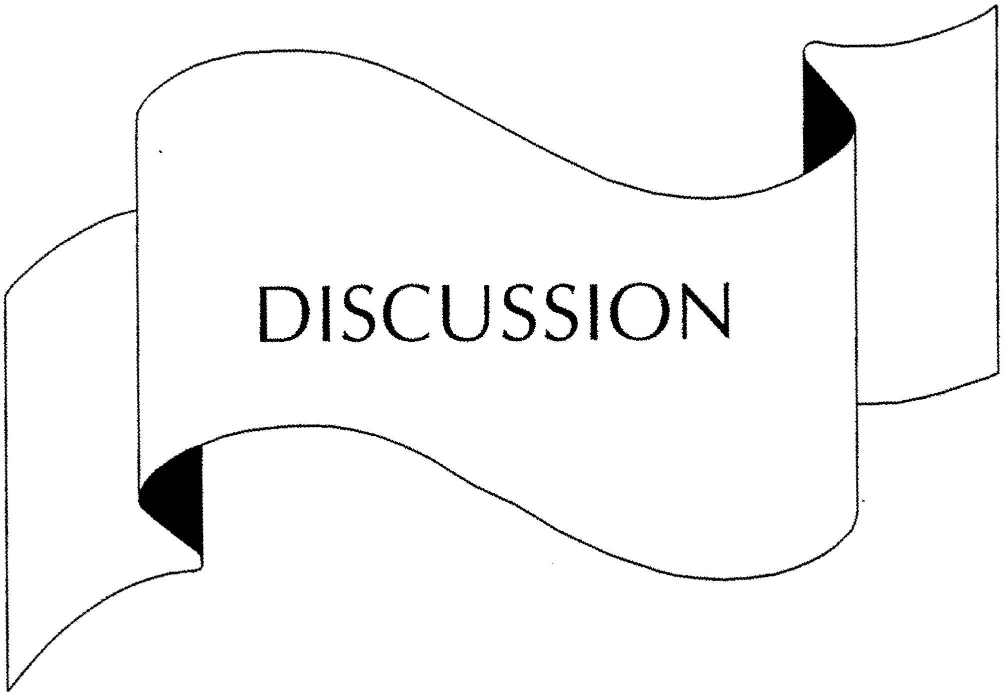


Plate 6. Thin section micrograph of laterite after treatment with cowdung slurry (20 per cent)

and cracks are found lined with oriented kaolin with low degree of iron impregnation.

A vacuolar network of iron is found in Plate 1 and the vacuoles are composed of kaolinite and the network is formed by closely crystallising goethite. The goethite is found as a strong rigid framework.



DISCUSSION

5. DISCUSSION

5.1 Pedogenic environment of the study sites

An analysis of the pedogenic and geoclimatic parameters of the three study sites indicate that humid tropical conditions with alternate wet and dry seasons prevail in all the selected locations which, under favourable conditions, promotes the process of laterisation to take place depending on the type of vegetation or land use.

The laterite number (L) of the locations showed an increasing trend as we go from the southern to northern location. Higher L values favour the formation and induration of laterites. The very high L value of the locations at Angadipuram and Kannur is attributed to the very high markedly seasonal rainfall and high temperature. The difference between wet season and dry season semi-annual precipitation is more towards the northern location while the rainfall, though low, in Thiruvananthapuram is distributed more evenly and hence have a low laterite number. The distribution of rainfall rather than the total annual rainfall is more important to have the requisite laterite number (Mc Farlane, 1976). The increase in the period of dry spell as we go towards the northern location at Kannur indicates that rainfall is concentrated in a few months in this location which, in turn, is responsible for the very high L value in this location.

Kerner - Marilaun (1927) introduced laterite number to assess the climatic limits of laterite and hard crust formation. This method considers the quantity of precipitation, its seasonality and temperature to be the critical variables and based on empirical evidence, it is proposed that laterite will form where L exceeds a value of 50.

The geology as well as the pedoclimatic conditions such as soil moisture and temperature regimes of the three study sites show that the three selected sites were ideal to study the processes of hardening and softening of laterites under different land uses.

5.2 Pedon Morphology

An analysis of the soil profile characteristics reveals that laterisation process is intense in all the pedons studied. This is due to the most conducive geoclimatic and pedogenic environments for the process of laterisation prevalent in all the three study sites. Visual observations like soil colour itself indicate wide variations in characteristics of these laterite soils and especially the hard laterite Bt_2 layer present in all pedons. In almost all pedons, the Bt_2 layer or hard laterite layer had red or dark red moist soil colour while much variations could be observed in the moist colour of the overlying textural B-horizon or Bt_1 layer. Its colour varied from reddish yellow to dark reddish brown to dark red. These variations in colour are due to the oxides of iron in various degrees of hydration and sometimes also to manganese (Maignien, 1966 and Davy *et al.*, 1975). Under conditions of oxidation, iron yields ochre, red or reddish brown colour. Silica, which is ordinarily whitish and when impregnated with hydroxides of iron may yield a red or rust red colour common in the matrix of these pedons. It is the mixture of these differently coloured constituents which gives the extremely varied colouration of laterites.

Another important observation from the study of the pedon morphology is the presence of Bt_1 and Bt_2 layers in all the pedons studied which indicate that the selection of pedons was appropriate, based on geoclimatic and pedogenic environments, to study the process of hardening and softening of laterites under three different land use systems. Since the land use systems were selected adjacently and have similar geoclimatic and pedogenic environments, the difference in the extent of laterisation could be attributed to the different land uses.

The present study also indicated an increase in value of soil colour notation from textural B-horizon to hard laterite below in most of the pedons studied. Also the passage from solum to hard laterite below is shown by an increase in massiveness, hardness and a firmer consistency. With depth, laterite tends to become still firmer and harder and more coherent.

The Khondalite and Charnockite laterites observed at Thiruvananthapuram and Angadipuram are massive, but are slightly more friable than the schist laterites observed at Kannur, for different reasons (i) the high content of incompletely weathered crystals of quartz, muscovite and feldspar and (ii) the intense weathering stage of Khondalites and Charnockites (Stott *et al.*, 1991).

5.2.1 Soil Taxonomy

All the nine pedons studied belonged to one soil order, Ultisols. All the pedons had either an argillic or kandic horizon and the base saturation (sum of cations) values were less than 35 per cent throughout the profiles which qualified them to be classified under ultisols. Since the soil moisture regime is ustic, all the nine pedons come under the suborder ustults.

All the pedons except those under uncultivated barren belonged to the great group Haplustults since they didn't qualify to be grouped under other five great groups, viz., Plinthustults, Kandiustults, Kanhaplustults, Paleustults or Rhodustults. The pedons under uncultivated barren at Thiruvananthapuram and at Kannur are classified under the great group plinthustults since these profiles have horizons within 150 cm of the mineral soil surface in which plinthite constitutes one-half or more of the volume (Soil Survey Staff, 1998). The pedon under uncultivated barren at Angadipuram is classified under the great group Rhodustults. Here the epipedon has a colour value moist of 3 and the entire argillic horizon has a hue of 2.5 YR, and a value moist of 3 and the dry value is one unit higher than the moist value. These factors qualify it to be grouped under Rhodustults.

Since the pedons under cassava at Thiruvananthapuram and Angadipuram have more than 5 per cent (by volume) of plinthite within 150 cm of the mineral soil surface, they were grouped under the sub group - Plinthic Haplustults. The pedon under rubber at Angadipuram belonged to the sub group Kanhaplic Haplustults since they didn't come under plinthic haplustults and have a CEC (1 N NH_4OAc pH 7.0) of less than 24 cmol(+)/kg clay in the argillic horizon. All other Haplustults came under the subgroup Typic Haplustults.

The plinthustults under uncultivated barren at Thiruvananthapuram and Kannur are classified under the sub group Typic Plinthustults since they don't have the features to be grouped under the other subgroup, Haplic Plinthustults. The Rhodustults under uncultivated barren at Angadipuram do not have properties to be grouped under the subgroups Lithic Rhodustults and Psammentic Rhodustults and hence it is grouped under Typic Rhodustults.

Ultisols are low activity clay (LAC) soils formed by several individual reactions and processes. When high temperature and extensive leaching are combined over a low period of time, the result is rapid and fairly complete alteration of weatherable minerals into secondary clays and oxides. A clay mineral suite results that is stable under the ambient environment Lessivage, leading to the formation of argillic horizons is very pronounced in ultisols. Apart from clay illuviation, clay formation as a result of *in-situ* weathering is also significant in Ultisols (Simonson, 1949, Buol *et al.*, 1980 and Tan, 1982).

Role of iron and aluminium ions in hardening and softening of laterites is studied by many workers (Gamble *et al.*, 1970, Bohn *et al.*, 1979). The low fertility and low base status of these ultisols have been the major limitation to agricultural use and different land uses influence the hardening and hard crust formation in these soils.

5.3 Physico chemical characteristics related to hardening and softening of laterites

5.3.1 Single Value Constants

Among different single value constants studied, the bulk density showed some important changes (Fig.3). At all locations, there was a significant increase in bulk density from epipedon to Bt_1 layer to Bt_2 layer. Among similar horizons under different land use systems at each study site, significant changes could be observed in epipedons especially as we go from southern to northern location. At the southern most location, Thiruvananthapuram, the bulk density of the epipedons did not show any difference. But at Angadipuram, both soils under cassava and rubber had no difference in bulk density but were significantly lower than that of uncultivated barren. When we go to the northern most location at Kannur, only epipedon of soils under rubber had significantly lower bulk density than uncultivated barren and soils under cassava had a value on par with other two land uses.

The soil bulk density is a major determinant of soil moisture content, hydraulic conductivity and penetrability by roots (Hamdan and

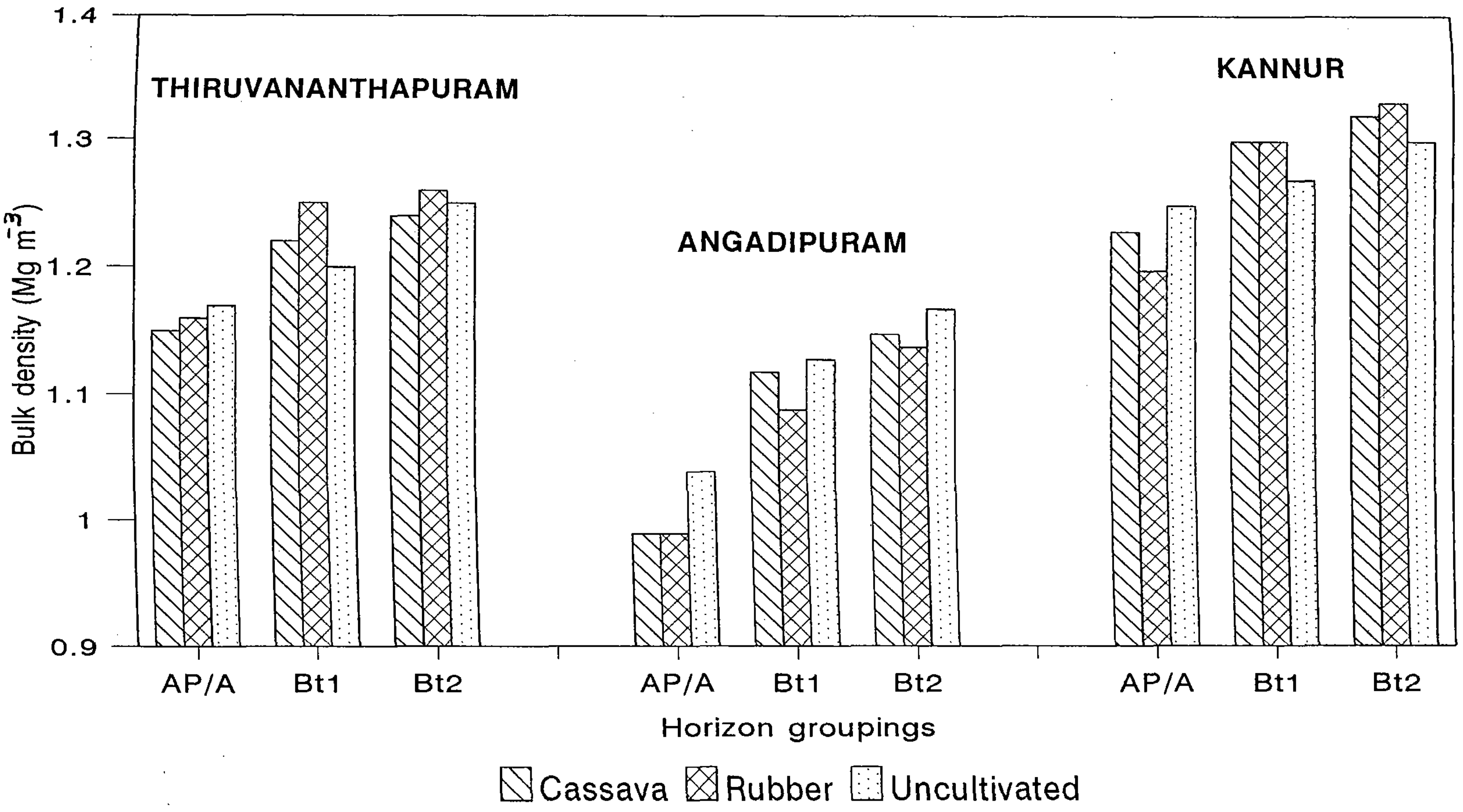


Fig. 3. Bulk density among similar horizons under different land uses

Burnham, 1997). Increase in bulk density down the profiles at all locations is attributed to the significant lowering of organic matter content down the profiles as well as to clay illuviation. The variation in bulk density of surface horizons from southern to northern locations can be attributed to the difference in various climatic parameters as seen from table 1 and figure 2. Laterite number showed an increasing trend towards north and it is one of the main reasons for the increased rate of decomposition of organic matter under uncultivated barren and in soils under cassava than that of rubber. Since the climatic parameters are more favourable to laterisation process towards northern locations, the organic matter decomposition was faster in soils under cassava and uncultivated barren since both these land uses did not have a vegetative cover to protect soil from insolation as well as they did not add much organic matter to soil. But, rubber, due to its dense foliage and vegetative cover provided, is a better alternative in laterite soils as far as lowering of bulk density is concerned. Increased soil bulk density due to loss of organic matter by increased rate of decomposition as a result of change in soil moisture and temperature regimes, reduced soil biodiversity and raindrop impact, resulted in decreased macroporosity and reduced infiltration capacity (Ghuman *et al.*, 1991).

Results of the study of particle density did not show any significant observation with respect to different land uses. Analysis of the porosity values indicated that the surface horizons did not differ in porosity under different land uses at all the three study sites.

Results of pooled analysis indicated that water holding capacity of epipedons as well as Bt_1 layers decreased in the order : rubber > cassava uncultivated barren. Volume expansion was significantly higher in soils under rubber than that of cassava and uncultivated barren. All these observations indicate the changes in organic matter content under different land uses though the geoclimatic and pedogenic situations are identical. The rate of weathering will be more intense in soils which are exposed to sunlight and where the addition of organic matter is less. These results indicate the significance of choosing appropriate land use systems taking into consideration the soil type, climate, geology and other environmental parameters to have a sustainable crop production without having a detrimental impact on the physical properties of the soil. Otherwise, it may hasten the processes leading to an increase in bulk density and lowering of water holding capacity and volume expansion which will accelerate the process of laterite induration or hardening and thereby soil degradation.

5.3.2 Particle size analysis

Though results of pooled analysis (Appendix 1.2) showed no difference in gravel content due to different land uses, location wise analysis show that as we go from southern to northern sites, there were changes in gravel content in similar horizons under different land uses. At Angadipuram and Kannur, surface horizons differed with respect to gravel content. It was lower in soils under cassava at Angadipuram while lower value could be recorded in soils under rubber at Kannur. Both Bt_1 and

Bt_2 horizons at each site had gravel contents which were on par. Increase in gravel content increases induration and it can depress plant growth if it occupies significant volume in coarse soils (Armson, 1977 and Pritchett, 1979).

Among the soil separates of sand, silt and clay, downward movement could be observed in the case of finer fractions viz. silt and clay. Coarse sand fraction did not show any difference among similar horizons due to different land uses. The changes in the content of fine sand fraction were not uniform at all locations and no conclusive observations could be made.

In the case of silt, no difference could be observed among epipedons as evidenced by analysis of pooled data. But in the case of Bt and Bt_2 layers, soils under cassava and rubber had significantly higher contents than that of uncultivated barren.

Clay, being the finest and most reactive of the various soil separates showed much difference among the three land uses at northern locations while at Thiruvananthapuram, no significant difference in clay content could be observed. At Thiruvananthapuram, the clay content of the textural B horizon was not more than 1.2 times than that of the overlying layer under all land uses.

At Angadipuram, there was significant difference in clay content of Bt_1 layer from that of the overlying eluvial horizon (E layers) under all land use systems. Maximum clay increase could be observed in soils under rubber (1.36 times) and cassava (1.36 times) and the increase was less than 1.2 times only in soils under uncultivated barren. At Kannur, maximum clay increase was observed in soils under rubber (1.27 times) followed by uncultivated barren (1.20) and Bt_1 layer of soils under cassava had a clay increase less than 1.2 times only than overlying eluvial layer.

These observations clearly show the influence of land use on clay illuviation. Even under similar temperature and rainfall conditions, clay migration was at a faster rate in soils under rubber both at Angadipuram and Kannur. At the southern location of Thiruvananthapuram, a clay increase of 1.2 times could not be observed under any of the land use system studied. At Angadipuram where the value for laterite number was in between those of Thiruvananthapuram and Kannur, both soils under rubber and cassava had same clay increase while at Kannur where the value for laterite number is 85, rubber cultivation resulted in maximum clay illuviation. A clay increase of 1.2 times is required for it to be qualified to call an argillic horizon (Buol *et al*, 1980). When the extent of mechanical eluviation and clay migration increases, the process of laterisation and thereby hardening of laterites proceeds at a faster rate. This was earlier observed in the laterite soils of Kerala by Varghese (1981). Studies conducted by Arca and Weed (1966) show strong correlation between clay content and aggregation of soil particles.

Van Wambeke (1959, 1962) employed the silt/clay ratio (L/A value) as an index of weathering and soil formation and index of the extent of laterisation. The critical value is considered to be 0.25 (Buringh, 1970). At all study sites, the silt/clay ratio was lower than 0.25 even in the surface horizons indicating that ferrallitisation proceeds at a faster rate at these sites (Fig. 4). Decreasing trend in the ratio down the profiles indicates that induration is more in the Bt_2 layers compared to surface horizons. Also, the silt/clay ratio showed a decreasing trend from the southern to northern locations indicating a more favourable environment for laterisation to proceed faster in northern Kerala compared to southern districts.

5.3.3 Organic carbon and organic matter contents

The organic carbon and organic matter contents decreased significantly down the profiles at all locations. Another important observation was the organic carbon and organic matter contents in the surface horizons. While no difference in organic carbon and organic matter contents could be observed in the surface horizons under different land uses at Thiruvananthapuram and at Kannur, at Angadipuram significantly lower contents were observed in uncultivated barren compared to that under cassava and rubber, which were on par. Pooled analysis showed similar results as that of Angadipuram.

Organic matter content expressed as kg m^{-2} to a depth of 1 m showed very close values under the three land uses at Kannur while at Thiruvananthapuram and Angadipuram, uncultivated barren had a lower content of organic matter compared to that of rubber and cassava (Fig. 5).

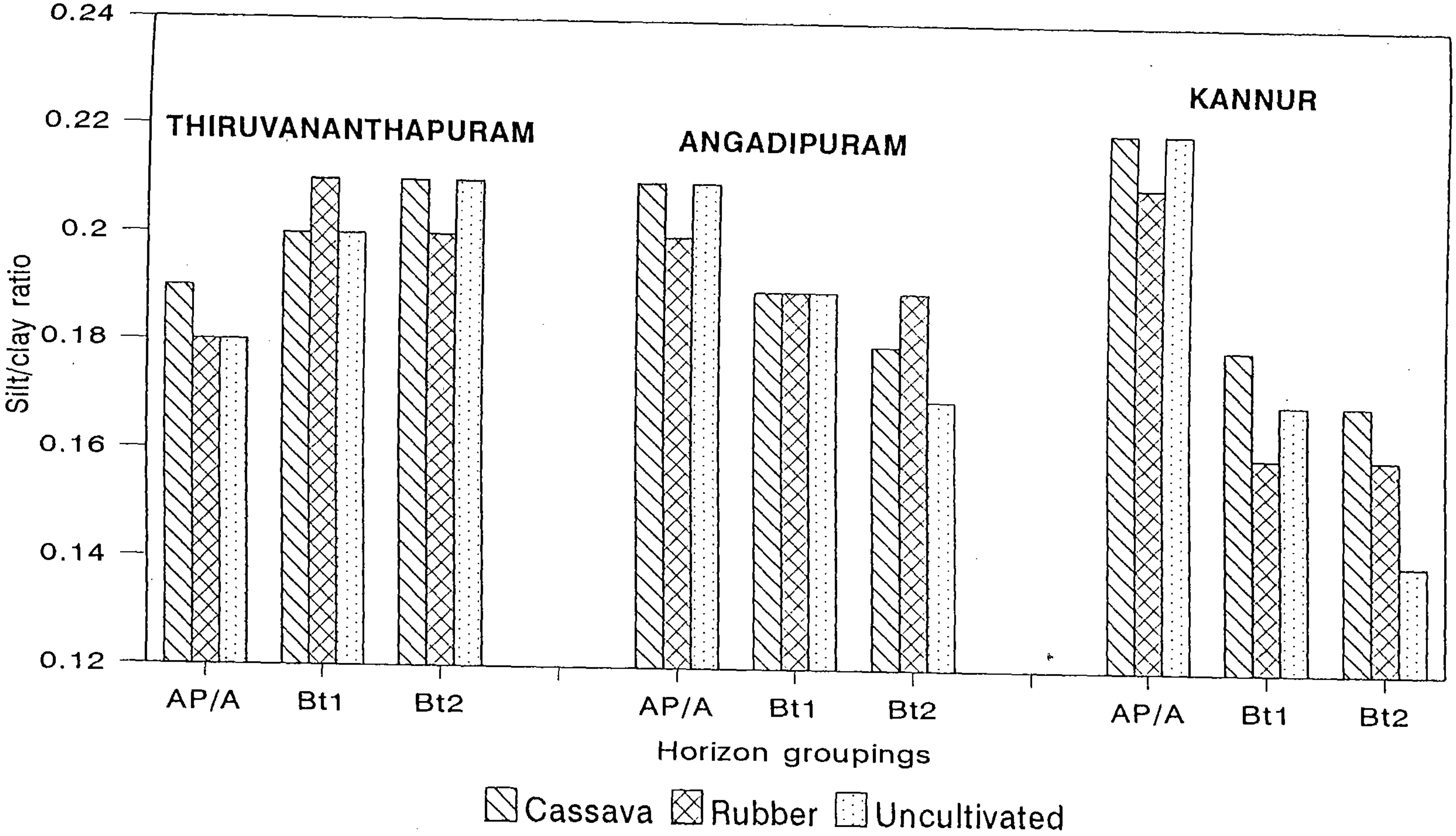


Fig. 4. Silt/clay ratio among and similar horizons under different land uses

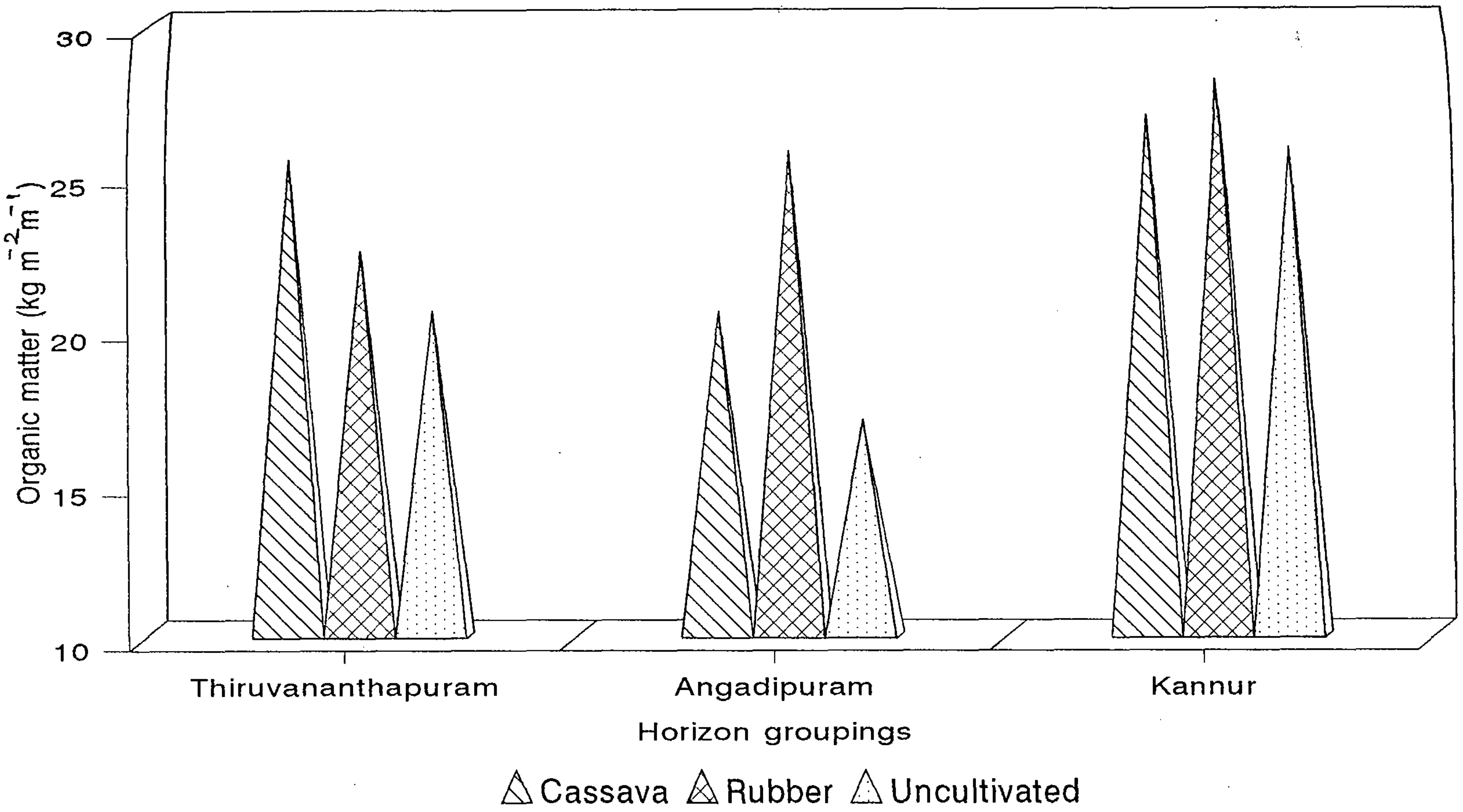


Fig. 5. Organic matter content to a depth of one metre under different land uses

Above observations show that climatic effects can have a marked impact on decomposition rates and the pattern of mineralisation resulting from biogeochemical nutrient cycling (Swift *et al.*, 1979 and Cornejo *et al.*,1994). This is very much evident as we go from the southern location of Thiruvananthapuram to Angadipuram, the 'type locality' of laterite. While no difference in organic matter content of epipedons was noticed at Thiruvananthapuram, the rate of decomposition was more in soils under uncultivated barren at Angadipuram. The environmental conditions at Angadipuram are more conducive to organic matter decomposition compared to that at Thiruvananthapuram. Though no difference in organic matter content could be noticed under different land uses at Kannur, an analysis of the organic matter content to a depth of 1m indicates that rate of decomposition was uniform which may be due to the very high laterite number of this site. The soil temperature and moisture regimes at Kannur might have enhanced the decomposition of organic matter so that the influence of land use on organic matter content might have been surpassed by the climatic influence.

