Sulphur dynamics in major rice-growing soils of Kerala

By

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THESIS

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DECLARATION

I, hereby declare that this thesis entitled **"Sulphur dynamics in major rice-growing soils of Kerala"** is a bona-fide 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, fellowship or other similar title, of any other university or society.

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Certified that this thesis, entitled **"Sulphur dynamics in major rice-growing soils of Kerala"** is a record of research work done independently by **Mr. Unnikrishnan, R.** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associate ship to him.

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We, the undersigned members of the Advisory Committee of **Mr. Unnikrishnan R (2016-21-029)**, a candidate for the degree of **Doctor of Philosophy in Agriculture** with major in **Soil Science and Agricultural Chemistry,** agree that the thesis entitled **"Sulphur dynamics in major rice-growing soils of Kerala"** may be submitted by Mr. Unnikrishnan R. in partial fulfilment of the requirements for the degree.

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Introduction

1. INTRODUCTION

Soil is the basic medium for agriculture, in which all food producing plants grow. Plants require 17 essential elements for growth, of which, carbon, hydrogen and oxygen are derived from the atmosphere and soil water, while the remaining 14 are supplied either from soil minerals and soil organic matter or by organic or inorganic fertilizers. Healthy soils are the foundation of the food system. Advances in agricultural technology and increased demand due to a growing population have put our soils under increasing pressure, jeopardizing the productive capacity of soils and its ability to meet the needs of future generations. Management of nutrient elements is one of the major environmental constraints in farming. Fertilizer best management practices focus on maximizing crop yield while minimizing the amount of nutrients that are lost from the soil system through surface run off or leaching.

Sulphur is one of the essential elements required for both plants and animals, which in turn, is playing a crucial role in many reactions in the living cells. This secondary nutrient element is best known for its role in the formation of amino acids *viz.*, methionine, cystine and cysteine which are essential for the synthesis of proteins and chlorophyll, oil content of the seeds and improving the nutritive quality of forages (Tandon 1986: Jamal *et al.,* 2005, 2006 and 2009). Use of high analysis, low S fertilizers, utilization of high yielding varieties, intensification of agriculture, declining use of farm yard manure and S containing fungicides, significant reduction in SO_2 emissions as a result of national policies to reduce concentrations of primary air pollutants have led to a negative S balance in many parts of the world (Scherer, 2001), including some parts of India. Deficiency of S is higher in areas cropped with oilseeds and pulses owing to the increased removal of S by these crops. Among the major soil groups, S deficiency was mainly reported in light textured soils particularly alluvial (Entisols, Inceptisols), coastal alluvial, laterites (Oxisols), and red (Alfisols) soils (Naik and Das, 1964).

Kerala, commonly referred to as 'Gods Own Country' stretches as a narrow belt along the south-western portion of India sand witched between Western Ghats in the east and Lakshadweep in the west. For the people of Kerala, rice is the staple food and its cultivation has occupied a pride of place in the agrarian economy of the State as early as 3000 B.C. The lush green paddy fields are one of the most captivating features of the State's landscape. It is grown in a wide range of ecological niches ranging from regions situated 3 meters below MSL as in *Kuttanad* to an altitude of 1400 meters in purely rainfed uplands with no standing water as in high ranges like Wayanad. However, Palakkad district, along with *Kuttanad* region in Alappuzha and coastal areas in Thrissur district constitute the main rice producing regions. To describe further on the rice growing soils focused in the study, the *Onattukara* sandy soils are confined to the Onattukara region comprising Karunagapally, Karthikapally and Mavelikara taluks of Kollam and Alappuzha districts. The soils are coarse textured, very deep, well drained, low in organic matter, acidic and deficient in plant nutrients and bases.

Poonthalppadam or slushy paddy land soils are found in lowlands of Chittoor taluk in Palakkad district. These are base rich fertile clayey soils, near neutral in reaction, imperfectly drained, medium in organic matter and poor in workability.

Black cotton soils are identified in alluvial plains, terraces and undulating plains of Chittoor taluk in Palakkad district in patches. These soils are very deep, black and calcareous, possessing high shrink-swell capacity, and hence, exhibiting the characteristic cracking during dry periods withneutral to moderately alkaline pH (ranging from 7 to 8.5).