5.3.4 Water Dispersible Clay and Loss on Ignition

The water dispersible clay contents (Fig. 6) in the epipedons under different land uses showed no difference at Thiruvananthapuram and Kannur while at Angadipuram, the epipedon of soils under cassava had a lower content. Another major observation is the significantly lower water dispersible clay content only in Bt_2 layer of soils under rubber than that of other two land uses at Angadipuram. At Thiruvananthapuram, the Bt_1

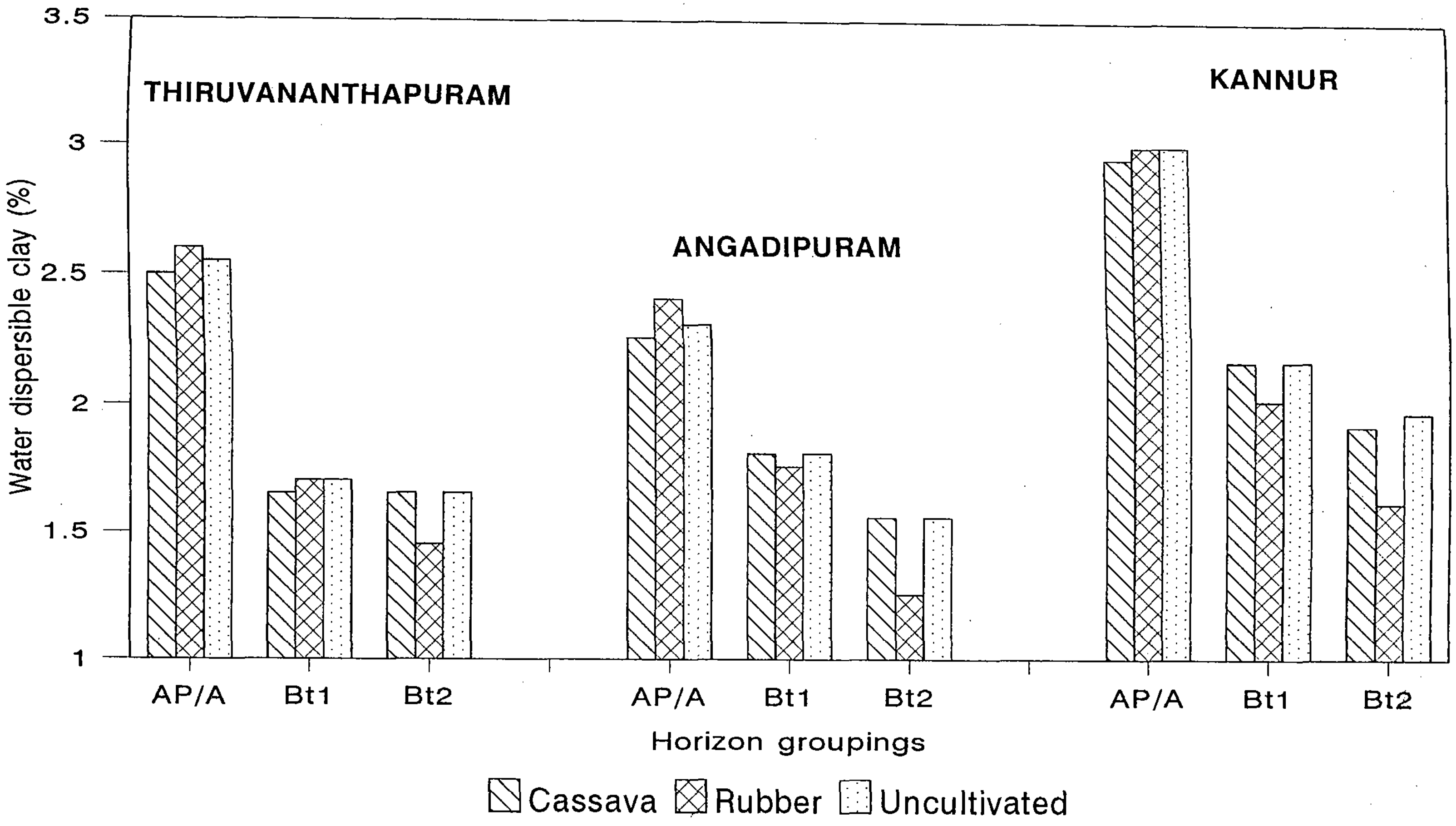


Fig. 6. Water dispersible clay content among similar horizons under different land uses

layer of soils under rubber had significantly higher content than the underlying Bt_2 horizon. At all locations water dispersible clay content decreased down the profiles. Results of pooled analysis show that in the case of surface horizons, soils under cassava had a lower value while in Bt_2 horizons, soils under rubber had a lower content.

Decrease in water dispersible clay content is suggested as an index of induration and laterisation (Buringh, 1970; Soman, 1982 and Narayanaswamy, 1986). Based on this, it can be inferred that when cassava is grown continuously, even the surface layer gets more indurated than when rubber is grown or when the land is kept barren. The impact of high rainfall in tropics may be higher in this land use system so that water dispersible clay migration is more in soils under cassava and thereby the water dispersible clay content in surface layer is reduced. When we compare the hard laterite layer, it is observed that induration and extent of laterisation with respect to water dispersible clay content is more in soils under rubber.

At all sites, the water dispersible clay content was highest in the epipedons which is in agreement with the findings of D'Hoore (1974) and Hamdan and Burnham (1997). The water dispersible clay content of Bt_2 horizons was lowest suggesting insignificant clay dispersion in these materials and consequently indicate more induration or hardening. According to Uehara and Keng (1975), minimum water dispersible clay values are reached at the depth where the pH of the soil approaches their point of zero net charge (PZNC) value. PZNC is the pH value where equal amounts of H^+ and OH^- have been adsorbed on to the hydroxylated surface so that the net surface charge from this source is zero, it determines the sign of the net surface charge. The significantly low water dispersible clay content in Bt_2 layer of soils under rubber is in agreement with the absence of clay argillans.

Analysis of the results of loss on ignition (LOI) showed that at the southern location, LOI of epipedons was highest in soils under rubber followed by cassava and least value in uncultivated barren. When we move towards Angadipuram, though LOI of the epipedon of soils under rubber was significantly higher, that of cassava and uncultivated barren were on par. At the northern most location, Kannur, the LOI was on par in similar horizons including epipedons.

Loss on ignition which constitutes both organic matter and water of constitution is a good index of the rate of weathering and laterisation under different climatic regimes and land uses (Sivarajasingham *et al.*, 1962). Results of the present study indicated that as we proceed from the southern to northern parts of Kerala, the intensity and rate of decomposition of organic matter increased due to the difference in intensity and duration of rainfall as well as temperature. A reasonable period of drying is necessary for laterites to harden, due to crystallisation of goethite or similar minerals, and such a condition is found in northern parts of Kerala compared to southern regions. Studies by Sivarajasingham *et al.*, (1962) suggest that approximately equal wet and dry seasons favour laterite hardening and some degree of alternating wet and dry season is probably essential for this process.

5.3.5 Total Elemental Analysis

Laterisation is a soil forming process occurring in humid tropics where alternate wet and dry seasons prevail. The process can be defined in a general sense as the leaching out and elimination of silica, alkali and alkaline, earths under alkaline hydrolysis and the accumulation of hydrated oxides of iron and aluminium, the latter being partly combined with silica (Varghese and Byju, 1993).

5.3.5.1 Basic cations

The three major basic cations involved in laterisation process in Kerala are K, Ca and Mg (Varghese, 1981). In the case of total K_2O content, at Thiruvananthapuram, though epipedons did not show any difference, both Bt_1 and Bt_2 horizons under rubber had significantly higher K_2O than that of cassava and uncultivated barren. But, at Angadipuram, both Ap and Bt_1 layers under rubber had significantly higher K_2O followed by cassava and then uncultivated barren. In hard laterite Bt_2 layer, the K_2O content was significantly higher in soils under rubber than that of cassava and uncultivated barren, which were on par. At Kannur, K_2O content did not differ significantly.

In the case of total CaO, at Thiruvananthapuram significantly higher amount could be observed in Bt_1 layers of soils under both cassava and rubber compared to the Bt_1 layer of uncultivated barren. But at Angadipuram, significantly higher value in Bt_1 layers as well as Bt_2 layer was recorded in soils under cassava than that of rubber. No difference could be observed among similar horizons under different land uses at Kannur. One important observation at all study sites was the marked increase in CaO content in Bt and C layers compared to overlying eluvial horizons.

With regard to MgO, both at Thiruvananthapuram and Angadipuram, textural B-horizon and hard laterite layer under cassava and rubber had significantly higher MgO content than the respective horizons under uncultivated barren. But at Kannur, the hard laterite layer under uncultivated barren had higher MgO content than that under cassava. Pooled analysis showed no difference in content of all the three basic cations among similar horizons under different land uses.

Analysis of the above results indicated that the process leading to leaching of bases down the pedons is at a faster rate in soils under rubber and cassava. Though this movement was not much evident in surface layers of soils at Thiruvananthapuram, the downward movement of bases could be more evident at Angadipuram and Kannur. All these basic cations have been shown to be dominant constituents that are mobilised from primary minerals and are subject to loss by downward movement from upper layers in tropical laterite soils (Lal, 1994).

5.3.5.2 Silica and Sesquioxides

With regard to SiO_2 content in epipedons under different land uses, a significantly lower value was observed in soils under uncultivated barren than that of cassava at Thiruvananthapuram while at Kannur, soils under both uncultivated barren and cassava had significantly lower value than that of rubber. When we analyse the downward movement of SiO_2, at Thiruvananthapuram significant increase from epipedon to underlying layer could be observed only in soils under cassava and rubber while at Kannur, soils under all land uses showed an increase. No significant SiO_2 movement could be noted at Angadipuram. At Thiruvananthapuram and Kannur, there was a significant lowering of silica content from Bt_1 to Bt_2 layer in soils under cassava only.

The iron content increased significantly down the profile in all land uses at Thiruvananthapuram (Fig. 7). But among similar horizons, the hard laterite layer under cassava and rubber had significantly higher amount than that of uncultivated barren. Also, in soils under all land uses, there was a significant increase of iron content from Bt_1 horizon to Bt_2 horizon. The Bt_2 layer of soils under uncultivated barren had lower iron content than that of rubber and cassava. At Kannur, the Fe_2O_3 content in the Bt_2 layer of soils decreased significantly as uncultivated barren > cassava > rubber. Another major finding is the significantly higher iron content in the second layer compared to the epipedons.

Alumina content did not show any difference among similar horizons at Thiruvananthapuram, while at Angadipuram both epipedons and Bt_2 horizons under rubber had higher alumina content than the corresponding layers under other two land uses. At Kannur, only epipedon of soils under rubber recorded higher alumina content while no difference could be observed among Bt_2 layers.

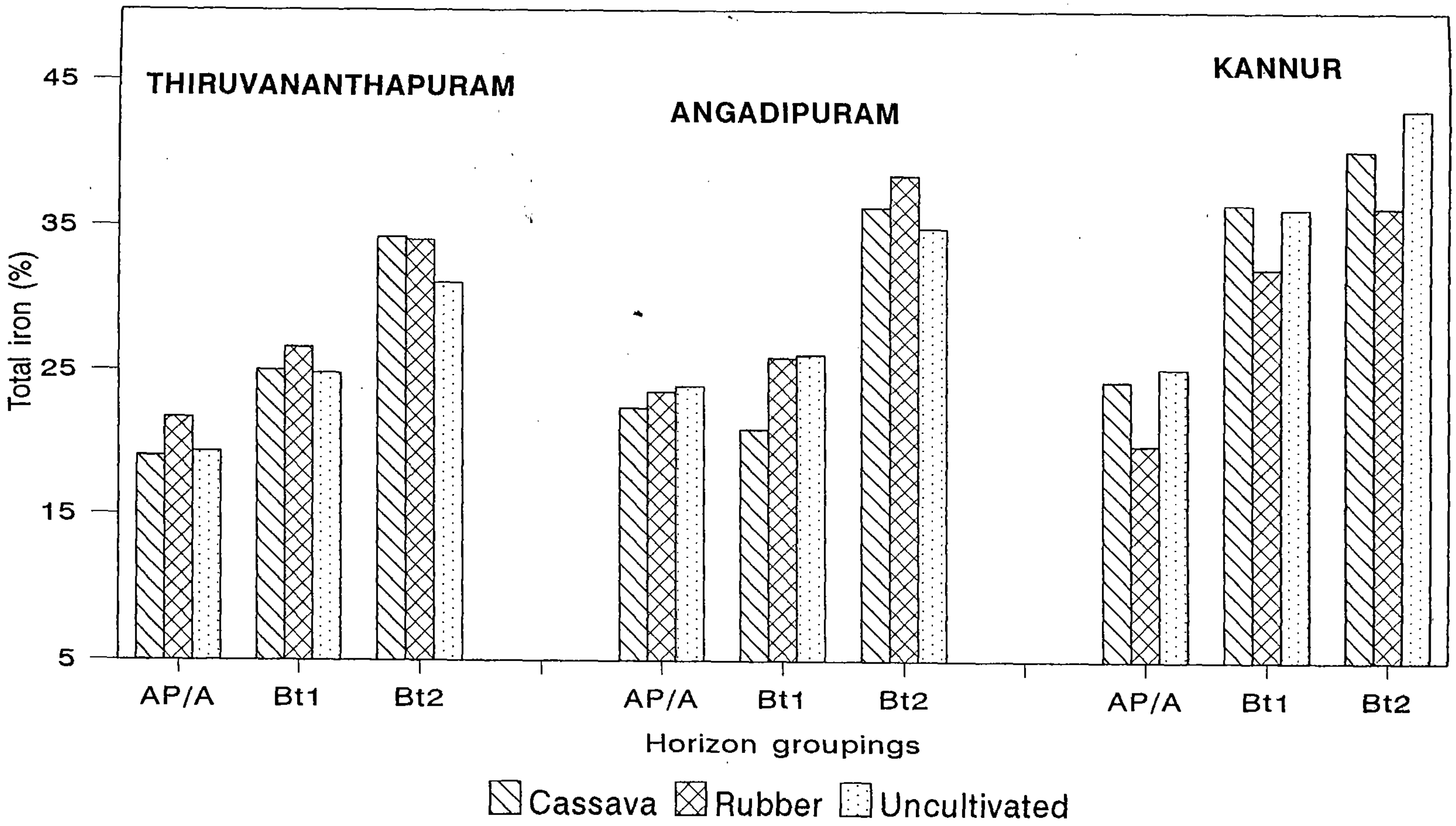


Fig. 7. Total iron content among similar horizons under different land uses

The impoverishment of combined silica and concentration of sesqiuoxides during weathering and laterite formation are clearly evident from the above results. But the variations even at the same site may be due to the different land use systems and the variations among different sites are mostly due to the differences in geoclimatic and pedogenic environments. No consistent relationship seems to exist between the relative amounts of silica, iron and alumina and the degree to which the physical properties of laterites are developed. At all study sites, the overlying soil materials were lower in iron than the hard laterite below and it varies under different land uses and locations from southern to northern parts of Kerala. Iron in the upper layers would be more mobile than that deeper in the profile as a result of complexing with organic decomposition products. Also, the downward moving ferrous iron is immobilised by sorption on ferric ion particles or clays of deeper layers (Sivarajasingham *et al.*, 1962). Enrichment from above layers, which is a minor source, along with relative accumulation due to downward leaching of bases and combined silica resulted in induration of laterites down the profiles and the differences can be attributed to difference in organic matter, rainfall, temperature and land uses (Schwertmann, 1985).

In the northern locations at Angadipuram and Kannur, which are in-situ formations, the enrichment of iron may come about mostly by removal of other constituents. But in sedimentary laterites like those at Thiruvananthapuram, the iron also might have come from outside sources, transport in seeping groundwater from higher forested land is probably the most common external origin.

After enrichment, mobilisation of iron is a pre-requisite for hardening to take place. Considering the relatively high solubility of ferrous ions, reduction is a major mechanism in systems that contain the necessary reducing agents. Wetness alone is not sufficient; organic decomposition products are the most likely sources of reducing agents. Mobilisation as complexes or chelates of organic substances may be more important than reduction. (Brumner, 1973, Eswaran *et al.*, 1990). Herbillon and Nahon (1985) have estimated that reduction may occur in deep-seated situations where the system is free of oxygen. But in actual soil situations, especially in the organic matter rich parts of the soil, the role of microorganisms considerably accelerates the processes (Ottow, 1973).

Oxidation of the ferrous to the ferric form upon introduction of oxygen, destruction of organic complexing or chelating agents, adsorption of ferrous forms either alone or complexed with organic compounds on ferric forms already present, adsorption on kaolin or similar compounds, and slow accretion on microcrystals with associated energy changes, are the most likely mechanisms of immobilisation and thereby laterite hardening. All these factors are influenced by the prevailing climate and land use and hence the variations in hardening under different land uses and locations are observed in the present study (Stoops, 1970; Gallaher *et al.*, 1974a and Eswaran *et al.*, 1990).

Silica as a cation Si^{+4} $4H_2O$, constitutes a very strong acid ($pKa = -1.2$) and is commonly present as a hydroxide, $Si(OH)_4$, with limited molecular solubility (Millot, 1964; Charlot, 1966).

Aluminium forms a hydrate, $Al^{3+}6H_2O$, with intermediate acidity (pKa=5), and as a result, below pH of 4.2 it is rather soluble but at higher pH it precipitates as $Al(OH)_3$, which may crystallise as gibbsite (Hem and Roberson, 1967). The solubility of gibbsite is low (KsP about 32), and once it is precipitated, it is a rather stable mineral.

5.3.5.3 Molar Ratios of Silica, Alumina and Iron

No definite trend could be observed with regard to the change in sa ratio due to land uses at the study sites. At Thiruvananthapuram, sa ratio of hard laterite decreased as uncultivated barren > cassava > rubber. At Angadipuram it did not show any variation while at Kannur the trend was rubber > cassava > uncultivated barren. Down the profiles, a significant increase was recorded from Bt_1 to Bt_2 layers in soils under cassava and uncultivated barren at Thiruvananthapuram. At Angadipuram , both Bt_1 and Bt_2 layers, sa ratios of which were on par, had a significantly higher sa ratio than the respective epipedons.

The sf ratio of epipedons was significantly higher than the underlying Bt_1 and Bt_2 horizons under all land uses at Thiruvananthapuram. But at Angadipuram, this difference could be noted under rubber and uncultivated barren only. When we go to the northern location of Kannur, this difference could not be observed under any land use.

The ss ratio did not show any difference due to land use at Thiruvananthapuram. But at Angadipuram, Bt_1 and Bt_2 layers had a significantly lower ratio than the respective epipedons both in soils under cassava and uncultivated barren. Among different land uses at Kannur, the similar horizons under cassava and uncultivated barren had a lower ratio than that of rubber. Pooled analysis of these ratios showed no difference due to land uses.

Those who regarded the breakdown of kaolinite to free alumina as a measure of laterisation stressed the sa ratio as an index (Alexander and Cady, 1962) to assess the process. It can be seen that all the pedons studied have got low molar ratios indicating that laterisation proceeds faster in all the study sites selected and the variations observed are due to different land uses and variations in climatic parameters especially temperature and rainfall. The increased ferrallitisation could be noticed in the northern site of Kannur compared to the southern location of Thiruvananthapuram. Very low molar ratios of Bt_1 and Bt_2 layers indicate that laterisation is proceeding at a faster rate by the influence of climate and vegetation or land use.

5.4 Soil Acidity Parameters

5.4.1 Soil pH measurements

The fluctuations in ΔpH among similar horizons under different land uses are given in Fig. 8. At all the study sites, the ΔpH was negative and they showed a gradual, though irregular, increase with depth. The high negative ΔpH in the surface horizon is due to organic matter content (Eswaran and Wong Chaw Bin, 1978) and it can be observed that highest

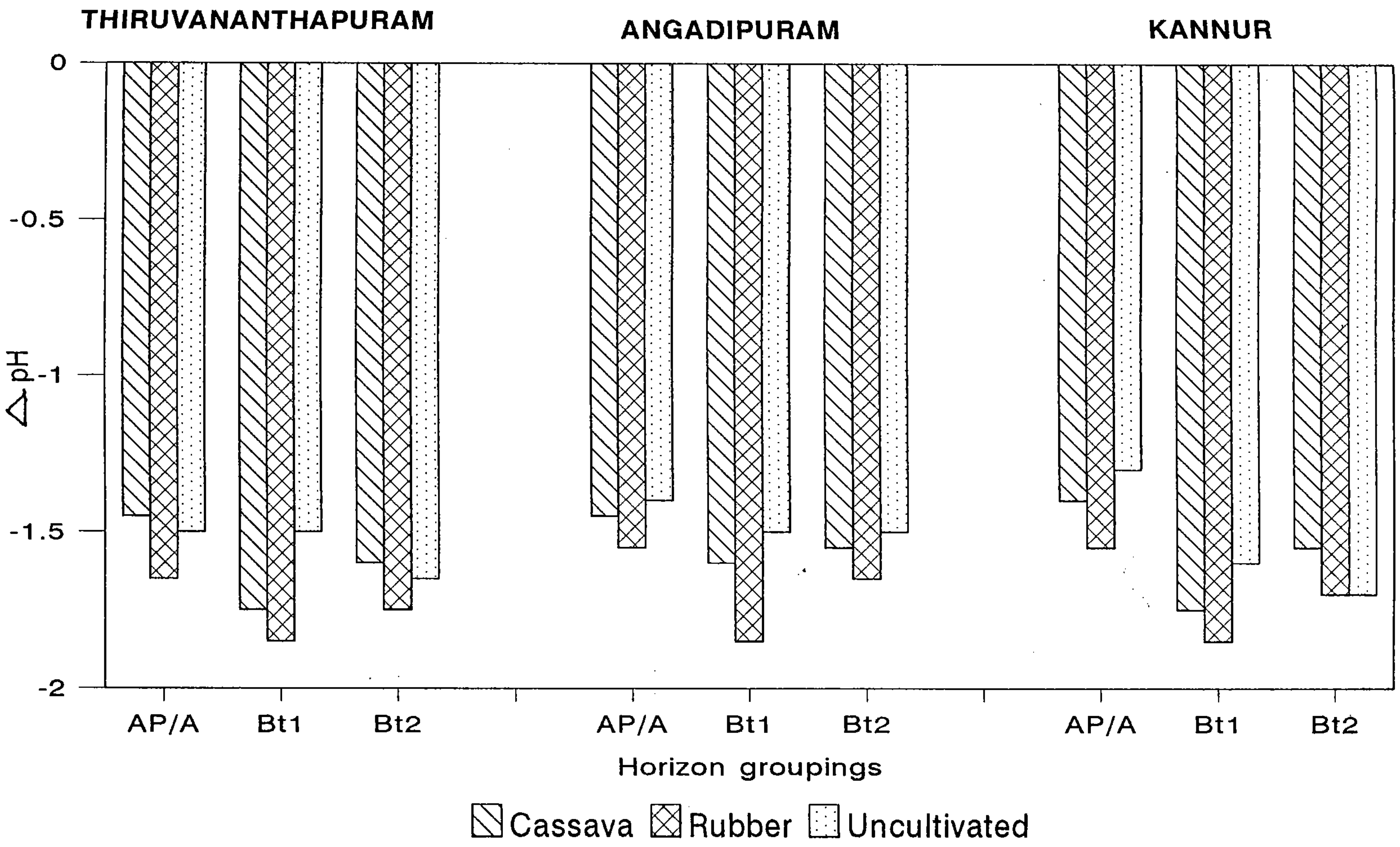


Fig. 8. Fluctuations in ΔpH among similar horizons under different land uses

value could be noted in epipedon of soils under rubber followed by cassava and uncultivated barren. Down the profiles, a least value of negative ΔpH was recorded in the Bt_1 layers under rubber while the Bt_1 layer of soils under cassava had the highest value, and in uncultivated barren, the Bt_2 horizon had the highest value of negative ΔpH. The sign of the ΔpH corresponds to the net surface charge [Parks and de Bruyn (1962) , Yopps and Furestenau (1964), Atkinson *et al.* (1967); Mekaru and Uehara (1972); Uehara and Gillman, 1981 and Uehara, 1995] and accordingly it could be observed that all the horizons of this study had a net negative surface charge and highest values for epipedon as well as for hard laterite layer could be observed in soils under rubber compared to other two land uses. Also the Bt_1 horizon of soils under rubber had the least value for negative ΔpH compared to similar horizons in other land use.

Pooled analysis showed no difference in either pH-water or pH-KCl among similar horizons under different land uses.

The pH-$CaCl_2$ measurement is independent of dilution over a wide range of soil-solution ratios. Also, the soil-pH measured represents more nearly the pH of the soil solution under actual field conditions, and, therefore, should reflect more accurately the H^+ ion environment of plant roots and soil microorganisms than pH-water.

Pooled analysis showed a significantly higher pH in the epipedons of soils under rubber and cassava, which were on par, than the epipedon of soils under uncultivated barren. But Bt_1 and Bt_2 horizons did not show any difference under different land uses. Down the pedons, pH-$CaCl_2$ decreased significantly from epipedons to Bt_1 horizons to Bt_2 layers.

The pH-NaF is a measure of “active Al” in soils. Very high pH-NaF of above 10.00 was recorded in the surface horizons at Thiruvananthapuram. The surface horizons as well as textural Bt_1-horizon of soils under rubber had a higher pH-NaF. While pedons at Angadipuram showed no difference in pH-NaF, at Kannur the surface horizon under rubber had a higher pH-NaF than that of cassava. Both Bt_1 and Bt_2 layers did not show any difference. The higher pH-NaF observed is indicative of the presence of amorphous alumino-silicates in these horizons. (Eswaran and Wong Chaw Bin, 1978). A decrease in pH-NaF down the pedons at Thiruvananthapuram and Kannur is indicative of the increase in amounts of crystalline alumino-silicates as we go down from surface horizons to hard laterite below. This change could not be observed at Angadipuram.

5.4.2 Exchangeable and Extractable Acidity

With regard to exchangeable acidity of soils at Thiruvananthapuram, the surface horizon of soils under rubber had a lower value while in the case of Bt_1 layer, soils under rubber had significantly higher value than that of other two land uses. No change in exchangeable acidity was noticed due to land uses at Angadipuram. At Kannur, only the surface horizons showed difference in exchangeable acidity due to different land uses, with soils under cassava and rubber having lower value than that of uncultivated barren.

With respect to exchangeable hydrogen, one important observation was the significant increase from the Bt_1 layer to Bt_2 layer in soils under rubber at Thiruvananthapuram. The exchange sites and soil solutions of the different pedons studied are dominated by exchangeable Al as shown by the high extractable acidity values. At Thiruvananthapuram, surface horizon of soils under rubber had significantly lower exchangeable aluminium while at Angadipuram, surface horizon of soils under cassava had significantly lower value. Only the Bt_2 layer under uncultivated barren had significantly higher value compared to those of the other two land uses. At Kannur, land uses did not make any influence on exchangeable aluminium content.

The extractable acidity was very high compared to exchangeable acidity at all study sites. Though no definite trend could be observed at different sites, pooled analysis showed that surface horizons of soils under different land uses did not differ with regard to extractable acidity. But in Bt_1 layer, soils under cassava had a significantly higher value and in the case of the hard laterite layer, soils under different land uses had extractable acidity which were on par.

Numerous studies have shown that exchangeable aluminium is generally the predominant cation in highly leached tropical soils when the soil pH is 5.0 or less (Coleman *et al.*, 1958; Mc Cart and Kamprath, 1965; Pratt and Alvahydo, 1966 and Torrent, 1987). Aluminium in the soil solution has been identified as a factor responsible for poor growth in many acid soils.

Soil acidity is produced both by natural processes like laterisation and its intensity is affected by different land uses. Removal of basic cations during biomass harvesting and accelerated leaching of base cations will contribute in a significant way to soil acidification (Knoepp and Swank, 1994 and Marcar and Khanna, 1997).

All the highly leached tropical soils tend to become acid in time, the rate of change will, however, depend upon the rate at which protons are added (fertilisation, atmospheric inputs) or produced (mineralisation, cation uptake) and the nature and rate of proton buffering. Land use or vegetation affect the content of bases in soils. Removal of vegetation may change the microclimate and hydrological cycle of a site, resulting in increased mineralisation of organic matter and accelerated soil erosion and leaching which can cause depletion of bases and an increase in soil acidity. A major constraint to plant growth in highly acid soils may arise from water stress which results from the restriction of root growth (root length and root hairs) into deeper soil horizons where the B horizon has been acidified, as observed in the present study, often as a direct result of Al toxicity.

5.4.3 CEC, ECEC and Base Saturation

Though no definite pattern of CEC (NH_4OAc) was observed among similar horizons under different land uses at Thiruvananthapuram, the CEC (sum of cations) of the hard laterite layer under rubber had significantly lower value compared to other land uses. Down the profiles, CEC determined by both the methods decreased significantly from surface horizon to Bt_1 to Bt_2 horizons. At Angadipuram also, CEC (NH_4OAc) didnot show any difference among similar horizons under different land uses. But CEC (sum of cations) of surface horizons of soils under rubber and cassava was significantly higher compared to that of uncultivated barren. In the case of both Bt_1 and Bt_2 horizons, CEC (sum of cations) of soils under rubber was significantly higher compared to that of cassava and uncultivated barren, which were on par.

At Kannur, CEC (NH_4OAc) of epipedon as well as Bt layers of soils under rubber was significantly higher than that of other two land uses. The CEC of Bt_2 horizons was on par. The CEC (sum of cations) showed no difference. There was a reduction in CEC, determined by both methods, as we go down the profiles.

The CEC (sum of cations) values in all the studied pedons were higher than CEC (NH_4OAc) values. Results of pooled analysis of CEC (NH_4OAc) showed no difference among similar horizons while CEC (sum of cations) of the epipedons under cassava and rubber was significantly higher than that of uncultivated barren. In the case of Bt_1 layers, they followed the order cassava > rubber > uncultivated barren, and in the case of Bt_2 horizons, soils under rubber had a lower CEC (sum of cations) compared to that of other two land uses.

The effective cation exchange capacity (ECEC) of epipedons as well as Bt_2 horizons under rubber was significantly lower than that of other two land uses at Thiruvananthapuram. In the case of Bt_1 horizons, lowest value was observed in soils under uncultivated barren. No difference was observed at Angadipuram. At Kannur, the epipedons showed no difference in ECEC values. Both Bt_1 and Bt_2 layers of soils under rubber had lower ECEC compared to that of other two land uses. Pooled analysis showed no difference among epipedons. In the case of Bt_1

horizons, it was significantly lower under uncultivated barren than that of cassava and rubber. The Bt_2 horizon of soils under rubber had a significantly lower ECEC than that of cassava and uncultivated barren.

Per cent base saturation determined by both NH_4OAc and sum of cations methods revealed that there was no difference in epipedons due to different land uses at Thiruvananthapuram. But in textural Bt_1-horizon, highest value was noted in soils under rubber and uncultivated barren than that of cassava. In the case of hard laterite layer, lowest value was observed in soils under cassava followed by uncultivated barren and rubber.

At Angadipuram, a higher base saturation values determined by both the methods, were noted in soils under cassava compared to other two land uses, though the difference was not significant in hard laterite layer.

At all locations, the base saturation (sum of cations) was lower than that base saturation (NH_4OAc). Pooled analysis showed a significantly higher base saturation, by both methods, in epipedon of soil under cassava compared to other two land uses. In the case of Bt_1 and hard laterite layer, no significant difference in base saturation could be seen.

5.5 Free oxides of iron and aluminium and hardening and softening of laterites

It is not the absolute amount of Fe_o and Fe_d that are important in hardening and softening of laterites, but the amount of oxalate extractable iron relative to the amount of dithionite extractable iron. Apart from the active iron ratio, the content of crystalline iron oxides, estimated as Fe_d-Fe_o, the aluminium bound in iron oxides because of isomorphous substitution and aluminium substitution in iron oxides are also important parameters which can be used for assessing hardening and softening of laterites.

With regard to the absolute content of oxalate and dithionite extractable iron, a definite trend could be observed down the profiles at all study sites. The Fe_o content showed a decreasing trend from surface to hard laterite below, while the Fe_d increased down the profiles. Pooled analysis showed a higher content of Fe_o in epipedons as well as in Bt_1 layers of soils under rubber than that of cassava and uncultivated barren. The Bt_2 horizons did not show any difference in Fe_o content due to different land uses. There was a significant lowering of Fe_o in the Bt_2 horizons compared to the overlying horizons. The dithionite extractable iron showed no difference due to land uses, though a definite increase could be noted in the Bt_2-horizons compared to the respective overlying layers.

In the case of free oxides of aluminium, the Al_o did not show any difference due to land uses. But there was significant difference in Al_d content both among Bt_1 horizons as well as among Bt_2 horizons. While the Al_d content of Bt layer was significantly higher in soils under uncultivated barren, followed by cassava and rubber, in the case of Bt_2 horizons, the trend was cassava > uncultivated barren > rubber.

An analysis of the results of active iron ratio (Fig.9) shows a decreasing trend with depth and the ratios were significantly lower in the

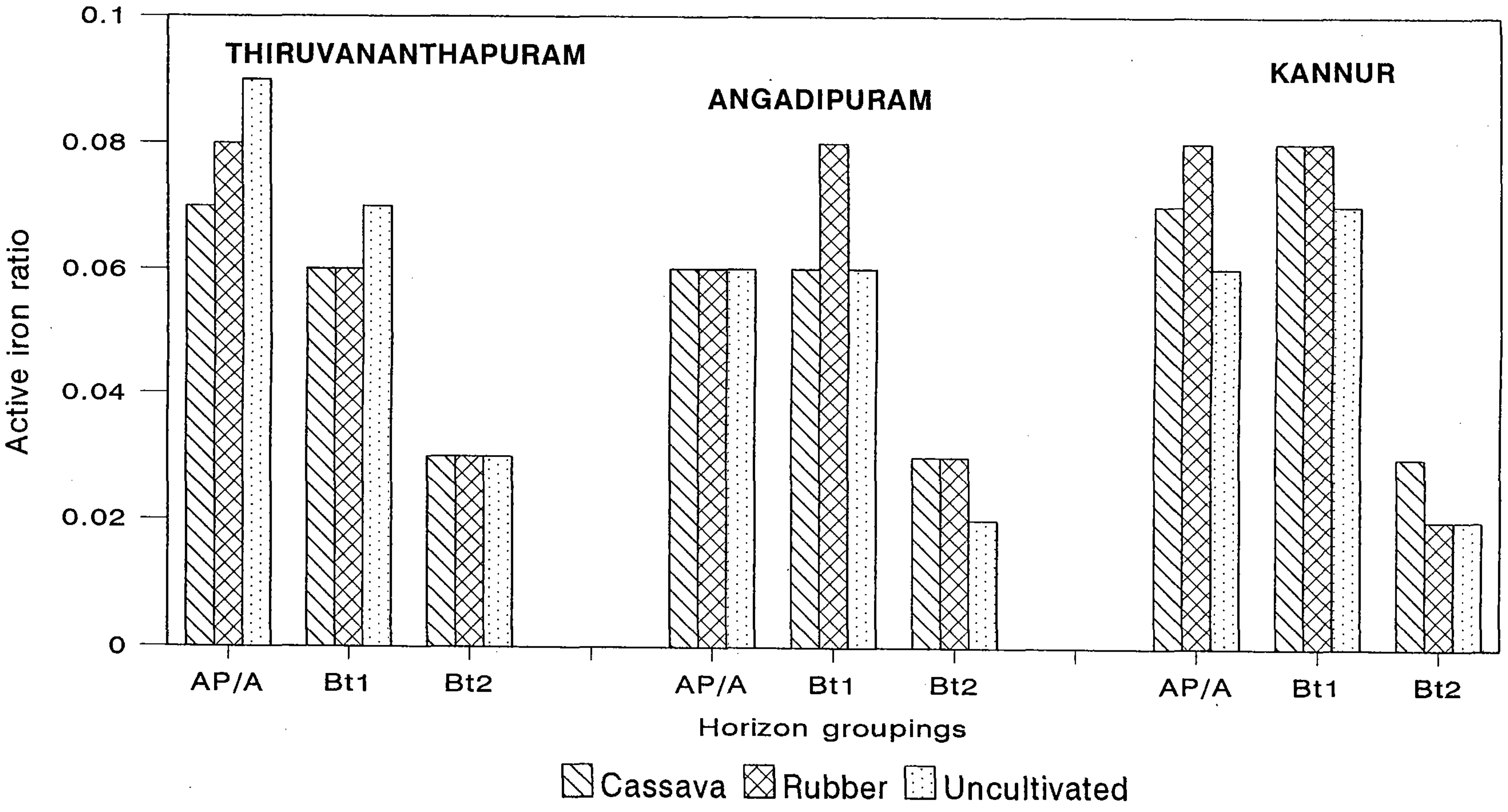


Fig. 9. Active iron ratio (Fe_o / Fe_d) among similar horizons under different land uses

hard laterite layer compared to the overlying horizons, suggesting that the degree of crystallinity of Fe oxides is higher in the hard laterite layers compared to the overlying horizons. Zainol (1985) and Hamdan and Burnham (1997) also reported similar relation between active iron ratio and crystallinity in a number of laterite and associated soils. On the basis of the data obtained, haematite is expected to be present in the top soil whereas goethite is perhaps present in the hard laterite horizon.

Laterite hardening is a very complex process. The iron may be combined with or mixed with clay but the hard materials contain free crystalline iron oxides. Hydrous, amorphous iron oxides lose water and crystallise as goethite. Old, very hard laterites are high in haematite. Goethite decreases and haematite increases with increasing age and increasing hardness in material of similar origin (Sivarajasingham *et al*, 1962).

Mc Keague and Day (1966) introduced the ratio of Fe_o /Fe_d as a measure of relative proportion of amorphous and crystalline iron oxides and suggested this as an index of the degree of ageing or crystallinity of free iron oxides. The higher values of Fe_o/Fe_d in all surface horizons are indicative of their relative enrichment of amorphous iron oxides than crystalline ones (Borggaard, 1990). Though no difference in the ratio could be observed in similar horizons under different land uses at Thiruvananthapuram and Angadipuram, the surface horizon of soils under rubber had a higher ratio than that of uncultivated barren at Kannur. Higher organic matter content reduces the extent of crystallisation of iron oxides (Schwertmann, 1966). Even in the surface horizons at different study sites, the active iron ratio was less than 0.1 indicating the high rate of ferrallitisation since highly weathered laterite soils normally have Fe_o/ Fe_d ratios less than 0.1 (Toreu *et al.*, 1988; Fontes and Weed, 1991 and Wendt *et al.*, 1993).

The crystalline iron oxide content (Fe_d – Fe_o) showed no difference among epipedons or among Bt_1 layers (Fig.10). Pooled analysis show that in the case of hard laterite layer below, both soils under rubber and uncultivated barren had a significantly higher amount than that of cassava. This is indicative of the increased rate of crystallinity of iron oxides in soils under rubber than under cassava.

The aluminium bound in iron oxides because of isomorphous substitution is calculated as Al_d-Al_o. Since ammonium oxalate and sodium dithionite may be considered of comparable strength in dissolution of aluminium compound, such as aluminium oxides, the differene between Al_d and Al_o may be considered to originate from Al bound in crystalline Fe oxides because of Al for Fe substitution (Fontes and Weed, 1991). The aluminium bound in iron oxides because of isomorphous substitution in Bt_1 layers as well as in Bt_2 layers was significantly higher in soils under uncultivated barren as seen from the pooled analysis.

The aluminium substitution in Fe oxides among similar horizons under different land uses is shown in Fig. 11. Pooled analysis show that the aluminium substitution in iron oxides (Fig. 11) was lower in Bt_1 layer as well as in Bt_2 layer of soils under rubber than the other two land uses indicating increased crystallinity and hardening under rubber (Norrish and

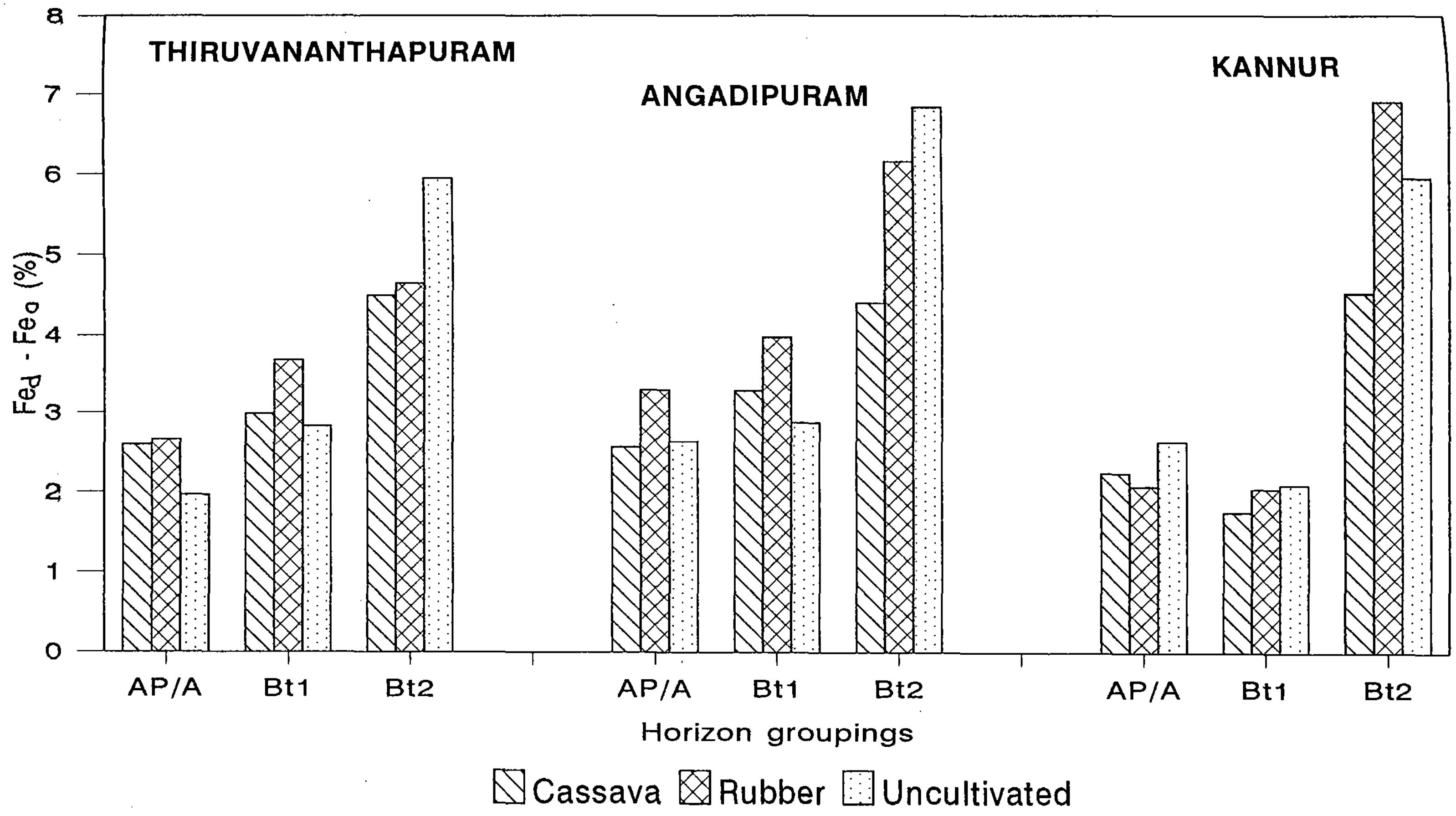


Fig. 10. Crystalline iron oxides (Fe_d - Fe_o) among similar horizons under different land uses

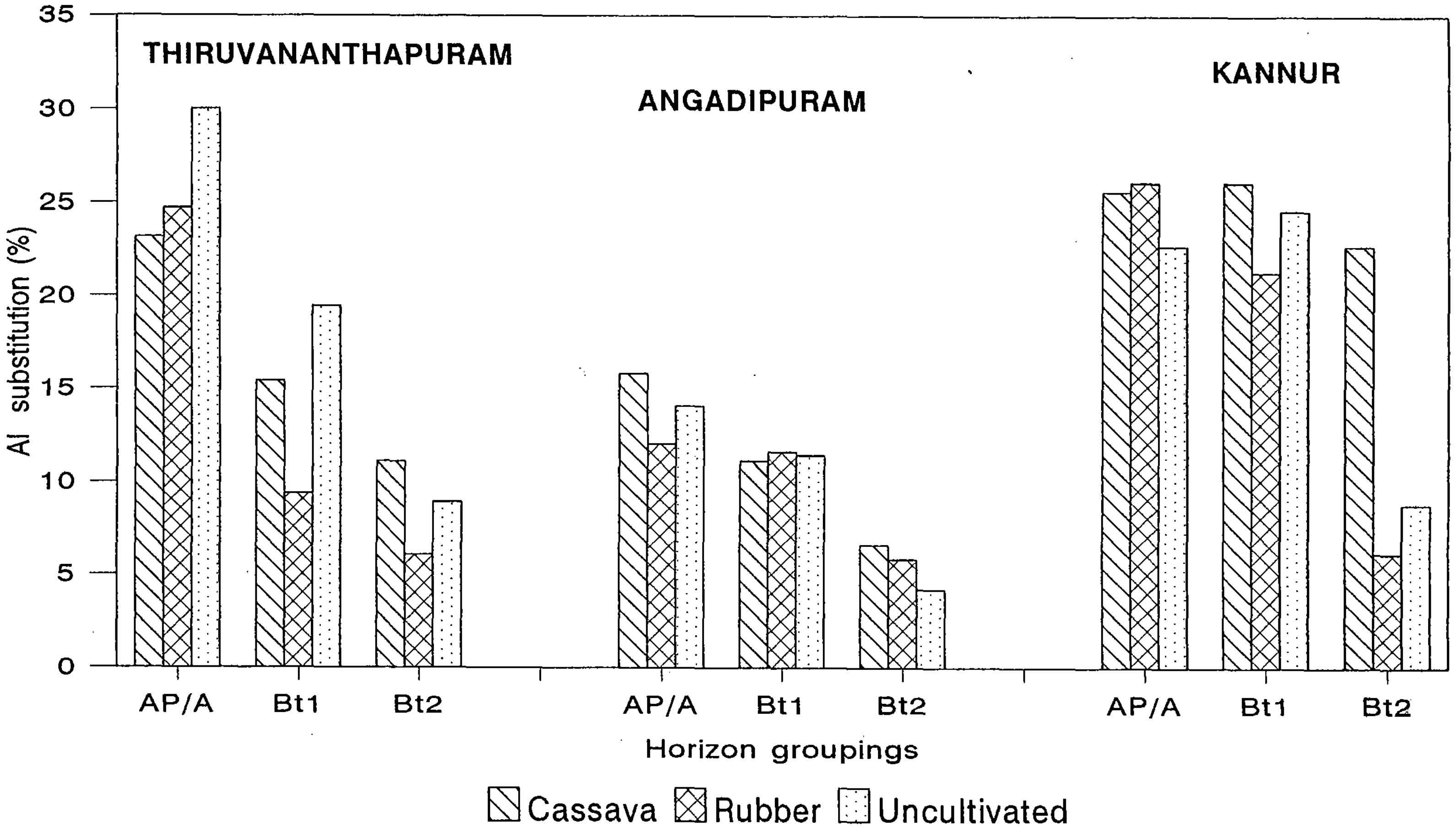


Fig. 11. Aluminium substitution in iron oxides among similar horizons under different land uses

Taylor, 1961 and Schwertmann *et al.*, 1977). Though no difference could be noticed in Al substitution due to different land uses at Angadipuram, in Bt_2 horizons under all land uses, the substitution was significantly lower compared to respective Bt_1 horizons. Same trend was noticed at Kannur too.