Kari soils of *Kuttanad* lies 2-2.5 m below MSL. *'Kari'* literally means 'Charcoal' and these soils are abnormally black in colour and rich in organic carbon, often spotted with deeply buried, partly burnt out big pieces of timber specimens of ancient periods. The lower pH of the *Kari* soils of *Kuttanad* is due the formation of sulphuric acid, both by the oxidation of pyrites and by the conversion of organic form of sulphur to sulphuric acid brought about by the sulphur oxidizing and sulphur reducing bacteria present in the soil.

The *Kole* wetlands region, with a vast expense of fields below sea level spread across the districts of Thrissur and Malappuram in an area of 13,632 ha. The principal cultivated crop here is rice. The Malayalam word *Kole* roughly means 'luck' or bumper yield, a reference to the nature of cultivation in these regions. Soils are classified mainly under acid saline category with the exception of those formed from river alluviums and sulphur rich marine deposits and some areas along the coast, which come under the category of potential acid sulphatesoils.

Pokkali is a unique mode of rice production system in central Kerala using saline tolerant rice varieties cultivated exclusively in an organic away in the water logged acid saline soils in the coastal regions of Ernakulam, Alappuzha and Thrissur districts of Kerala extending to a total area of 6274 ha. The name *Pokkali* has originated from the traditional variety of rice called *Pokkali*, In Malayalam, *Pokkali* means "One who grows tall". The origin, genesis and development of these soils have been under peculiar physiographic conditions, making it distinctive from saline soils occurring in other parts of the country.

The low land brown hydromorphic laterite soils have been formed as a result of transportation and sedimentation of material from adjacent hill slopes and also through deposition by rivers. Presence of laterite and gravel suggests that these are formed by the action of gravity. The lateritic soils are acidic, deep, poorly drained, low to medium in organic matter and deficient in plant nutrients, with high level of iron.

Most of the soils in Kerala are rich in total S and the maximum amount of sulphates has been reported in *Kari* and *Pokkali* soils (Jacob, 1966). With the exception of coastal sandy soils, available S was found sufficient in soils of Kerala (Rajasekharan *et al.,* 2014). For predicting the S supplying power of soils and to manage it accordingly, a sound understanding of the S mineralization process is essential. But in a soil system, the mineralization process is often beyond prediction for the reason that the elements combine with soil organic matter and also because of the interdependent nature of C, N and S cycles (Parton *et al*., 1988). Though sulphur is increasingly being recognized as the fourth major plant nutrient after nitrogen, phosphorous and potassium in regulating plant growth and production, when compared to nitrogen, there has been little conceptualization to help design S fertilization strategies for cropping systems.

The way nutrients are taken up, retained, transferred, and cycled over time and distance in an ecosystem (Allan and Castillo, 2007) is broadly defined as nutrient dynamics, an extensive knowledge, on which warrants the sustenance of crop productivity by improving nutrient use efficiency.

A knowledge on the dynamics of sulphur and its interaction with other nutrients can contribute muchfor arriving at better management practices with reference to sulphur fertilizers in the major rice growing soils of Kerala. Literature available in this line is limited for want of comprehensive studies on this direction. It is against this backdrop that the present investigation has been framed with three major objectives viz;

- To understand sulphur dynamics in major rice soils of Kerala.
- To figure out the relationship of sulphur with carbon, nitrogen and phosphorous
- To unfold the antagonism/ synergism between sulphur and other nutrients, if any

Review of literature

2. REVIEW OF LITERATURE

Sulphur, one of the critical plant nutrients in agriculture is a naturally occurring element that supports more efficient use of Earth's resources. It acts as a crucial source to slow down the loss of productive land from soil erosion. Sulphur is tagged as an 'advantaged element' and can deliver numerous benefits in variety of areas. The importance of S in agriculture and its role in crop production is being greatly emphasized (Jamal *et al.,* 2005). Plants take up and use S in the sulphate form, which like nitrate (NO_3 -N), is highly mobile in the soil and is subjected to leaching in wet soil conditions, particularly in sandy soils.

This element is essentially required in the formation of proteins and coenzymes whose metabolism usually starts with sulfate reduction. Soil must be regularly replenished with a balance of crop nutrients, like macronutrients, secondary nutrients and micronutrients in order to achieve higher yield production in agricultural crops. Sulphur (S) ranked as fourth major nutrient next to N, P and K. Sulphur occurs naturally as an element found in many minerals like iron pyrites, galena, gypsum and epsom salts. In Igneous and Sedimentary rocks S occurs as sulphides, in soil it is present as organic compounds, contained in industrial wastes, sea water as well as gaseous emission in the atmosphere. It is assumed that more than 95 per cent of total S in soil is present in the organic matter due to low decomposition rate especially under temperate conditions.