The aluminium substitution in iron oxides in all the studied pedons was lower than 33 per cent indicating that there is no contribution of aluminium from sources other than iron oxides since 33 per cent is considered the upper limit of Al for Fe substitution in geothite (Schwertmann and Taylor, 1989 and Fontes and Weed, 1991) which is the major crystalline iron oxide identified in hard laterites. Pooled analysis showed no difference in aluminium substitution in iron oxides due to different land uses.

5.6 Iron and Aluminium Oxides in Hard and Soft Laterites

The hard materials in laterite showed higher concentrations of dithionite extractable iron than the soft materials they are associated with. This trend has been widely reported in literature (Ahmad and Jones, 1969; Wood and Perkins, 1976 and Eswaran *et al.*, 1980). In the case of oxalate extractable iron, this trend was reverse as the soft materials contained higher concentrations compared to their hard counterparts. The high accumulation of dithionite extractable iron seemed to be associated with the increase in hardening and the strength of the material. The positive linear relationship between the strength of the materials, measured as penetration pressure, and dithionite extractable iron (Fig. 12) indicates

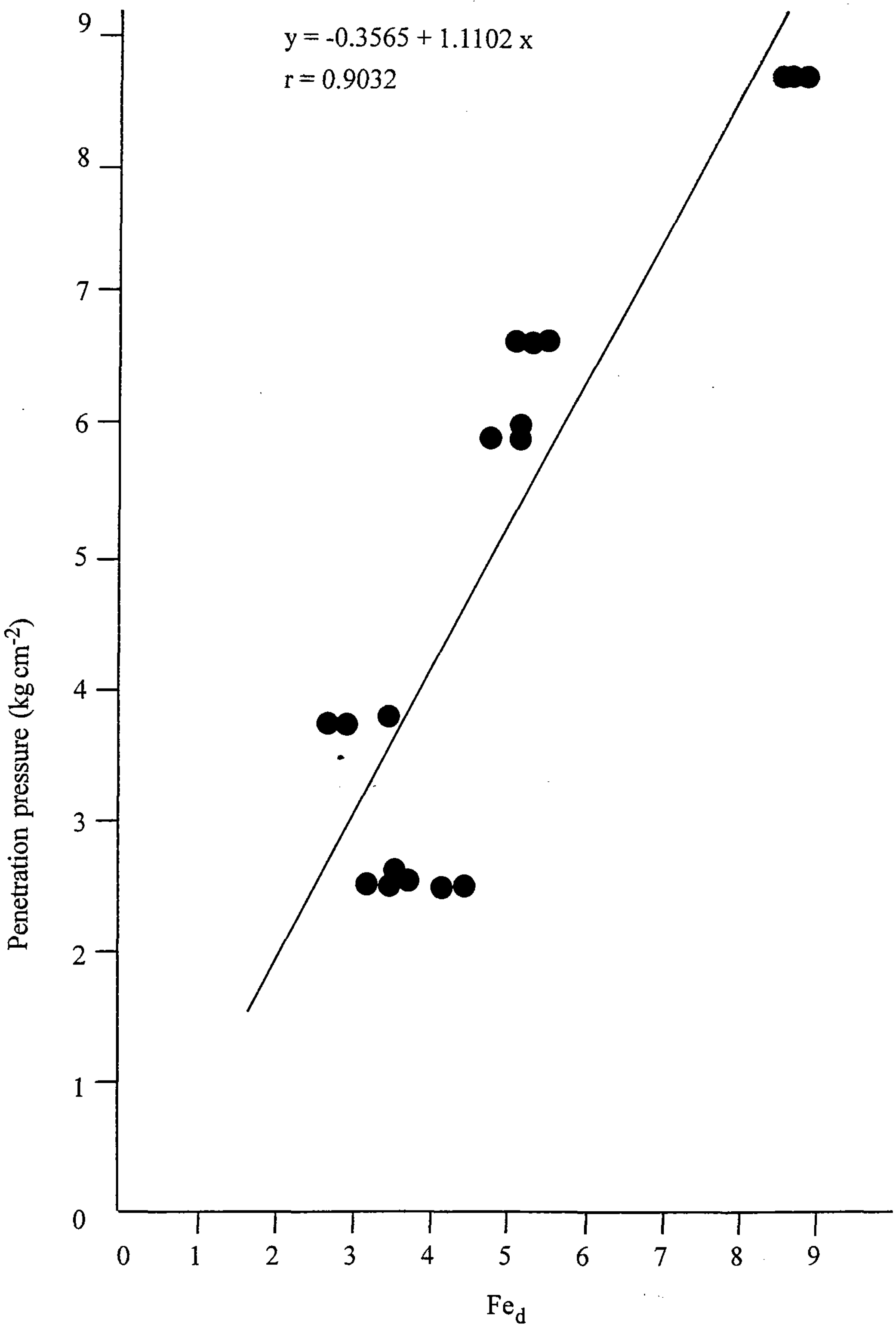


Fig. 12. Relationship between dithionite extractable iron and penetration pressure of laterite

the importance of high Fe-oxide accumulation to the hardening process. Oxalate extractable iron showed very low values, suggesting small amounts of amorphous (active) iron in these materials.

The Fe_o/Fe_d ratios for amorphous and crystalline iron oxides also showed lower values for the hard materials and significantly higher values were noted for the soft materials. Similar results were observed earlier by Gamble and Daniels, 1972 and Eswaran *et al.*, 1980. The negative quadratic relationship between the Fe_o/Fe_d ratios and the penetration pressure (Fig. 13) suggests that iron oxide crystallinity influences the hardening process.

Dithionite and, especially, oxalate-extractable aluminium showed low values in all samples. The amount of Al_d suggests some Al substitution in iron oxides, assuming that Al mainly came from Fe oxides. The per cent Al substitution values indicate appreciable amount of substitution in the soft materials compared to the hard materials with which they are associated with.

5.7. Efficacy of organic and inorganic ameliorants in softening of indurated laterites

5.7.1. Chemical changes in hard laterite due to treatment with different ameliorants

Though the K_2O content in the laterite samples didn't give any significant difference due to different treatments, both calcium and magnesium contents were found to be significantly affected by these

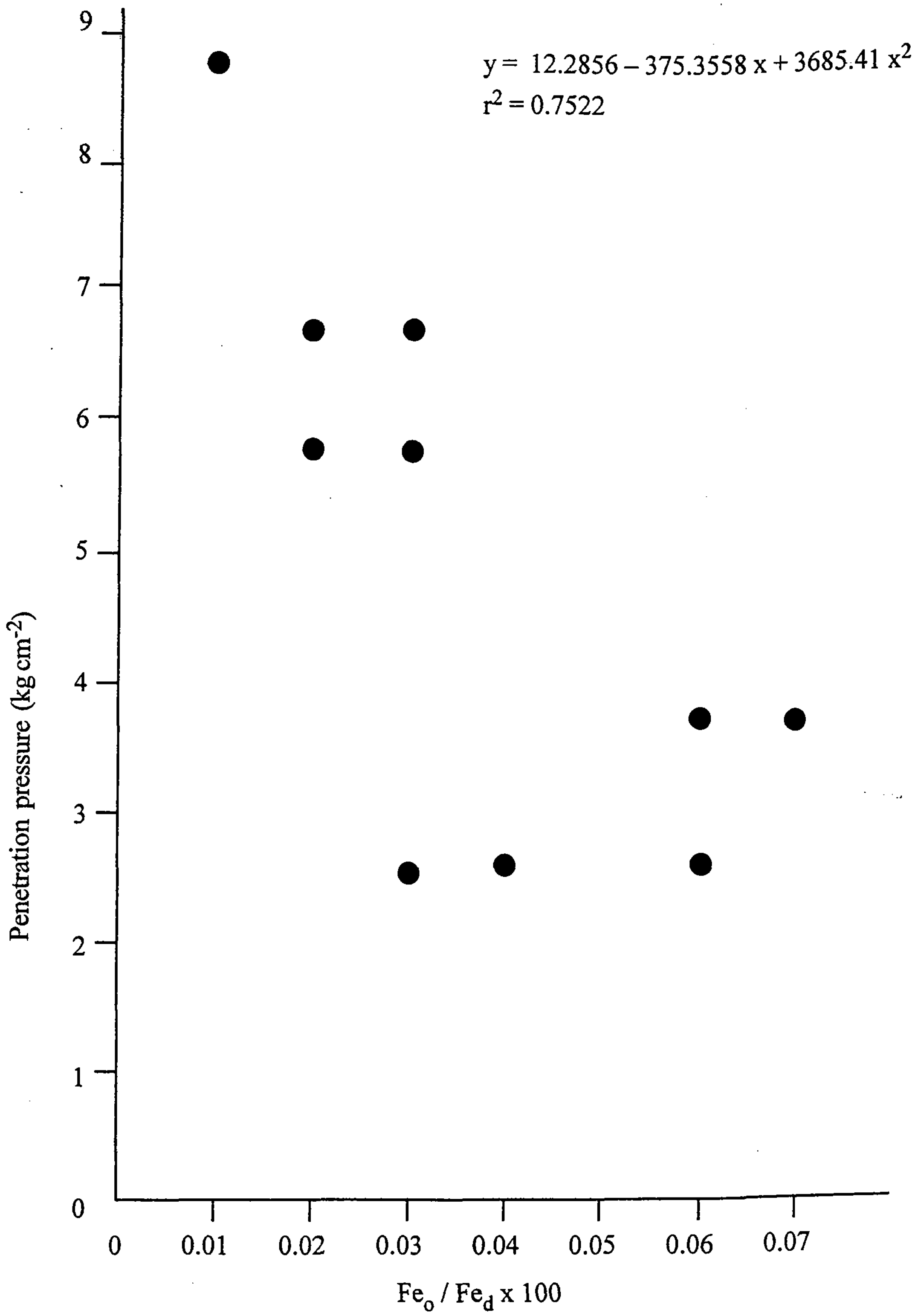


Fig. 13. Relationship between active iron ratio and penetration pressure of laterite

treatments. The calcium content was highest in the sample after treatment with calcium chloride and calcium silicate (Fig. 14). In the case of magnesium, highest values could be noted in samples after treatment with magnesium silicate followed by magnesium chloride (Fig. 15). The organic ameliorants also resulted in a significantly higher calcium and magnesium contents over the control. With regard to sodium content, a significantly higher value resulted only after treatment with sodium silicate and sodium chloride (Fig. 16).

In the case of sesquioxides, significant difference due to different treatments could be observed only in the case of iron. Highest iron content was observed in control treatment and a significant reduction in Fe content was recorded in the samples after treatment with calcium silicate, green leaf extract, cowdung slurry, magnesium silicate and sodium silicate (Fig. 17). Another major observation from the chemical data is that the different treatments didn't significantly alter the silica content in the hard laterite samples which implies that resilicification didn't take place due to these treatments under laboratory conditions.

The active iron ratio was found to be significantly increased due to treatments with calcium silicate, green leaf extract, sodium silicate and cowdung slurry (Fig. 18). Increase in the active iron ratio is suggested as an indicator of softening of laterites (Gamble and Daniels, 1972 and Eswaran *et al.*, 1980). Increase in the ratio indicates a relative enrichment of these samples with amorphous iron oxides than crystalline ones. This was supported by the Al substitution values in iron oxides. Treatments with green leaf extract, calcium silicate, cowdung slurry and

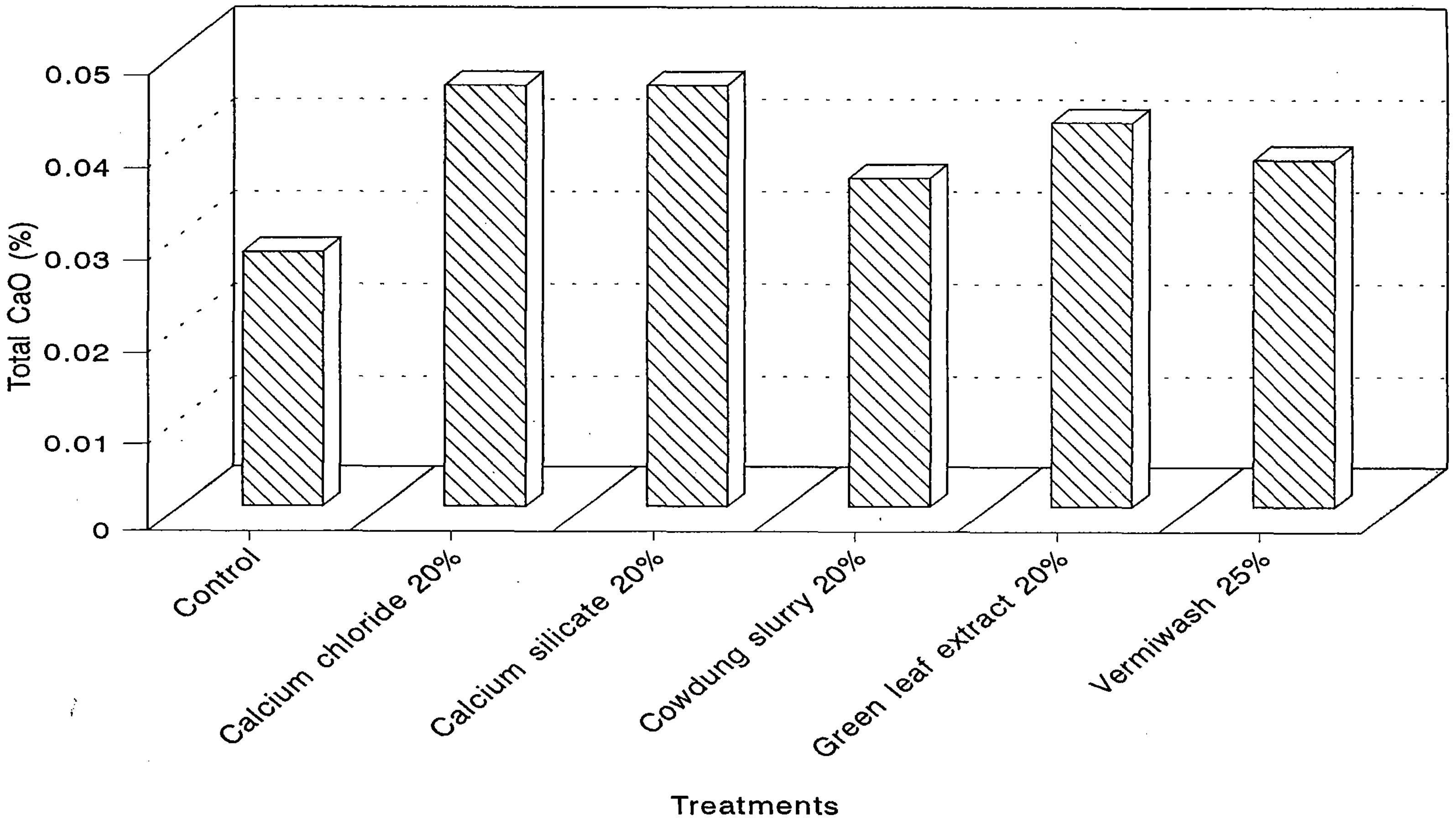


Fig. 14. Effect of treatments on total calcium in laterite

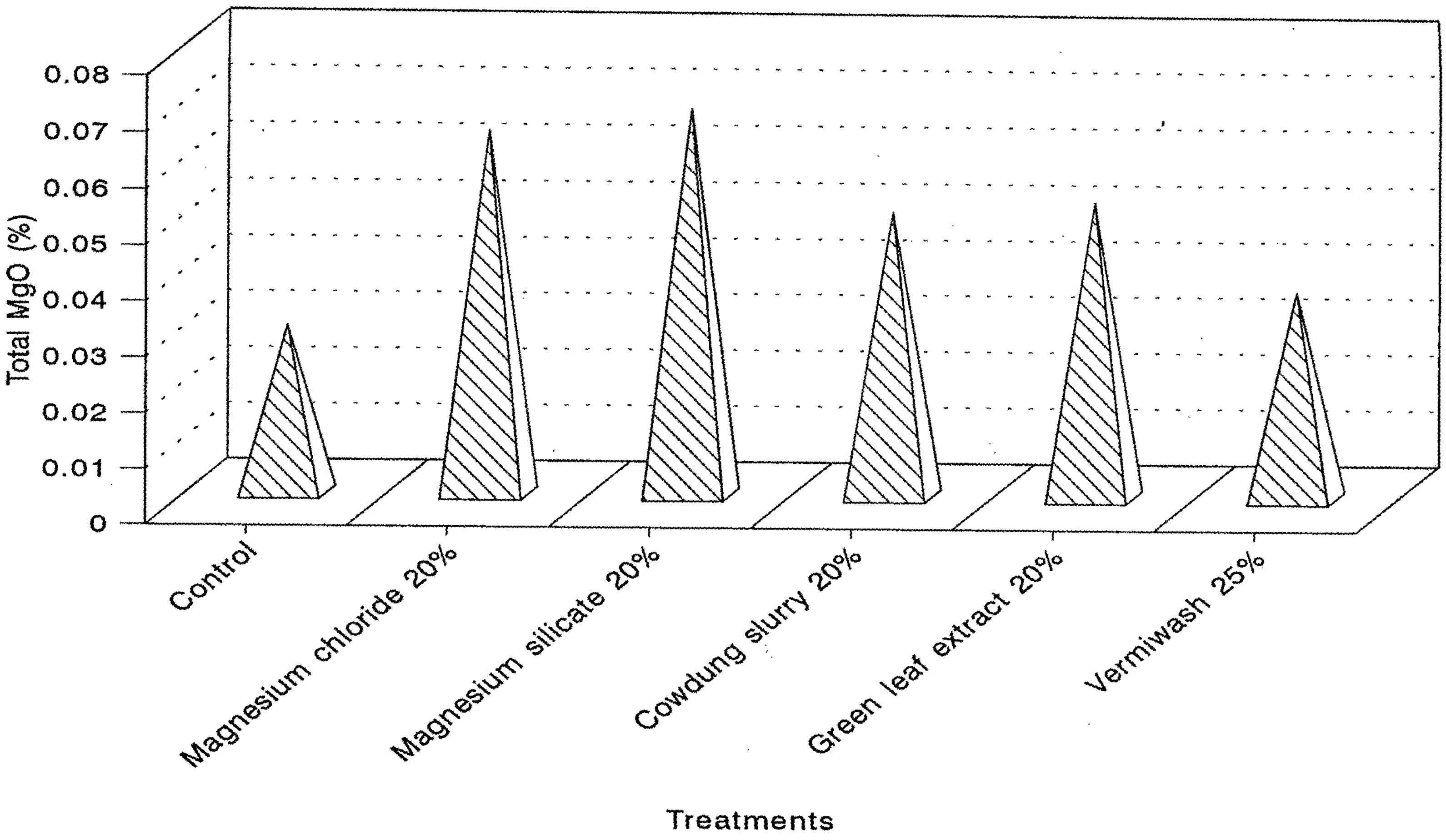


Fig. 15. Effect of treatments on total magnesium in laterite

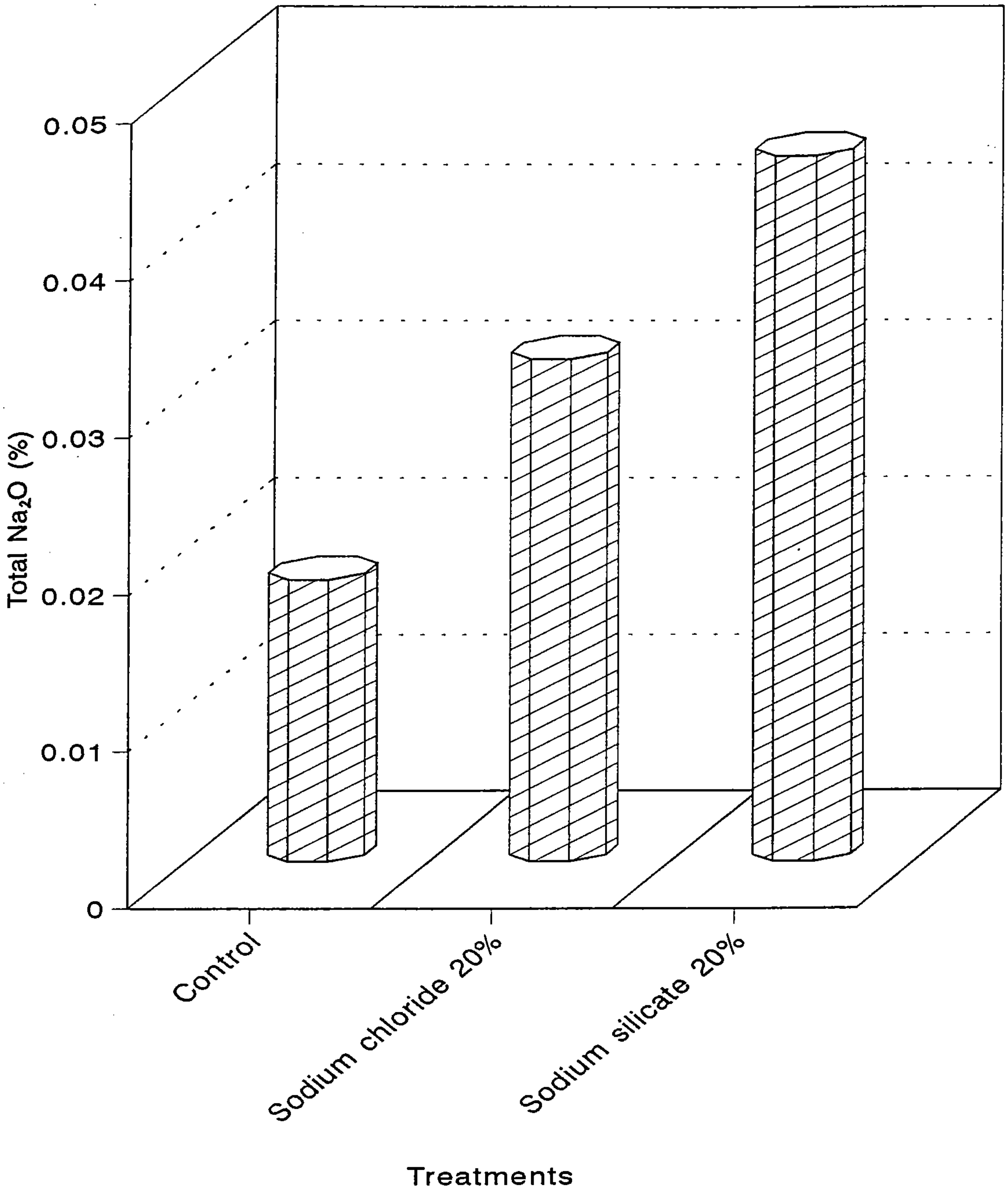


Fig. 16. Effect of treatments on total sodium in laterite

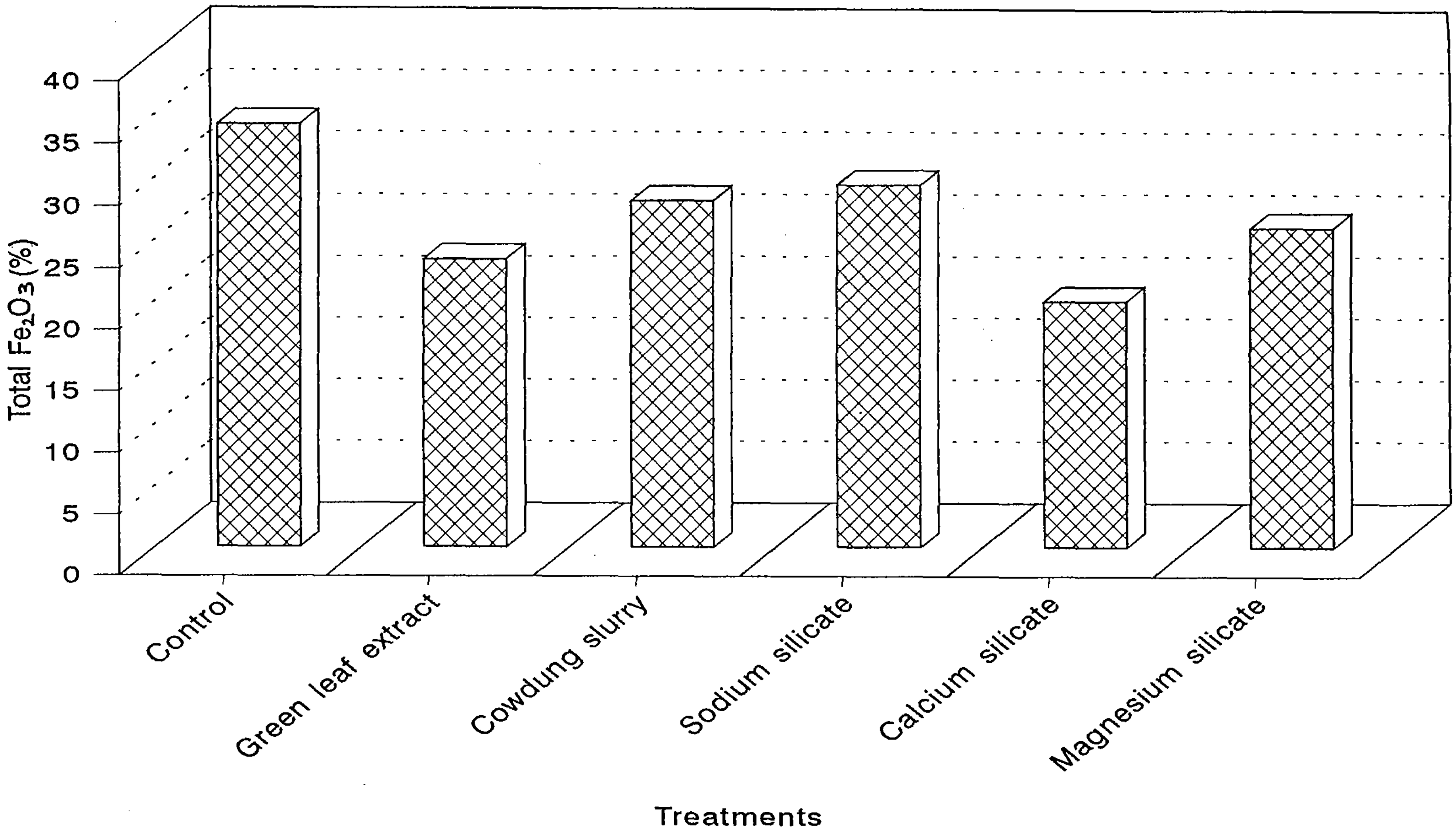


Fig. 17. Effect of treatments on total iron in laterite

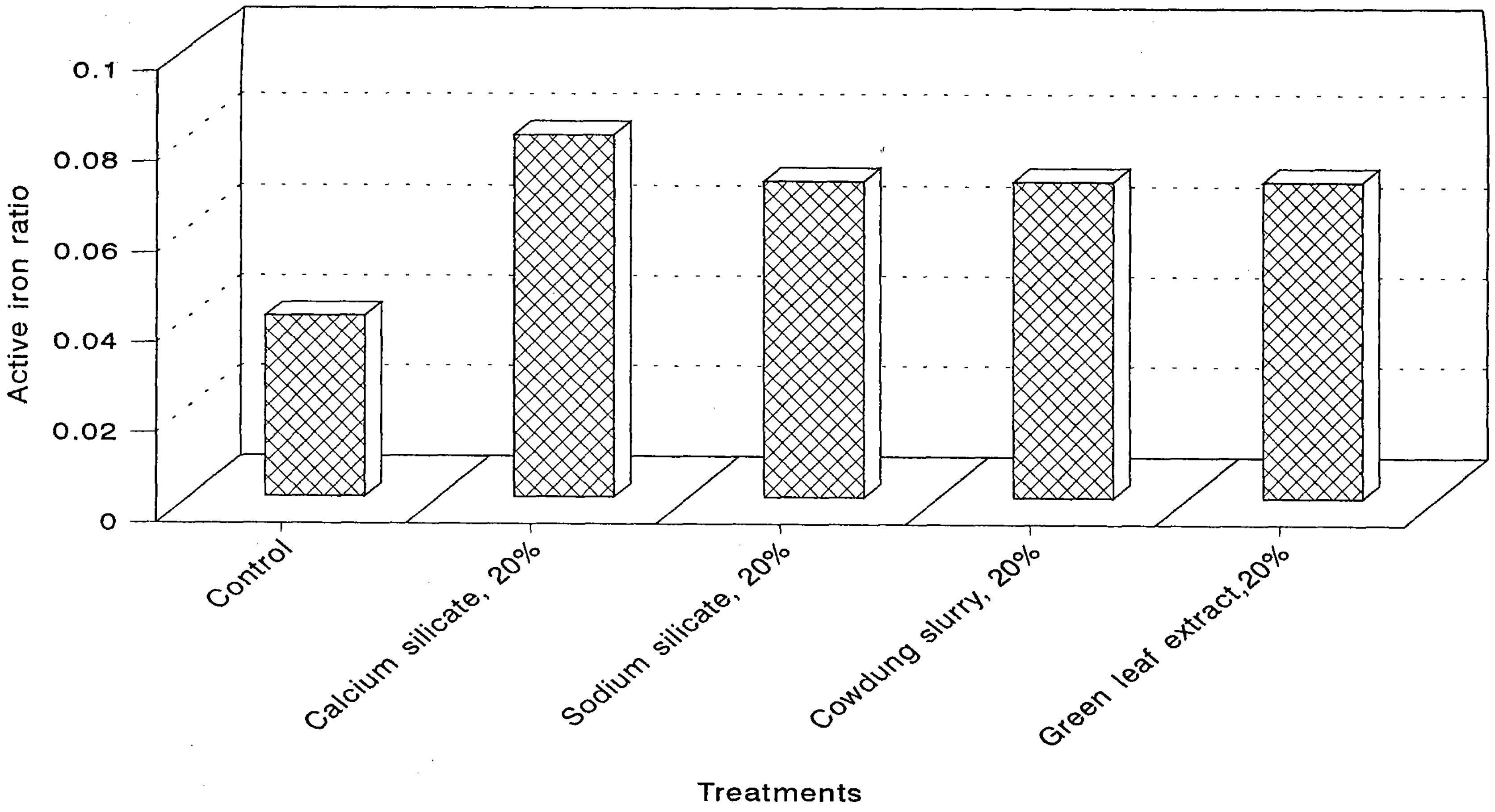


Fig. 18. Effect of treatments on active iron ratio in laterite

sodium chloride resulted in a significantly higher substitution over control (Fig. 19). A higher Al substitution in Fe oxides indicates lower crystallinity and hardening of these samples (Schwertmann *et al.*, 1977).

An analysis of the chemical data reveals that the status of basic cations in the samples could be improved significantly by certain treatments and iron content is significantly lowered. All the silicate treatments as well as organic ameliorants such as green leaf extract and cowdung slurry were found to have significant influence on the reversal of hardening process.

Organic matter under conditions unfavourable for humification or mineralisation produces strongly chelating, water-soluble organic acids. These compounds considerably enhance mineral weathering and cause preferential dissolution and migration of ferric ion, thus preventing laterisation.

In the presence of chelating compounds, the concentration of soluble iron chelates may be several orders of magnitude higher than the total concentration of dissolved ionic forms. This raises the total solubility of iron to levels as high as, or higher than that of silicon, resulting in their rapid removal.

All silicate treatments as well as organic ameliorants such as green leaf extract and cowdung slurry were found to have the maximum influence on softening of already hardened laterites. Minerals rich in iron are most susceptible to attack by humic materials (Schnitzer and

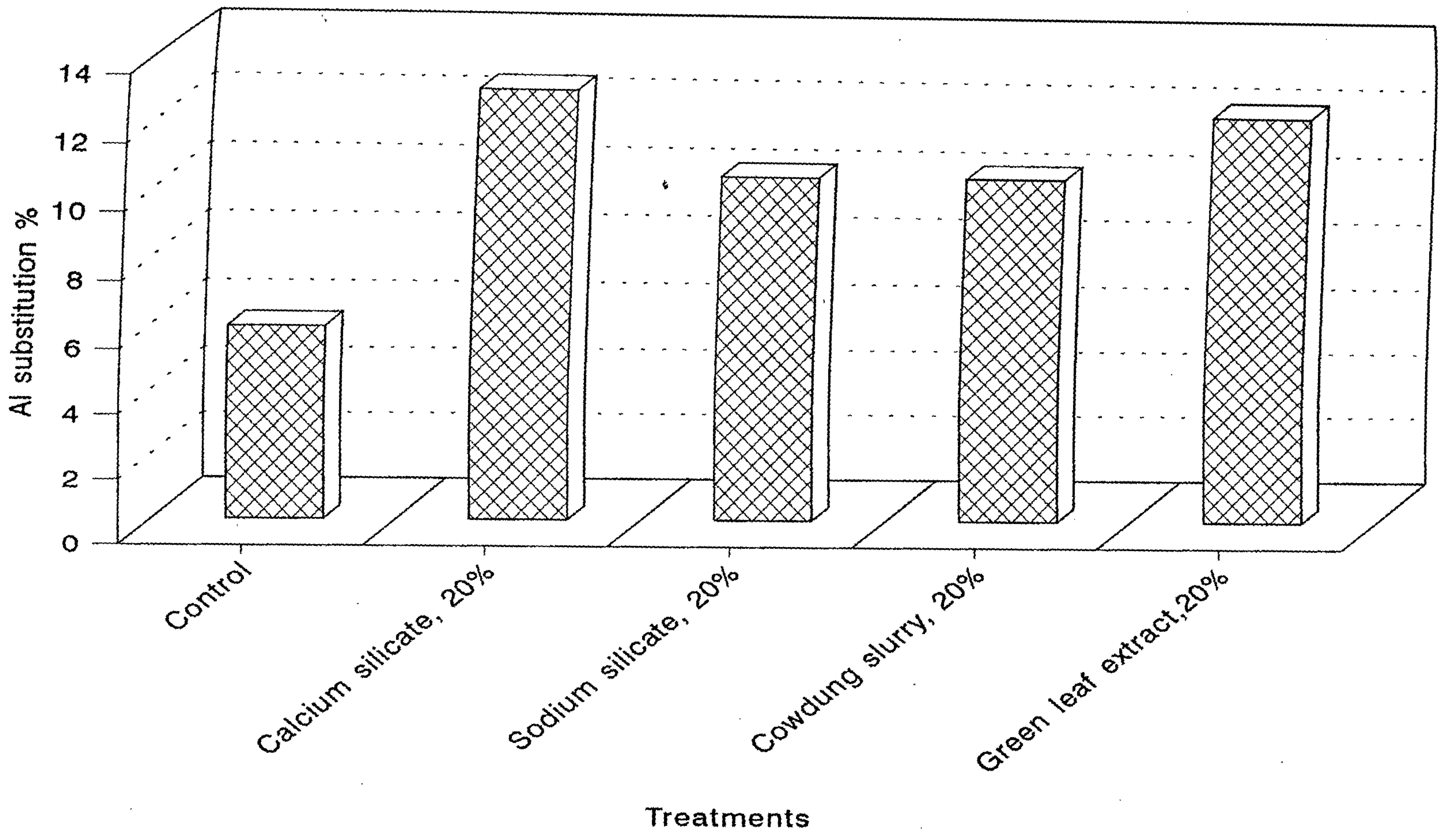


Fig. 19. Effect of treatments on Al substitution in Fe oxides in laterite

Khan, 1978) due to the high affinity of humid acid for iron and the low crystal field stabilisation energies of Fe^{3+} and Fe^{2+}. The complexing of iron by humic materials have an adverse effect on the structural stability of iron rich minerals.

Silicates are also reported to have the same effect as organic matter in lowering the zero point of charge (ZPC) and increasing the cation exchange capacity (CEC) of tropical laterite soils. The degree of chemical weathering is influenced by the ZPC as highly leached ferruginous soils low in organic matter generally show higher ZPC values (Sreekala, 1993).

5.7.2. Mineralogical and micromorphological changes in hard laterite due to treatment with different ameliorants

If we analyse the X-ray diffractograms (Figs. 20-25) it could be observed that the clay material of hard laterite sample before treatment had a very sharp kaolinite peak indicating the high crystallinity of this mineral which showed a broadening due to different treatments with organic and inorganic ameliorants and the peak width at half height (WHH) was maximum in the sample after treatment with cowdung slurry (20 per cent).

Alexander and Cady (1962) indicated that hardening of laterite is nearly always accompanied by a loss of kaolinite and observed destruction of kaolinite in thin sections. But in the present study to see whether already hardened laterite can be softened by different treatments, though an increase in kaolinite content could be observed, the kaolinite peaks

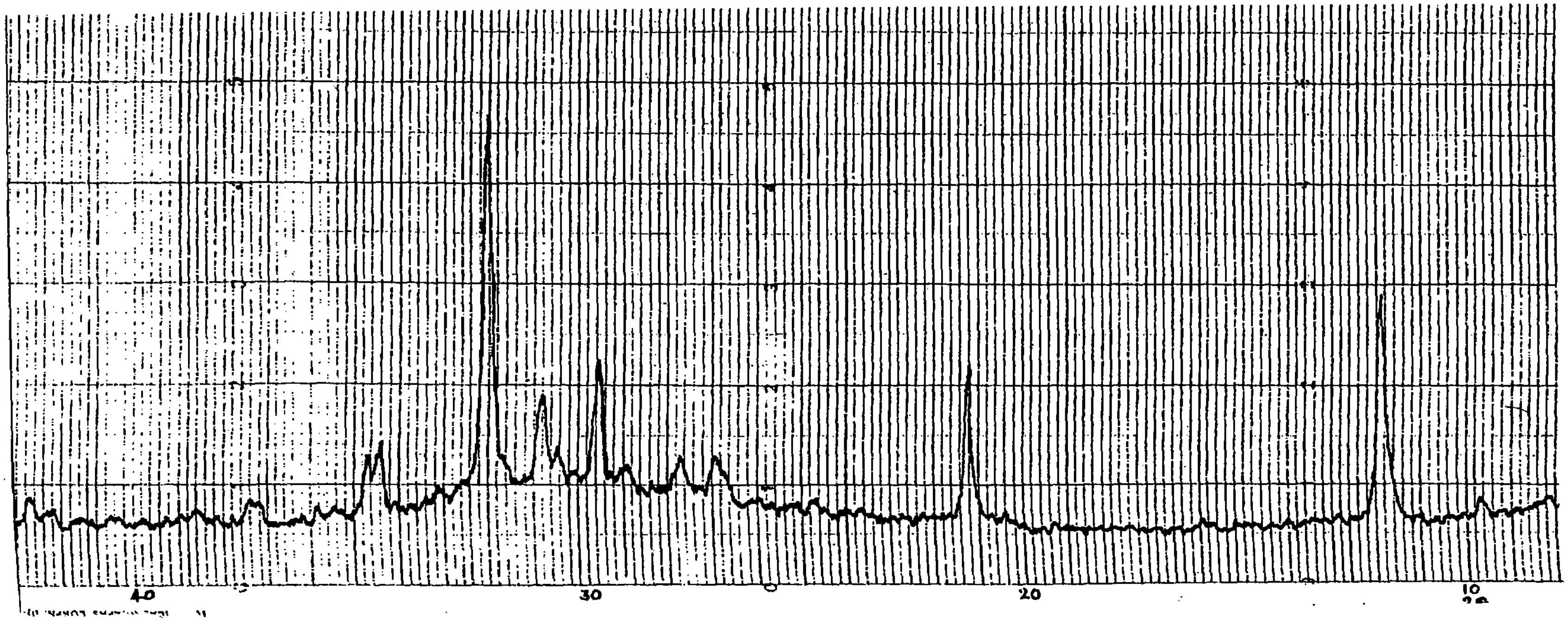


Fig. 20. X-ray diffraction pattern of powder sample from laterite before treatment

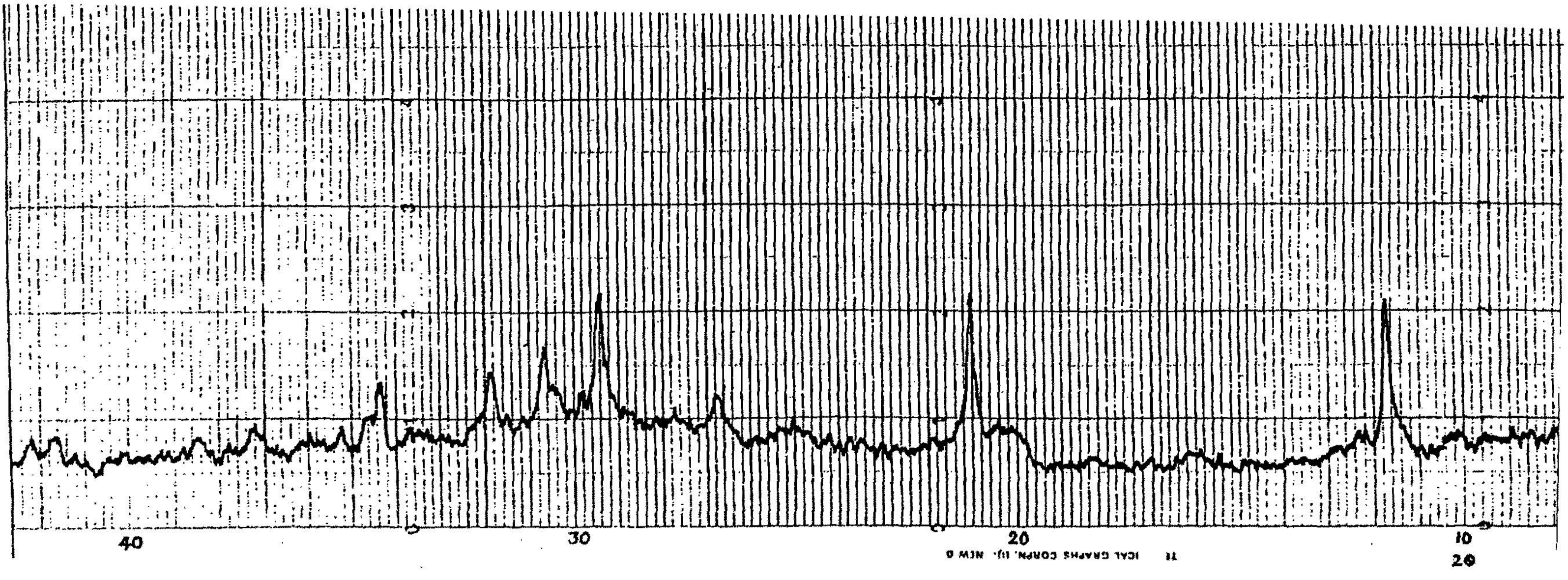


Fig. 21. X-ray diffraction pattern of powder sample from laterite after treatment with sodium silicate (20 per cent)

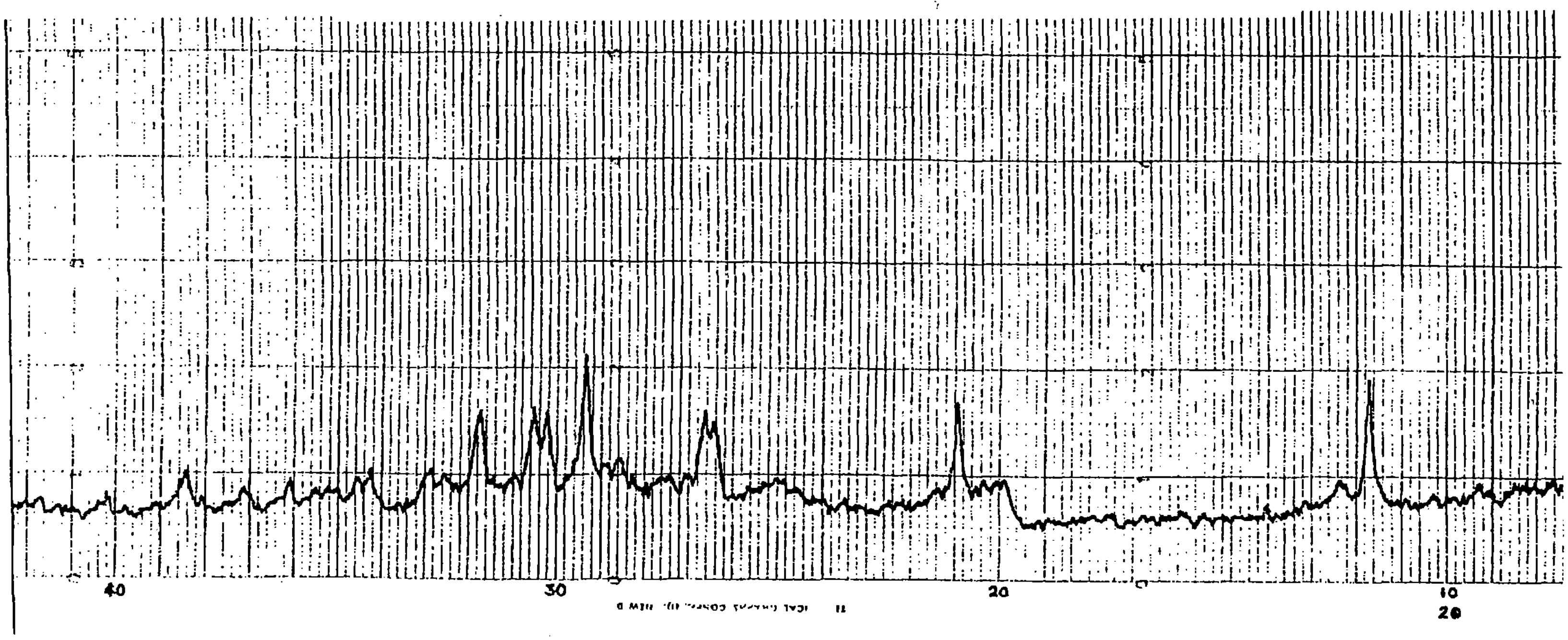


Fig. 22. X-ray diffraction pattern of powder sample from laterite after treatment with magnesium silicate (20 per cent)

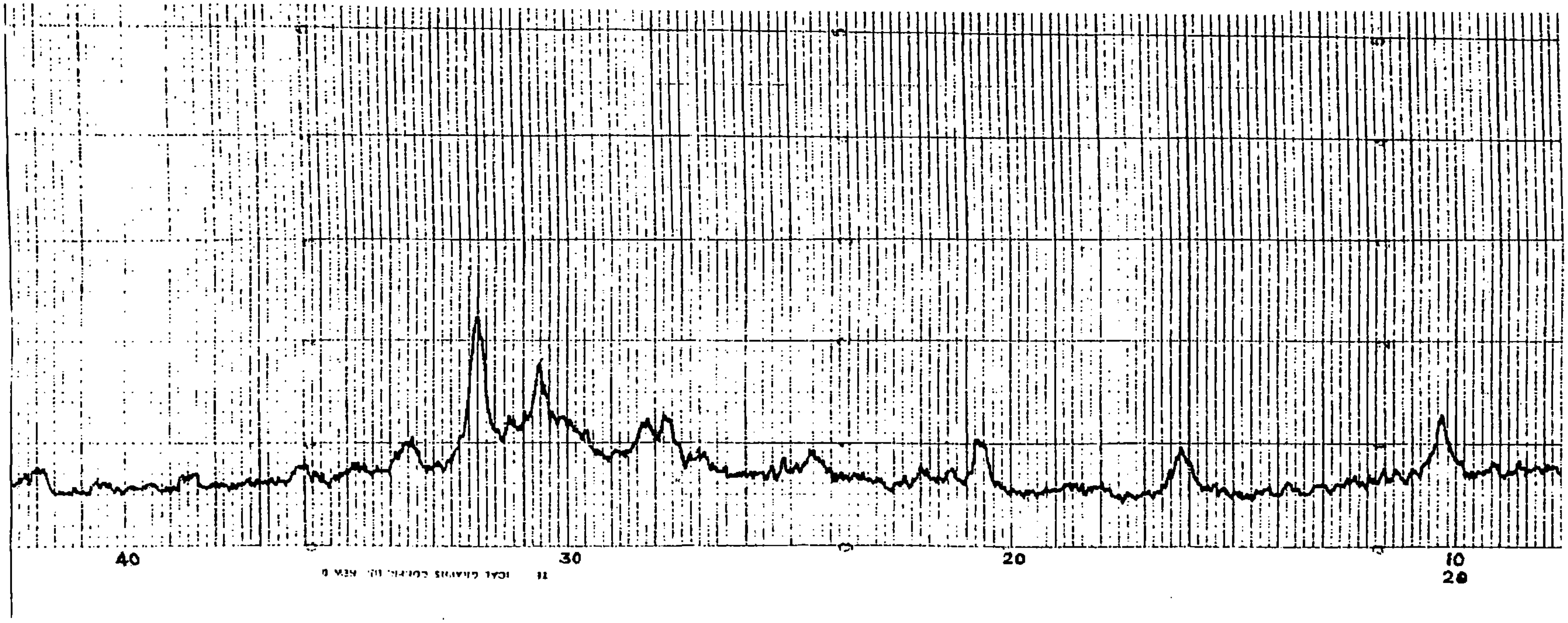


Fig. 23. X-ray diffraction pattern of powder sample from laterite after treatment with calcium silicate (20 per cent)

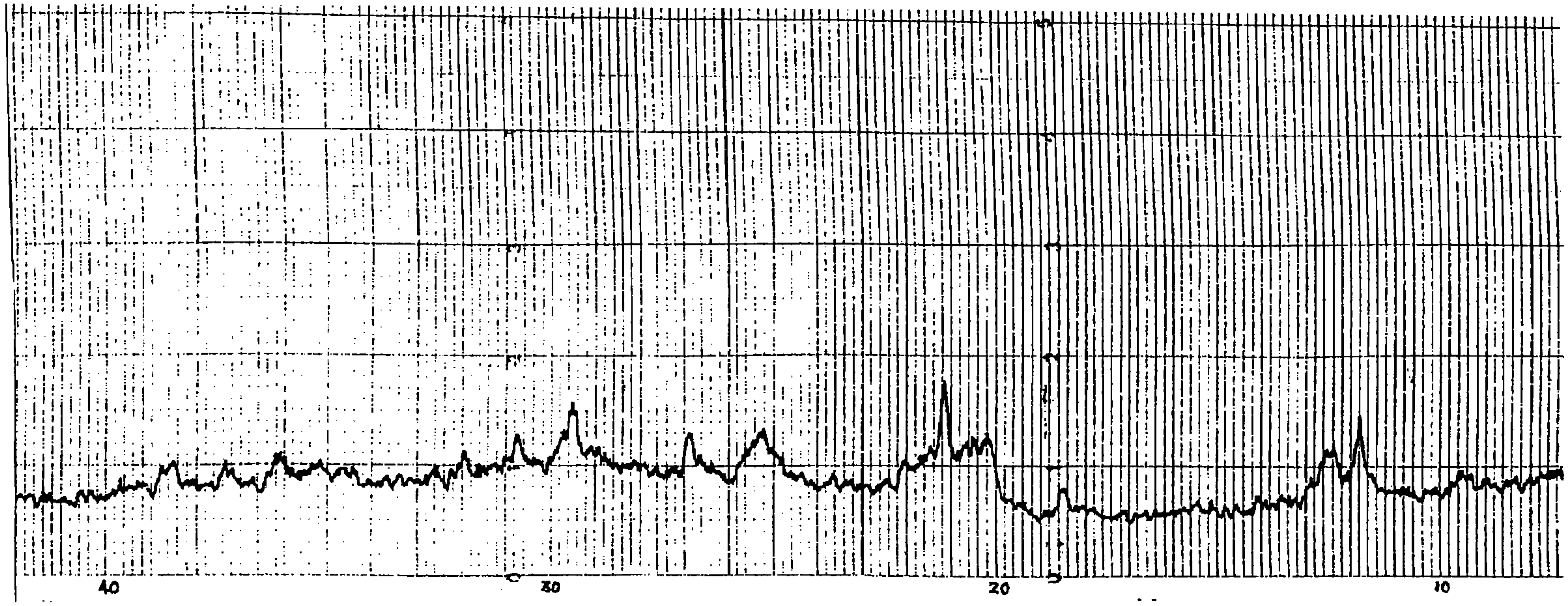


Fig. 24. X-ray diffraction pattern of powder sample from laterite after treatment with green leaf extract (20 per cent)

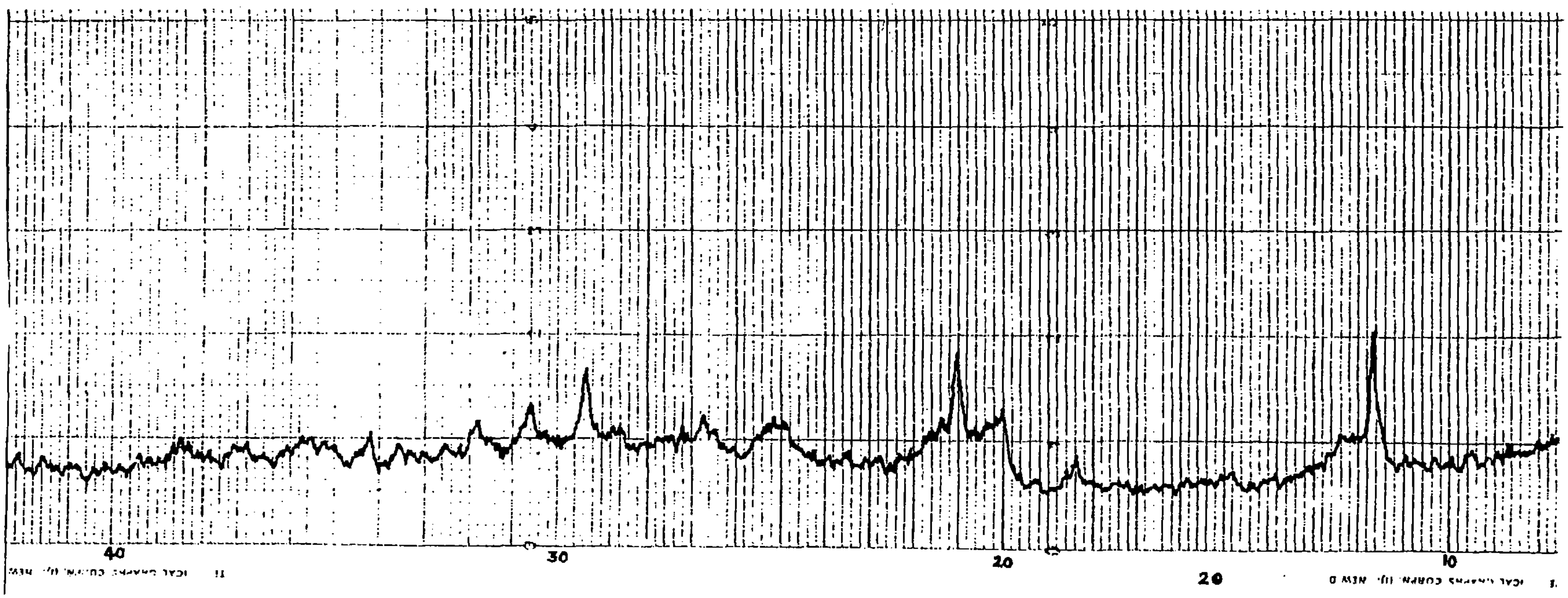


Fig. 25. X-ray diffraction pattern of powder sample from laterite after treatment with cowdung slurry (20 per cent)

were found to be broadened (Fig. 26) at half height indicating the loss of crystallinity of the mineral (Klug and Alexander, 1974). So the present study indicated that though the reversal of hardening could not result in an increase in kaolinite content, it could destroy the crystallinity of the mineral.

The transition from well crystallised to poorly crystallised kaolinite is shown by a broadening and weakening of the reflections especially after treatment with calcium silicate (20 per cent), green leaf extract (20 per cent) and cowdung slurry (20 per cent). The shift of the basal reflection from 7.14 A^{0} also indicates poor or loss of crystallinity of kaolinite after these treatments (Fig. 27). The group of lines from (020) (d=4.46 A^{0}) to (002) (d=3.57 a^{0}) particularity reflect the change to lower crystallinity.

In the case of the aluminium mineral, gibbsite, the hard laterite block treatment did not have any measurable quantity while a maximum value of 45 cts was seen after treatment with calcium silicate (20 per cent) followed by green leaf extract (20 per cent) and cowdung slurry (20 per cent) which resulted in a relative abundance of gibbsite of 37 cts each (Fig. 28). As pointed out earlier, these three treatments resulted in an increase in aluminium content and aluminium substitution for iron., This aluminium substitution can also be clearly observed from the shift of the 111 peak of goethite and of the 110 peak of haematite. The 111 goethite and 110 haematite peaks were used for comparison so as to minimise interference because all these samples contained appreciable quantity of kaolinite and gibbsite, as well as goethite and haematite. These

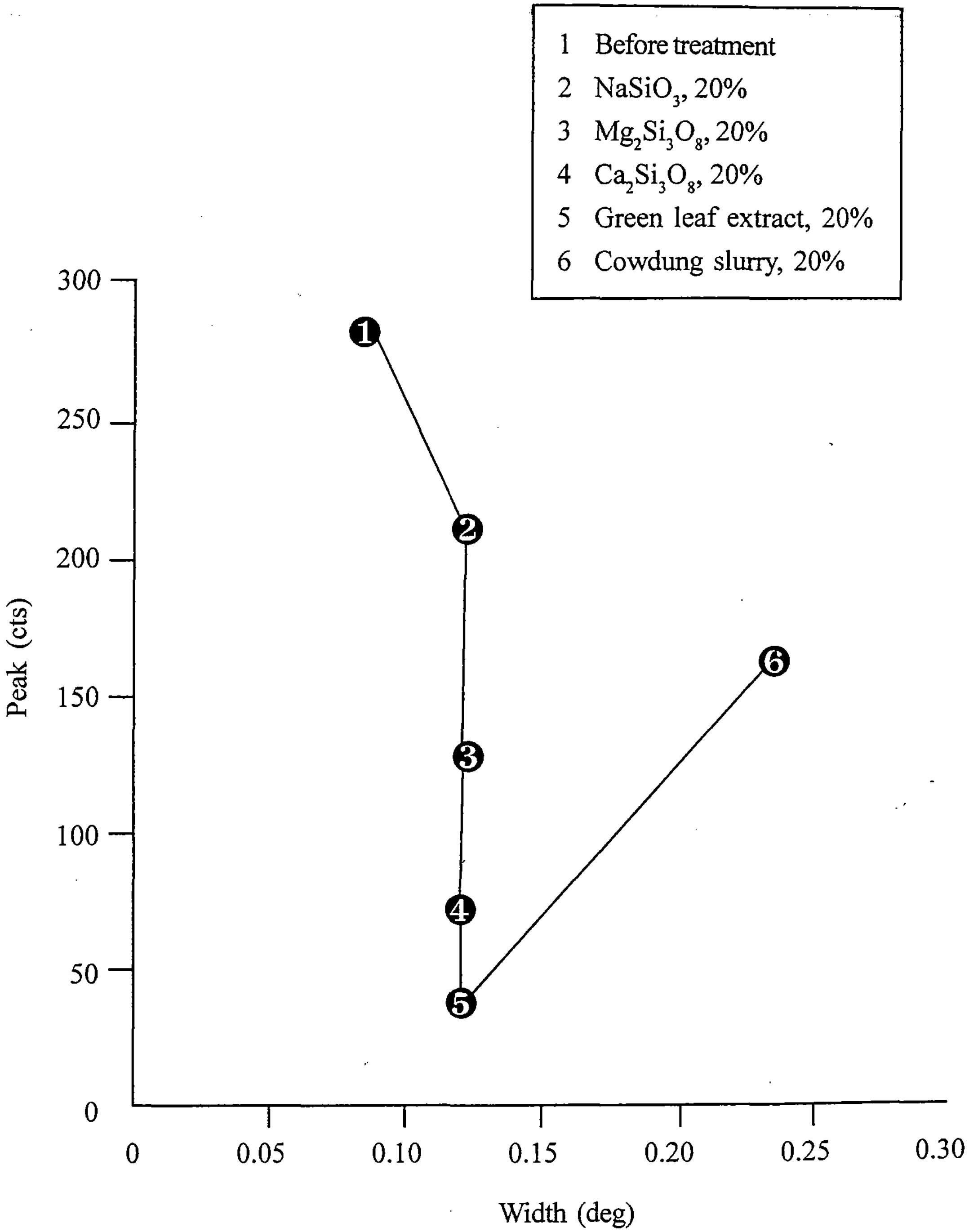


Fig. 26. Kaolinite peak vs. width due to different tretments

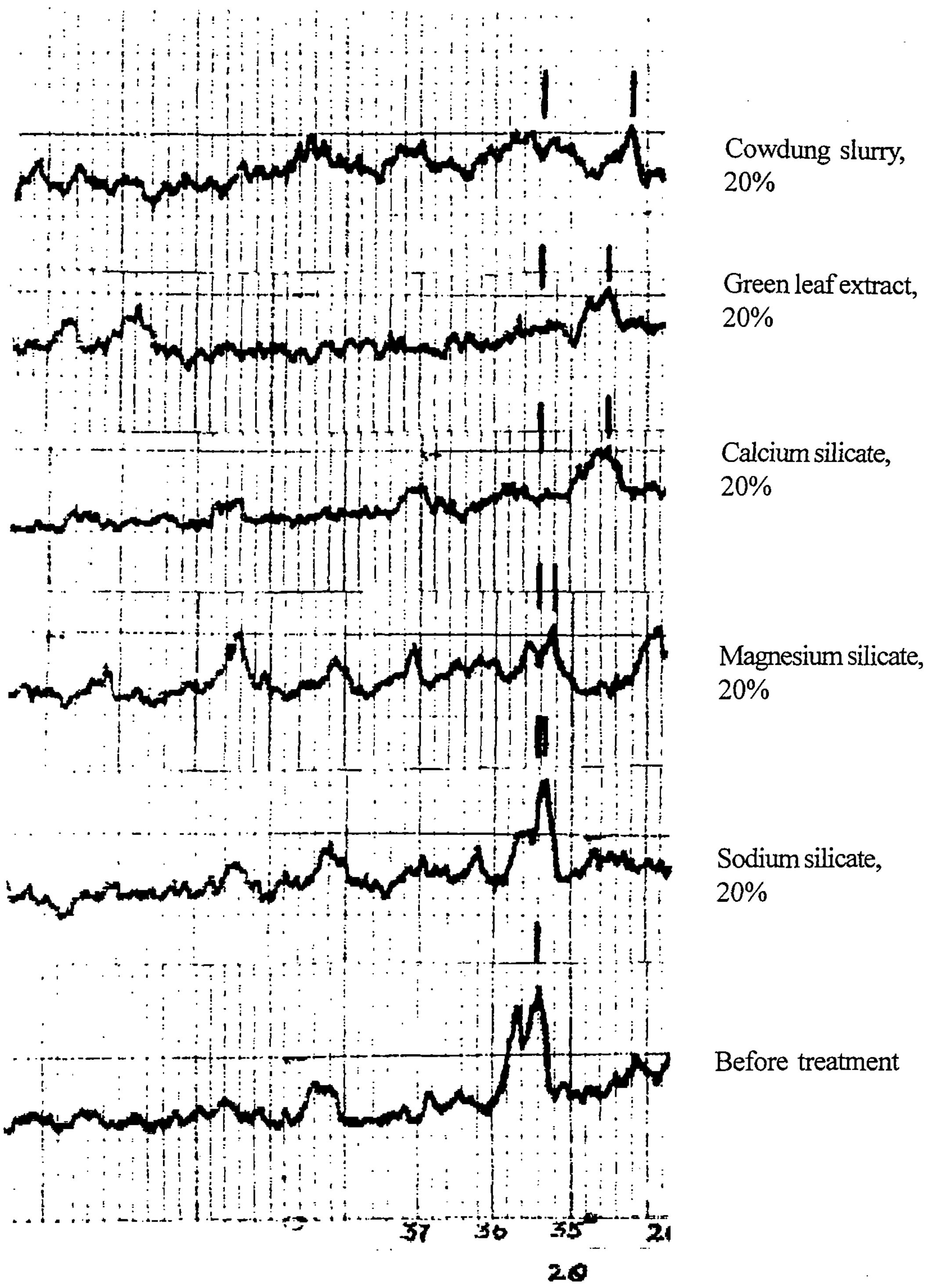


Fig. 27. Shift of the kaolinite peaks due to different treatments

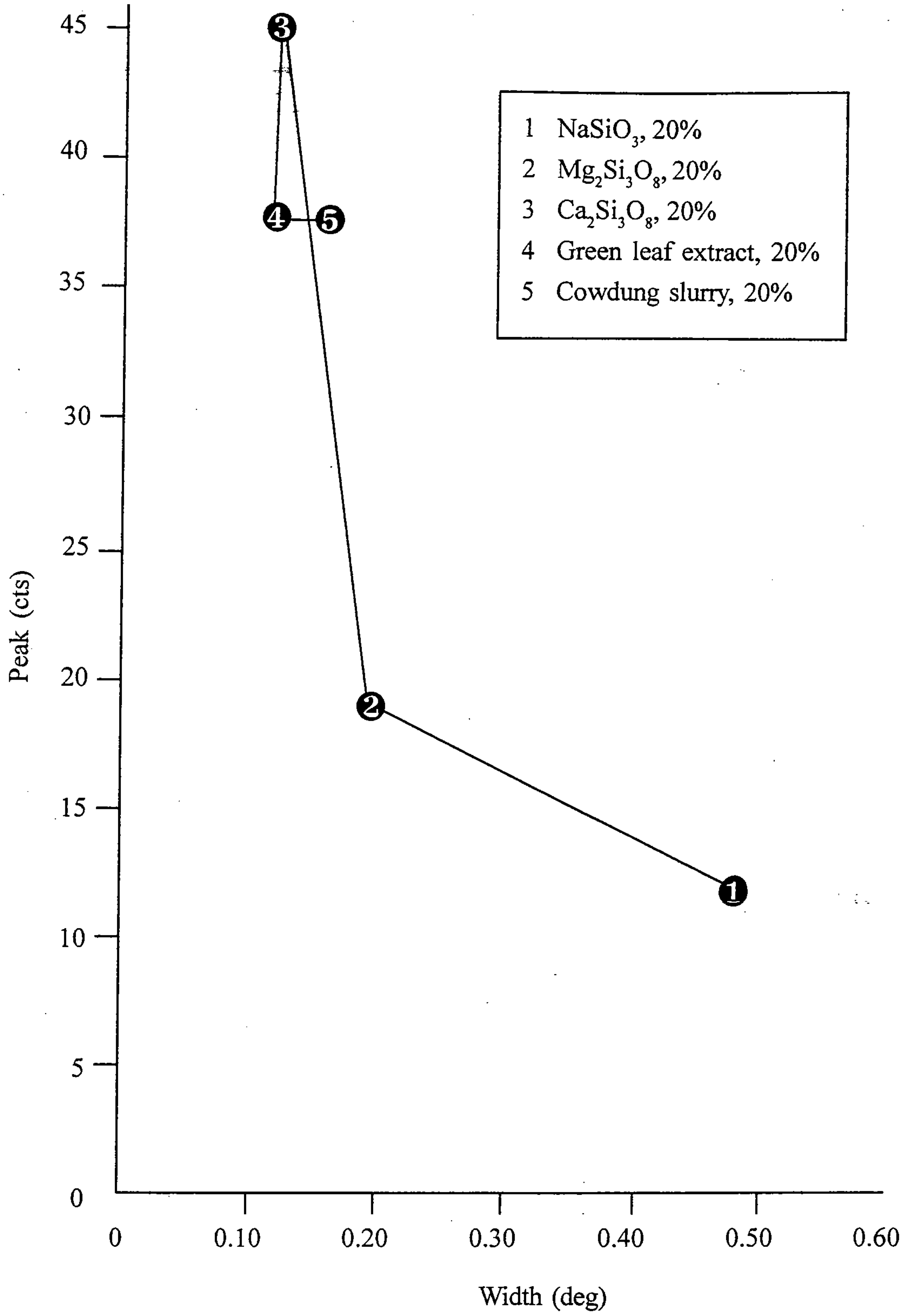


Fig. 28. Gibbsite peak vs. width due to different tretments

results indicate that though an increase in absolute amount of kaolinite couldn't be observed due to different treatments, an increase in the amount of gibbsite resulted due to the treatments of calcium silicate (20 per cent), green leaf extract (20 per cent) and cowdung slurry (20 per cent) and a higher aluminium concentration is associated with softening of laterite (Shadfan *et al.*, 1985).

The relation between aluminium substitution and penetration pressure of the laterite blocks before and after treatment is given in Fig. 29. A negative linear relationship was found between the aluminium substitution and the penetration pressure of the tested materials. Higher aluminium substitution in iron oxides is always associated with a decrease in particle size of these minerals which also results in softening of the materials (Norrish and Taylor, 1961; Thiel, 1963; Schwertmann *et al.*, 1977; Schwertmann *et al.*, 1979 and Fey and Dixon, 1981). Maximum aluminium substitution and lowest penetration pressure was recorded in samples after treatment with calcium silicate (20 per cent), green leaf extract (20 per cent) and cowdung slurry (20 per cent).

The iron oxide minerals, goethite and haematite, were more abundant in the hard laterite before treatment and both these minerals were found to be in lowest amount in the sample after treatment with calcium silicate (20 per cent), green leaf extract (20 per cent) and cowdung slurry (20 per cent). The sample before treatment showed a predominance of haematite over goethite (Table 32) and though a lowering of these iron oxide minerals could be observed after treatments, the haematite content was higher than goethite in all the treatments.

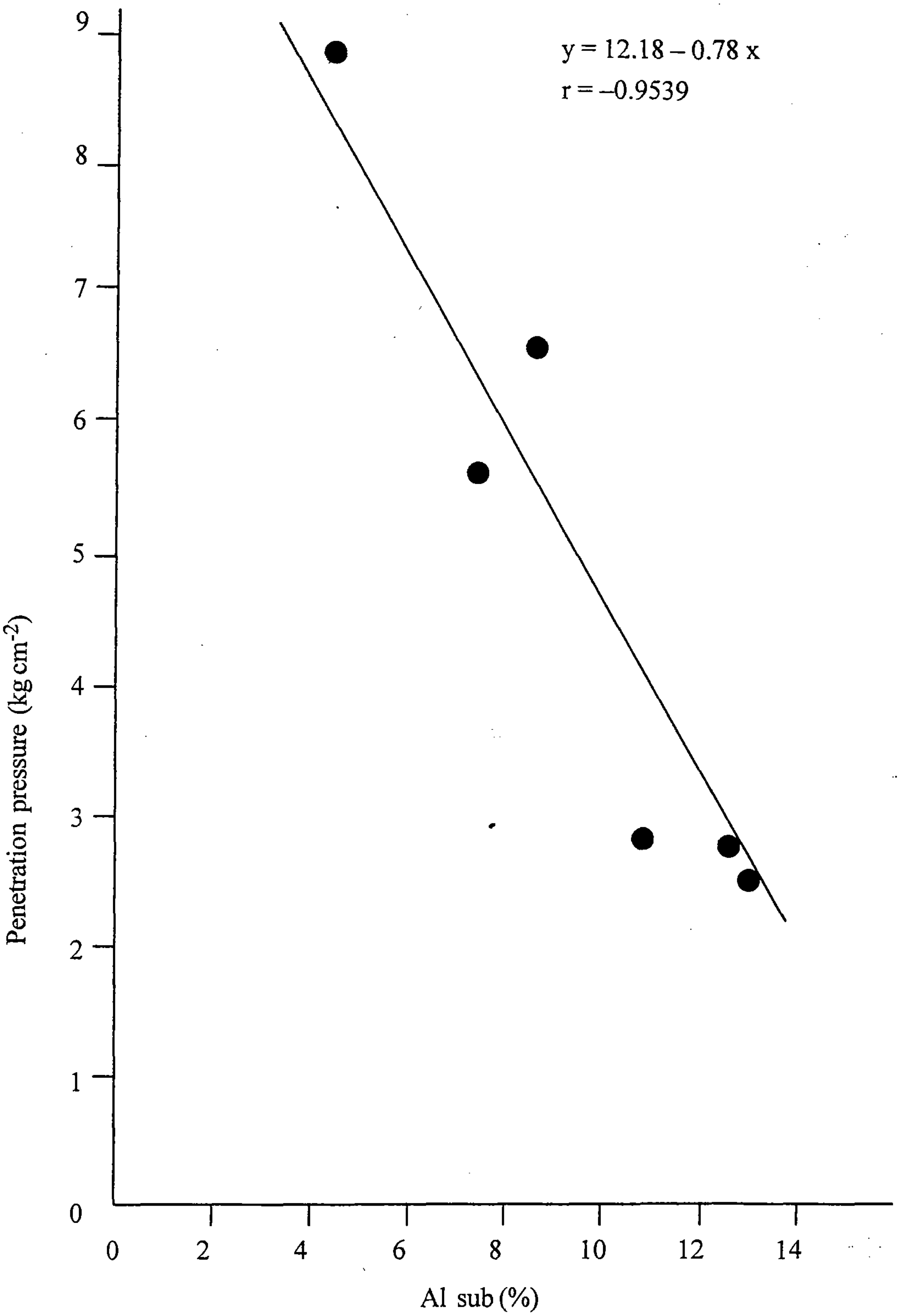


Fig. 29. Relationship between Al substitution and penetration pressure of laterite before and after treatments

Another important observation is that though the goethite content was lower in the hard laterite before treatment, it had a lower peak width at half height (Table 33) indicating the higher crystallinity of goethite than haematite. In the case of the sample after treatment with calcium silicate, though the haematite content was higher, it showed a wider peak at half height (Fig. 30) indicating the poor crystallinity or breakage of the mineral due to treatment with calcium silicate. The treatments of green leaf extract and cowdung slurry resulted in very low amount of goethite which also had a wider peak at half height (Fig. 31) showing loss of their crystallinity due to these treatments. The shift of the goethite peaks is shown in Fig. 32 which also indicates the effect of calcium silicate and cowdung slurry (20 per cent) and green leaf extract (20 per cent) treatments as softening of already hardened laterites. The shift of the peaks is due to increase in Al substitution for Fe which not only results in poor or loss of crystallinity as well as a decrease in particle size of these minerals (Schwertmann *et al.*, 1977 and Schwertmann *et al.*, 1979).

Though the mineral magnetite showed an increase after treatment with calcium silicate and magnesium silicate, if we analyse the width of peaks at half height (WHH), it can be seen that these treatments resulted in a broadening of the magnetite peaks which indicates a loss of crystallinity or poor crystallinity of the mineral which may be due to smaller size of the crystals (Shadfan *et al.*, 1985) which result in softening of the materials even if the absolute amount is higher.

In the case of lepidocrocite, though not much variation could be observed due to different treatments, no detectable quantity could be

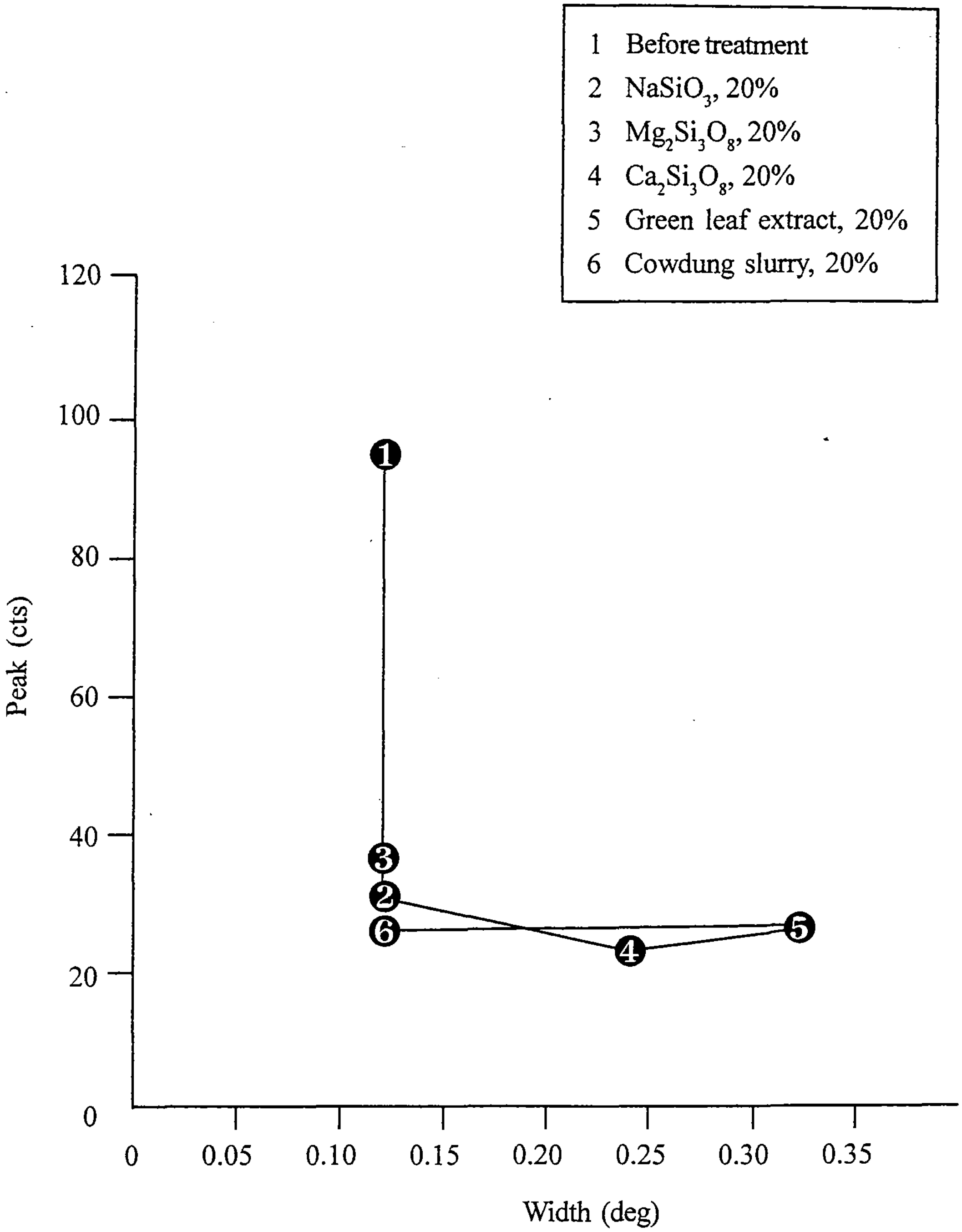


Fig. 30. Haematite (110) peak vs width due to different treatments

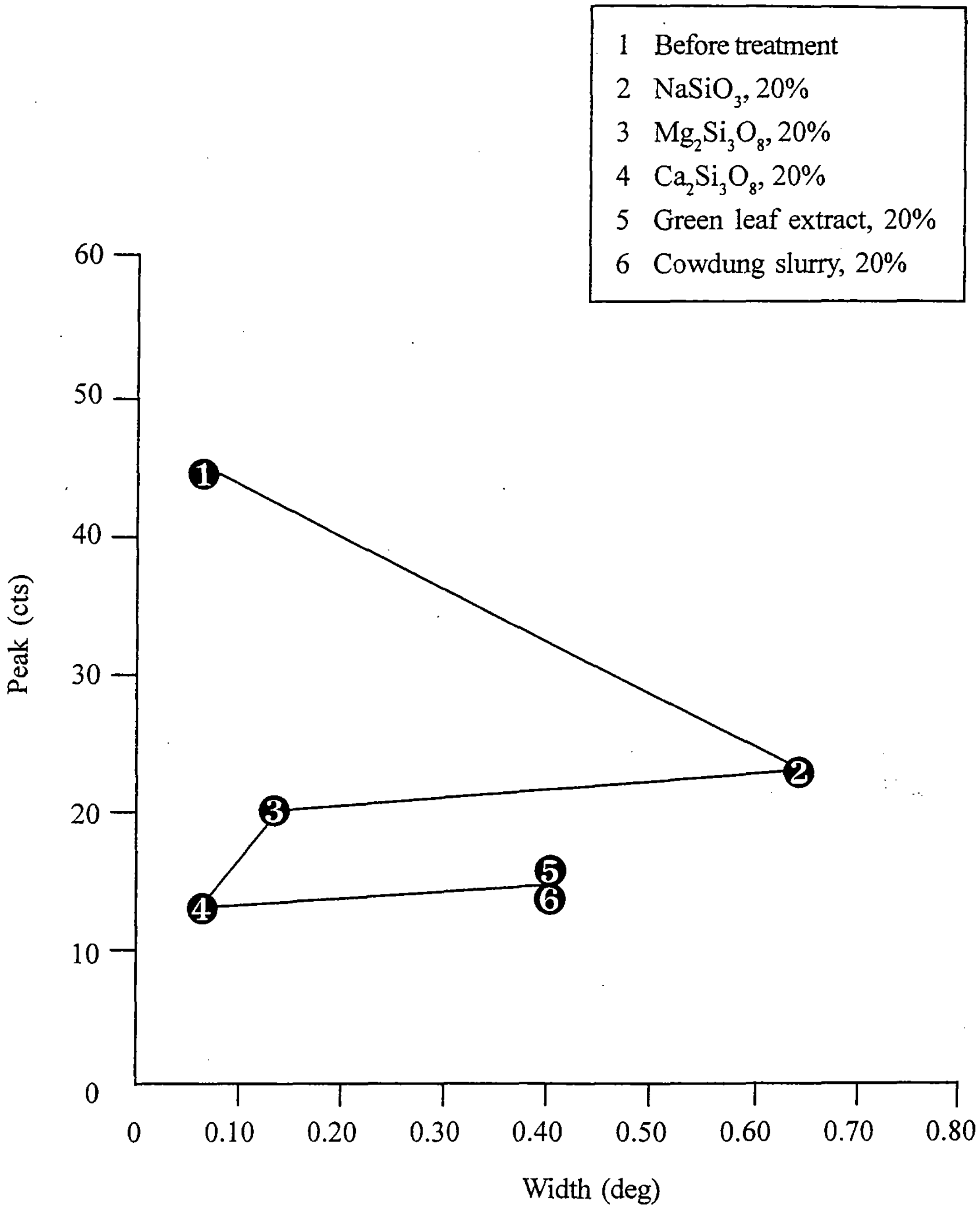


Fig. 31. Goethite (111) peak vs width due to different treatments

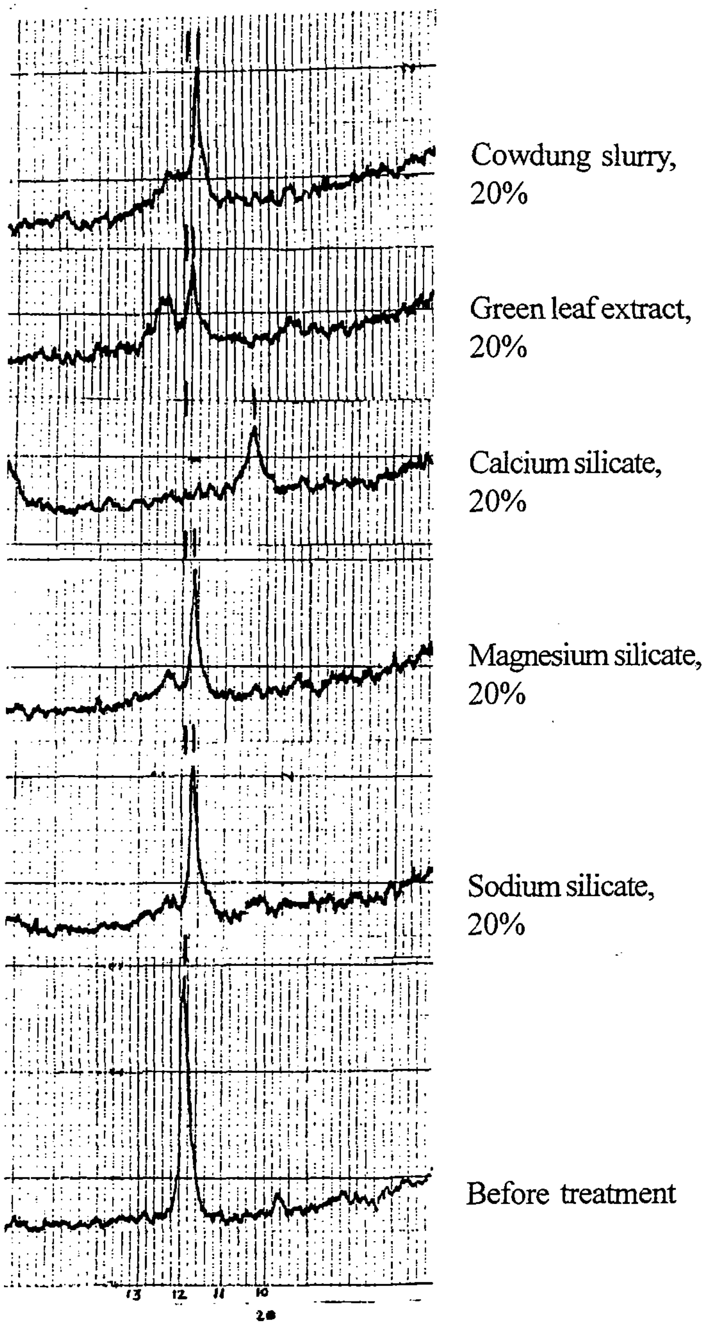


Fig. 32. Shift of the geothite peaks due to different treatments

observed after treatment with sodium silicate (20 per cent). Cowdung slurry (20 per cent) treatment resulted in a low value of 49 cts which is found to be highly crystallised as evidenced by the smallest peak width at half height.

Evidence has been reported that soil organic matter has a significant effect on weathering. By the decomposition of organic matter, a number of organic compounds are released or synthesised. Most of them, such as humic and fulvic acid, have the capacity to chelate or complex metal ions. Therefore they may be able to pry loose Al and Fe from micas, feldspars and kaolinite, accelerating in this way the decomposition process.

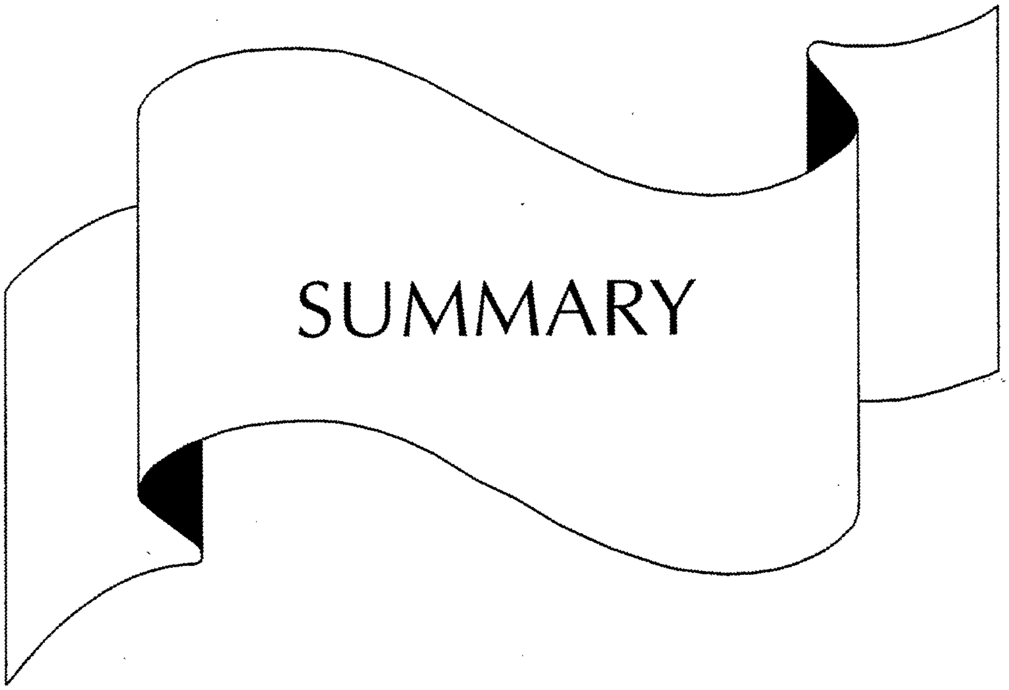
The effect of chelation on metal mobility is caused by a change in ionic behaviour. After chelation the cation is surrounded by the chelating lignands. The cation may be transformed into an anion. Anions will be repelled by negatively charged colloids. Therefore, they will remain mobile. Some of these released elements will be used for clay mineral synthesis, such as Si, Al and Fe and others will be adsorbed by soil colloids. Iron and aluminium compounds are usually insoluble at the normal pH range. However, the solubility of these substances can be increased by complex formation or chelation of iron and alumininium with soil humic compounds.

The migration of clay in soils requires that clay remains in suspension. Clay can form complexes with soil organic compounds and this increases its capacity to disperse and consequently increases its mobility within the soil system.

Kind of plants has got a significant effect on weathering. Certain plants accumulate major elements such as Si, Al, Mg, Ca and Fe. Many kind of plants, especially in the tropics, contain several per cent of silica by dry weight. Extracts of organic material from leaves of different trees have different degrees of deflocculating effects on kaolinite suspensions and this could influence weathering process.

A drastic change in the environment of alteration can lead to the regeneration of clay minerals or to the formation of new clay minerals more characteristic of an earlier stage of weathering. Regeneration of clay minerals can be the result of man-made activities.

Results of the petrological microscopic studies show that various organic and inorganic ameliorants have caused changes in the mineralogy and mineral assemblages. In plate-1 which is from the micromorphological slide of hard laterite before any treatment, it could be observed that the vacuoles are composed of kaolinite and a continuous closely crystallising network of goethite is formed and this is found as a strong rigid network. Alexander and Cady (1962), Sivarajasingham *et al.* (1962) and Eswaran *et al.* (1980) reported that hardening of laterite is related to the degree of crystallinity and continuity of the crystalline phase of the iron oxides. The present study clearly indicated that the degree of crystallinity as well as the continuity of the crystalline phase of iron oxides is affected by calcium silicate (20 per cent), cowdung slurry (20 per cent) and green leaf extract (20 per cent) treatments as evidenced by the photographs given in plates 4-6 from petrological microscopic observations of thin sections after the above treatments.



SUMMARY

SUMMARY

Pedological and management aspects of hardening and softening of laterites under different land use systems were studied in detail by selecting three study sites, viz., Thiruvananthapuram, Angadipuram and Kannur. At each location pedons were dug, in soils under cassava, rubber and uncultivated barren lying adjacent, to a depth of 2m and soil samples were collected from genetic horizons and analysis done. Apart from this, indurated laterite blocks were also collected from all the study sites and locations for detailed study of the role of iron and aluminium oxides in hardening and softening of laterites. Hard laterite block collected from a quarry in Thiruvananthapuram was used for laboratory incubation experiment to study the efficacy of organic and inorganic ameliorants in softening of already hardened laterites. The salient findings of this study are summarised here.

Study of the pedogenic environments revealed that all the study sites selected have a humid tropical climate with alternate wet and dry seasons favourable for the process of laterisation to proceed at a faster rate. Angadipuram and Kannur had L-values above 50 while the southern location at Thiruvananthapuram recorded a L-value of 35. All the three study sites have precambrian rocks as parent rock.

Pedon morphology shows that all studied profiles had a textural-B horizon (Bt_1) and a hard laterite layer (Bt_2) below it, apart from epipedon (Ap/A) and other genetic horizons. The colour of textural-B horizon varied from reddish yellow to dark reddish brown to dark red - due to oxides of iron in various degrees of hydration. All pedons belonged to the soil order Ultisols and suborder, ustults. At all the three study sites, soils under cassava and rubber came under the great group, haplustults and soils under uncultivated barren at Thiruvananthapuram and Kannur were grouped under plinthustults and that at Angadipuram under rhodustults.

An increase in bulk density down the profiles was observed and is due to significant reduction in organic matter levels as well as to clay illuviation. Pooled analysis showed a significant decrease in bulk density of epipedons of soils under rubber (1.11 Mg m^{-3}) and cassava (1.12 Mg m^{-3}), which were on par, compared to that of uncultivated barren (1.15 Mg m^{-3}). Maximum water holding capacity among epipedons as well as among Bt_1 layers under different land uses showed a significant decrease as rubber > cassava > uncultivated barren.

Among the different soil separates sand, silt and clay, clay content as well as movement were found to be significantly affected by land uses. Though the clay content of Bt_1 layer of soils under all land uses was less than 1.2 times than that of the overlying layer at Thiruvananthapuram, at Angadipuram, the clay increase was more than 1.2 times in soils under rubber (1.36) and cassava (1.36) and at Kannur, more than 1.2 times clay increase was observed only in soils under rubber (1.27). The silt/clay ratio (L/A value) at all study sites was lower than 0.25 which is considered as the critical value. The ratio was lowest in the Bt_2 layer than the overlying layers indicating that induration is more here. Pooled analysis showed no significant difference in the ratio due to land uses.

In all the profiles studied, the organic carbon and organic matter decreased significantly down the profiles. Epipedons under different land uses did not give any significant difference in organic carbon and organic matter content both at Thiruvananthapuram and Kannur. At Angadipuram, it was significantly lower in soils under uncultivated barren. When organic matter content is expressed as kg m^{-2} to a depth of 1m, both at Thiruvananthapuram and at Angadipuram, soils under uncultivated barren (20.48 and 16.94 kg m^{-2} to a depth of 1m) had a significantly lower content compared to that of other two land uses at each study site. No significant difference could be noted at Kannur.

Water dispersible clay content (WDC) decreased down in all the pedons studied. The WDC of Bt_2 layer of soils under rubber was significantly lower at all study sites indicating significant clay dispersion and more induration or hardening. In the case of epipedons, significantly lower value was observed in soils under cassava.

Loss on ignition, which constitutes both organic matter and water of constitution, of epipedons of soils under rubber was significantly higher both at Thiruvananthapuram (7.39 per cent) and at Angadipuram (10.25 per cent). At Kannur, no significant difference was observed. Pooled analysis also showed a significantly higher value for epipedons in soils under rubber (9.37 per cent) than that of cassava (8.08 per cent) and uncultivated barren (7.73 per cent), which were on par.

Basic cations like K, Ca and Mg didn't differ significantly among similar horizons under different land uses as revealed by pooled analysis of data. But leaching of basic cations is found at a faster rate in soils under rubber and cassava. This was more at locations of Angadipuram and Kannur.

With regard to downward movement of silica, at Thiruvananthapuram significant increase from surface horizon to the underlying layer was observed in soils under rubber only. While, at Kannur, this was observed in other two land uses viz., cassava and uncultivated barren. At Angadipuram, no significant increase in silica content from surface horizon to the underlying layer could be observed.

Surface horizons of soils under rubber had significantly higher Fe_2O_3 content (8.83 per cent) than that of uncultivated barren (7.90 per cent) as revealed by pooled analysis. Soils under cassava had a value (8.43 per cent) on par with other two. While the textural-B horizon (Bt_1) did not show any difference due to land uses, in hard laterite layer (Bt_2), Fe_2O_3 content was significantly higher in soils under uncultivated barren (15.18 per cent) than that of cassava (14.30 per cent) and rubber (13.82 per cent), which were on par.

The ΔpH was negative at all the study sites and it showed a gradual, though irregular, increase with depth. The highest value for ΔpH was observed in epipedon of soils under rubber followed by cassava and uncultivated barren. The hard laterite layer of soils under uncultivated barren had the highest value compared to that of other two land uses.

Exchangeable acidity of epipedons under different land uses decreased significantly as uncultivated barren (2.56 cmol kg^{-1}) > cassava (1.91 cmol kg^{-1}) > rubber (0.60 cmol kg^{-1}). Same trend was observed in hard laterite layer too. In the case of textural - B horizon, soils under cassava had a significantly higher amount of exchangeable acidity (3.90 cmol kg^{-1}) than that of rubber (3.76 cmol kg^{-1}) and uncultivated barren (3.24 cmol kg^{-1}).

The extractable acidity of epipedons as well as hard laterite layer of soils under different land uses didn't vary significantly. In the case of Bt_1 layers, soils under cassava (5.30 cmol kg^{-1}) had a significantly higher content than that of rubber (4.79 cmol kg^{-1}) and uncultivated barren (4.66 cmol kg^{-1}).

The cation exchange capacity (CEC) (sum of cations) values in all the studied pedons were higher than CEC (NH_4OAc) values. Similar horizons under different land uses didnot show any significant difference in CEC (NH_4OAc) values. The CEC (sum of cations) of the epipedons under cassava (10.15 cmol(p^+) kg^{-1}) and rubber (10.12 (10.15 cmol(p^+) kg^{-1}) were significantly higher than that of uncultivated barren (9.35 (10.15 cmol(p^+) kg^{-1}). In the case of hard laterite layer, they followed the order cassava > rubber > uncultivated barren. Hard laterite layer of soils under rubber had a significantly lower CEC (sum of cations) than that of other two land uses.

Results of pooled analysis showed no significant difference in effective cation exchange capacity (ECEC) of surface horizons under different land uses. While the Bt_1 layer of soils under uncultivated barren had a significantly lower value than that of other two land uses, the Bt_2 horizon of soils under rubber recorded significantly lower ECEC value compared to that of other two land uses.

The base saturation (sum of cations) values were lower than base saturation (NH_4OAc) values at all study sites. Base saturation (both of NH_4OAc) and sum of cations methods) values of surface horizons of soils under cassava were higher than those of rubber and uncultivated barren. Hard laterite layers of textural-B horizons under different land uses didnot show any significant difference.

While the Fe_o content decreased down the profiles from surface horizons to hard laterite, the Fe_d increased down the profiles. Among different land uses, the Fe_o was significantly higher in surface horizons and Bt_1 layers of soils under rubber than those of other two land uses. The Fe_d content didnot give any difference due to land uses, though a definite increase could be noted in the Bt_2 horizons compared to the respective overlying horizons.

The active iron ratio (Fe_o / Fe_d) showed a decreasing trend with depth and the value was significantly lower in hard laterite layer compared to the corresponding overlying layers, suggesting a higher degree of crystallinity of iron oxides in hard laterite layers. No difference could be observed in similar horizons under different land uses at Thiruvananthapuram and Angadipuram, while at Kannur, the epipedon of soils under rubber had a higher ratio than that of uncultivated barren. The ratio was less than 0.1 in all pedons indicating the high rate of ferrallitisation.

The content of crystalline iron oxides (Fe_d - Fe_o) of epipedons or Bt_1 layers didnot vary significantly due to different land uses. In the case of hard laterite layer, both soils under rubber and uncultivated barren had a significantly higher amount than that of cassava indicating the increased rate of crystallinity of iron oxides in soils under rubber than under cassava.

In the case of Bt_1 as well as Bt_2 layers under different land uses, the Al substitution in iron oxides was lower in soils under rubber than that of cassava and uncultivated barren. This also indicates the increased crystallinity and hardening of laterite in soils under rubber than under other two land uses.

A positive linear relationship was observed between the strength of materials, measured as penetration pressure, and Fe_d content. Fe_o / Fe_d ratio was significantly lower for harder spots in laterites compared to the softer spots they are associated with. A negative linear relationship was observed between active iron ratio and penetration pressure.

The per cent Al substitution in iron oxides indicates significant amount of substitution in the softer spots compared to the hard laterites they are associated with.

Studies were done on chemical, mineralogical and micromorphological changes in hard laterite upon treatment with different organic and inorganic ameliorants. Both calcium and magnesium contents in laterite were significantly increased due to treatment with different organic ameliorants such as cowdung slurry, green leaf extract and vermiwash and due to treatment with their respective chlorides and silicates. Sodium content was increased due to treatment with sodium chloride and sodium silicate.

With regard to sesquioxides, significant changes could be observed only in the case of iron. Highest value was observed in control (34.19 per cent) and lowest values could be recorded in the samples after treatment with calcium silicate, 20 per cent (19.96 per cent) and green leaf extract, 20 per cent (23.39 per cent). Other treatments like green leaf extract (both levels), cowdung slurry, 20 per cent and sodium silicate, 20 per cent also resulted in a significant lowering of iron content.

The active iron ratio was significantly increased due to treatment with calcium chloride, green leaf extract, sodium silicate and cowdung slurry. Highest value was observed in samples after treatment with calcium silicate (0.07 for both levels) and green leaf extract, 40 per cent (0.08). Increase in active iron ratio is suggested as an indicator of softening of laterites and also a relative enrichment of these samples with amorphous iron oxides than crystalline ones.

Above observation was also supported by Al substitution in iron oxides. Treatment with green leaf extract (12.36 and 13.07 per cent for higher and lower levels), calcium silicate (12.90 and 12.70 per cent for higher and lower levels), cowdung slurry (10.44 and 10.75 per cent for higher and lower levels) and sodium chloride (10.42 and 10.90 per cent for higher and lower levels) resulted in a significantly higher Al substitution in iron oxides over the control (5.90 per cent). A higher Al substitution in iron oxides indicates lower crystallinity and hardening of these samples.

X-ray diffraction (XRD) analysis of hard laterite before treatment showed a higher amount of highly crystallised kaolinite as evidenced by the width of the peaks (0.080 deg). While no appreciable amount of gibbsite could be observed in the sample before treatment, a maximum abundance of 45 cts was observed after treatment with calcium silicate, 20 per cent followed by green leaf extract, 20 per cent (37 cts) and cowdung slurry, 20 per cent (37 cts).

Goethite was maximum in hard laterite before treatment (44 cts) and lowest amount was observed after treatment with calcium silicate, 20 per cent (12 cts) followed by green leaf extract, 20 per cent and cowdung slurry, 20 per cent treatments (14 cts each). Haematite content was also maximum in hard laterite before treatment (94 cts) and least value was observed in sample after treatment with calcium silicate, 20 per cent (27 cts).

Relative abundance of magnetite was 77 cts in hard laterite before treatment which increased to 123 and 117 cts respectively after treatment with magnesium silicate, 20 per cent and calcium silicate, 20 per cent. But these two treatments resulted in a broadening of the peaks which indicated a loss of crystallinity of the mineral.

Micromorphological studies also revealed the presence of highly crystallised kaolinie in hard laterite before treatment seen as submicroscopic plates. The continuity of the crystalline phase of the impregnating iron is found to be broken after treatment with calcium silicate, 20 per cent, cowdung slurry, 20 per cent and green leaf extract, 20 per cent samples after these three treatments are found to have pisolitic forms of gibbsite, gibbsite pseudomorphs and goethite pseudomorphs.

The detailed studies conducted on the pedological and management aspects of hardening and softening of laterites have unveiled many intricate phenomena of these processes which are of great theoretical and practical importance. Contrary to the conventional concept that application of sodium chloride in laterite areas will soften it, the present study reveals the significance of amendments such as calcium silicate and application of cowdung and green manuring with leguminous crops such as *Sesbania* in softening already hardened laterites. However, it is necessary to confirm the results of these *in vitro* studies by adequate field studies in specific laterite tracts of Kerala state using these amendments.

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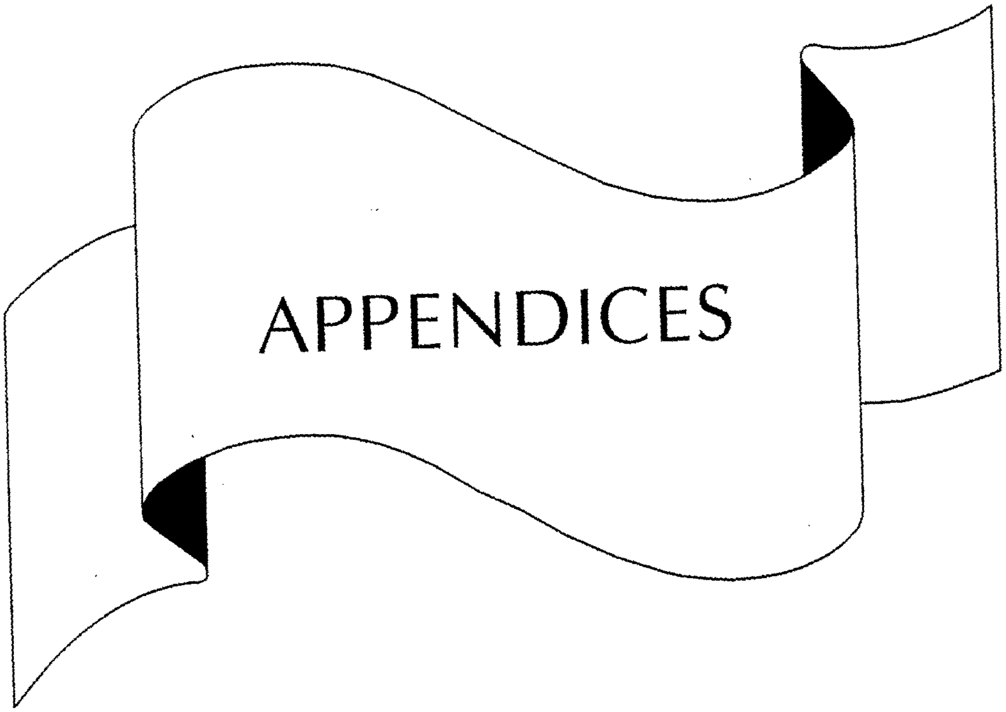

APPENDICES

Appendix 1

Results of pooled analysis of similar horizon groupings

Appendix 1.1. Single value constants

Horizon	B.D	P.D	Porosity	MWHC	Vol. Expansion
	Mgm^{-3}		%	%	%
Cassava					
Ap	1.12	2.36	39.04	38.07	1.58
Bt_1	1.21	2.54	48.82	39.15	1.47
Bt_2	1.23	2.60	49.29	36.00	1.39
Rubber					
Ap	1.11	2.36	48.41	40.07	1.62
Bt_1	1.21	2.57	49.88	40.02	1.48
Bt_2	1.24	2.62	50.06	36.30	1.41
Uncultivated Barren					
A	1.15	2.37	47.29	36.93	1.56
Bt_1	1.20	2.55	48.72	37.57	1.46
Bt_2	1.24	2.61	47.81	35.48	1.40
CD	0.01	0.02	N.S	0.62	0.02

Appendix 1.2. Mechanical Composition

Horizon	Gravel (%)	Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	Silt/clay
Cassava						
Ap	29.92	40.95	28.50	5.20	25.35	0.19
Bt$_1$	33.03	28.22	28.04	7.11	36.63	0.20
Bt$_2$	34.47	21.99	34.35	6.08	32.42	0.21
Rubber						
Ap	35.03	39.91	27.10	5.24	26.85	0.18
Bt$_1$	34.93	28.05	25.12	7.16	39.57	0.21
Bt$_2$	36.72	27.59	32.24	6.23	33.95	0.20
Uncultivated Barren						
A	37.82	41.36	22.60	5.36	20.60	0.18
Bt$_1$	33.40	29.83	32.58	5.97	31.62	0.21
Bt$_2$	33.95	25.85	36.20	5.55	32.37	0.19
CD	N.S	N.S	5.24	0.45	N.S	N.S

Appendix 1.3. Organic Carbon and Organic Matter

Horizon	O.C (%)	O.M (%)
Cassava		
Ap	2.01	3.47
Bt$_1$	0.55	0.94
Bt$_2$	0.34	0.58
Rubber		
Ap	2.01	3.46
Bt$_1$	0.85	1.46
Bt$_2$	0.41	0.71
Uncultivated Barren		
A	1.94	3.34
Bt$_1$	0.64	1.11
Bt$_2$	0.34	0.59
CD	0.06	0.10

Appendix 1.4. Water Dispersible Clay and Loss on Ignition

Horizon	WDC (%)	LOI (%)
Cassava		
Ap	2.57	8.08
Bt_1	1.87	4.27
Bt_2	1.70	1.80
Rubber		
At	2.67	9.37
Bt_1	1.82	3.61
Bt_2	1.43	2.45
Uncultivated Barren		
A	2.62	7.73
Bt_1	1.88	3.94
Bt_2	1.72	1.70
CD	0.09	0.51

Appendix 1.5. Total Elemental Analysis (per cent)

Horizon	N	P_2O_5	K_2O	CaO	MgO	Fe_2O_3	Al_2O_3	SiO_2
Cassava								
Ap	0.19	0.07	0.14	0.04	0.03	21.90	21.77	29.83
Bt_1	0.04	0.03	0.19	0.03	0.04	27.50	22.80	31.57
Bt_2	0.02	0.02	0.18	0.03	0.04	36.93	17.63	27.77
Rubber								
Ap	0.20	0.07	0.15	0.04	0.03	21.67	23.87	33.07
Bt_1	0.03	0.02	0.20	0.03	0.04	28.23	22.42	29.73
Bt_2	0.02	0.02	0.21	0.03	0.04	36.30	18.35	29.77
Uncultivated Barren								
A	0.18	0.05	0.12	0.03	0.03	22.80	23.32	29.87
Bt_1	0.05	0.03	0.17	0.03	0.03	27.07	21.23	31.10
Bt_2	0.02	0.02	0.18	0.03	0.03	36.37	16.85	28.93
CD	0.01	0.01	N.S	N.S	N.S	1.83	1.06	N.S

Appendix 1.6. Molar ratios of silica, alumina and iron

Horizon	sa ratio	sf ratio	ss ratio
Cassava			
Ap	2.35	3.71	1.43
Bt_1	2.34	3.13	1.32
Bt_2	2.80	1.99	1.15
Rubber			
Ap	2.38	3.98	1.48
Bt_1	2.29	2.75	1.23
Bt_2	2.66	2.17	1.19
Uncultivated Barren			
A	2.30	3.53	1.38
Bt_1	2.43	2.87	1.31
Bt_2	3.06	2.12	1.24
CD	NS	N.S	N.S

Appendix 1.7. Soil pH determinations

	Soil pH			
Horizon	H_2O	KCl	$CaCl_2$	NaF
Cassava				
Ap	5.03	3.60	3.58	10.28
Bt_1	5.18	3.48	3.25	10.08
Bt_2	4.95	3.38	3.13	9.60
Rubber				
Ap	5.07	3.48	3.57	10.17
Bt_1	4.40	3.43	3.30	9.63
Bt_2	5.13	3.43	3.13	9.55
Uncultivated Barren				
A	4.93	3.53	3.42	10.05
Bt_1	5.02	3.48	3.30	9.87
Bt_2	4.93	3.32	3.18	9.37
CD	N.S	N.S	0.11	N.S

Appendix 1.8. Exchangeable and extractable acidity

Horizon	Exchangeable acidity cmol kg^{-1}	Exchangeable H cmol kg^{-1}	Exchangeable Al cmol kg^{-1}	Extractable acidity cmol kg^{-1}
Cassava				
Ap	1.91	0.22	1.69	7.58
Bt$_1$	3.90	0.20	1.55	5.30
Bt$_2$	3.21	0.12	3.10	2.85
Rubber				
Ap	0.60	0.20	0.74	7.78
Bt$_1$	3.76	0.15	3.61	4.79
Bt$_2$	2.73	0.18	2.54	2.68
Uncultivated Barren				
A	2.56	0.20	2.36	7.62
Bt$_1$	3.24	0.13	1.45	4.66
Bt$_2$	3.31	0.18	0.99	2.81
CD	0.11	N.S	N.S	0.35

Appendix 1.9. CEC and ECEC

Horizon	CEC: NH_4OAc method $cmol(p+)kg^{-1}$	CEC: Sum of cations method $cmol(p+)kg^{-1}$	ECEC $cmol(p+)kg^{-1}$
Cassava			
Ap	5.75	10.15	4.27
Bt_1	4.37	6.32	4.72
Bt_2	2.38	3.42	3.67
Rubber			
Ap	6.92	10.12	4.10
Bt_1	3.90	5.72	4.53
Bt_2	2.12	3.13	3.00
Uncultivated Barren			
A	6.63	9.55	4.28
Bt_1	3.85	5.58	4.20
Bt_2	2.38	3.38	3.70
CD	N.S	0.13	0.21

Appendix 1.10. Sum of bases and per cent base saturation

Horizon	Sum of bases	PBS (%) NH$_4$OAc	PBS (%) Sum of cations
Cassava			
Ap	2.58	38.08	25.41
Bt$_1$	1.03	23.93	16.64
Bt$_2$	0.58	24.14	16.88
Rubber			
Ap	2.34	33.51	22.93
Bt$_1$	0.93	23.48	16.08
Bt$_2$	0.46	21.71	14.70
Uncultivated Barren			
A	1.93	28.82	20.03
Bt$_1$	0.93	23.78	16.45
Bt$_2$	0.58	24.13	16.98
CD	0.63	6.81	4.98

Appendix 1.11. Free oxides of Iron and Aluminium

Horizon	Fe_o (%)	Fe_d (%)	Al_o (%)	Al_d (%)
Cassava				
Ap	0.17	2.19	0.09	0.76
Bt_1	0.18	2.83	0.08	0.59
Bt_2	0.12	4.58	0.07	0.54
Rubber				
Ap	0.19	2.86	0.09	0.77
Bt_1	0.20	3.42	0.08	0.56
Bt_2	0.13	6.02	0.07	0.45
Uncultivated Barren				
A	0.16	2.56	0.08	0.76
Bt_1	0.17	2.76	0.06	0.64
Bt_2	0.13	6.36	0.05	0.54
CD	0.01	N.S	N.S	0.03

Appendix 1.12. Relationship between different forms of free oxides of iron and aluminium

Horizon	$\frac{Fe_o}{Fe_d}$	Fe_d-Fe_o (%)	Al_d-Al_o (%)	Aluminium substitution (%)
Cassava				
Ap	0.07	2.46	0.68	21.67
Bt_1	0.07	2.66	0.51	17.38
Bt_2	0.03	4.46	0.48	9.86
Rubber				
Ap	0.07	2.67	0.68	19.15
Bt_1	0.06	3.22	0.48	14.07
Bt_2	0.02	5.89	0.38	6.08
Uncultivated Barren				
A	0.07	2.41	0.68	22.21
Bt_1	0.06	2.27	0.58	18.69
Bt_2	0.02	6.23	0.49	7.45
CD	N.S	0.85	0.03	N.S

PEDOLOGICAL AND MANAGEMENT ASPECTS OF HARDENING AND SOFTENING OF LATERITES UNDER DIFFERENT LAND USE SYSTEMS

By

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ABSTRACT OF THE THESIS
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ABSTRACT

Crop production on laterite and associated soils have been found to be low due to constraints such as hardening and hard crust formation. However, there is considerable scope for improving the productivity of these acid soils through proper land management. It is generally agreed that iron plays a key role in the hardening process and in crust formation in the tropics. In the highly laterised soils of Kerala, cassava and rubber form the major crops involving entirely different management systems. So far no study has been conducted on the effect of different land use systems on hardening and softening of laterites as well as on the effect of different ameliorants in softening of already hardened laterites.

Three study sites were selected viz., Thiruvananthapuram, Angadipuram and Kannur. At each location, pedons were dug in soils under cassava, rubber and uncultivated barren lying adjacent, to a depth of 2m and soil samples were collected from genetic horizons and various analysis done. Apart from this, indurated laterite blocks were collected from all the study sites and locations for detailed study of the role of iron and aluminium oxides in hardening and softening of laterites. Hard laterite block collected from a quarry in Thiruvananthapuram was used for laboratory incubation experiment to study the efficacy of organic and inorganic ameliorants in softening of already hardened laterites.

From the detailed investigations on the physico-chemical characteristics related to hardening and softening of laterites, it has been observed that hardening and softening of laterites have been affected by the land uses and great variation could be recorded for parameters like bulk density, clay content and movement, organic matter, water dispersible clay and iron content.

The bulk density of epipedons was significantly higher in soils under cassava and uncultivated barren compared to that of rubber. Though the clay content of Bt_1 layer of soils under all land uses was less than 1.2 times than that of the overlying layer at Thiruvananthapuram; at Angadipuram, the clay increase was more than 1.2 times in soils under rubber (1.36) and cassava (1.36) and at Kannur, more than 1.2 times clay increase was observed only in soils under rubber (1.27).

Both at Thiruvananthapuram and Angadipuram soils under uncultivated barren had a significantly lower organic matter content (expressed as kg m^{-2} to a depth of 1m) compared to that of other two land uses at each study site. No significant difference could be noted at Kannur. With regard to water dispersible clay content of Bt_1 layer, soils under rubber had a significantly lower value at all the three study sites indicating significant clay dispersion and more induration or hardening. The total iron was significantly higher in soils under uncultivated barren than that of cassava and rubber.

Among the various soils acidity parameters studied, the exchangeable acidity of textural-B horizon was significantly higher in soils under cassava than that of rubber and uncultivated barren. Same trend was observed for extractable acidity too in this layer.

The active iron ratio showed a decreasing trend with depth and the value was significantly lower in hard laterite layer compared to the corresponding overlying layers. A ratio of less than 0.1 in all pedons indicated a high rate of ferrallitisation. The crystalline iron oxide content was significantly higher in soils under rubber than that of cassava indicating the increased rate of crystallinity of iron oxides in soils under rubber compared to soils under cassava.

A positive linear relationship was observed between the strength of materials, measured as penetration pressure, and Fe_d content of laterite and a negative linear relationship was observed between strength of materials and active iron ratio of laterite.

Studies on the efficacy of organic and inorganic ameliorants in softening of already hardened laterite showed a significant increase in basic cations as well as decrease in iron content due to treatments with organic ameliorants such as cowdung slurry, 20 per cent and green leaf extract, 20 per cent. Other treatments like calcium silicate (20 per cent), magnesium silicate (20 per cent) and sodium silicate (20 per cent), resulted in a significant increase in the respective basic cations as well as a decrease in total iron.

Treatment of laterite with green leaf extract (20 per cent), calcium silicate, cowdung slurry and sodium chloride resulted in a significantly higher Al substitution in iron oxides over the control.

X-ray diffraction (XRD) studies showed a loss of crystallinity of iron oxides especially goethite, haematite and magnetite after treatment with calcium silicate (20 per cent), cowdung slurry (20 per cent) and green leaf extract (20 per cent). The gibbsite content also showed an increase in its content after the above three treatments. Relative abundance of both goethite and haematite was more in the sample before treatment and a least value was observed in the sample after treatment with calcium silicate (20 per cent).

Thin section studies using a petrological microscope showed the presence of highly crystallised kaolinite in hard laterite before treatment seen as submicroscopic plates. The samples after treatment with calcium silicate (20 per cent), cowdung slurry (20 per cent) and green leaf extract (20 per cent) are found to have pisolitic forms of gibbsite pseudomorphs and goethite pseudomorphs.

The detailed studies on the pedological and management aspects of hardening and softening of laterites under different land use systems have unveiled many intricate phenomena of these processes which are of great theoretical and practical importance. Contrary to the conventional concept that application of sodium chloride will soften hard laterites, this study reveals the importance of amendments such as calcium silicate and application of cowdung and green manuring with leguminous crops such as *Sesbania* in softening already hardened laterites. However, it is necessary to confirm the results of these *in-vitro* studies by adequate field studies in specific laterite tracts of Kerala state using these amendments.