In India rice plays a major role in diet and economy and it covers 20 per cent of total gross cropping land (Mohanty and Yamano, 2017). Paddy cultivation is practicing in wide range of climatic conditions extending from 44° N latitude in North Korea to 35° S latitude Australia. It is cultivated at 6 feet below sea level and 2700 feet above sea level also.

The literature available that forms a part of this research project are classified in this section under ten titles.

2.1 Sulphur status in soil

2.1.1 Global Scenario

The increased removal of sulphur as higher yields in the current developing world has made sulphur deficiency a widespread problem. On an elemental basis, the overall crop sulphur requirements are somewhat similar or in some cases exceed the phosphorus requirements and hence the amount of sulphur removed by crops forms a substantial part of deficiency problems. According to a study conducted on regional plant nutrient sulphur balance in 2010, it gets revealed that China and India may present the largest long-term deficits while Europe has suffered sulphur deficiency problems due to environmentally mandated restrictions (Ceccotti *et al.,* 1998).

MacKenzie (1995) reported that the sulphur deposited on European fields had fallen from around 50 kg ha^{-1} in a year in the late 1970s to less than 10 kg at present. Wheat and other cereals seriously get affected by sulphur deficiencies in many countries such as the United Kingdom, Sweden, Denmark, Germany, and France (Schnug, 1992).

2.1.2 Indian scenario

Sulphur as a protein component is an essential element for plant growth, its deficiency thus adversely affecting the plant growth and its yield. At present, widespread deficiency of macro, secondary and micronutrients are emerging in agricultural lands. In the last two to three decades, increase in sulphur deficiency is becoming more crucial leading to reduction in crop yield, unbalancing nutrient level and distressing soil health.

Singh and Rao (2001) concluded that a mean sulphur deficiency of 41 per cent exists in the soils of Indian states. In India, sulphur deficiencies are exhibited by most of the soils and are most prevalent in the soils of Punjab, Haryana, Himachal Pradesh, Uttar Pradesh, Rajasthan, Bihar, West Bengal and many parts of the Southern India. Of the major soil groups, sulphur deficiency was mainly reported in light textured soils particularly alluvial (Entisols, Inceptisols), coastal (Alluvial), laterites (Oxisols), and red (Alfisols) (Naik and Das, 1964).

The scenario of S deficiency is more predominant in the states where cereal based cropping system is being followed (Gill and Singh, 2009).

In India, nearly half of the cultivated soils are deficient in available S and good crop yield responses to S application have also been reported (Singh, 2001;

Biswas *et al.,* 2004; Tandon, 2011). It is well proven that sulphur is a yield increasing as well as quality yield producing nutrient (yield + quality nutrients).

The S deficiency is remarkably increasing all around the world due to the use of high-analysis - low S containing fertilizers, decreased farm yard manure application resulting in low S returns, high yielding varieties and intensive agriculture, declining use of S containing fungicides and reduced atmospheric input caused by stricter emission regulation. The S deficiency in soils of India is caused by growing of sulphur responsive crops, high intensive cropping and use of sulphur free fertilizers (Tandon and Tiwari, 2007).

2.1.3 Kerala scenario

Sulphur deficiency is more likely to be reported in light and shallow soils with low organic matter content with highest deficiency in calcareous and waterlogged soils. Most of the soils in Kerala are rich in total S and the maximum amount of sulphate has been reported in *Kole* land as well as *Pokkali* soils (Jacob, 1966). Cicy (1989) reported that the *Kari* soils of Kuttanad had remarkably good non-sulphate S content.

From a massive project undertaken by the Kerala State Planning Board in collaboration with a consortium of Central and state government institutions including Kerala Agricultural University to identify and map the soil related constraints for crop production, it was reported that available sulphur is sufficient in soils of Kerala, with the exception of coastal sandy soils. Further it was identified that continuous application of sulphur containing fertilizers like ammonium phosphate sulphate might have corrected the deficiency of sulphur (Rajasekahran *et al.,* 2014).

2.2 Sulphur input to soil

Sulphur inputs to the soil system originate from three major sources, viz. mineral weathering, atmospheric deposition and organic matter decomposition. Sulphur in soils can be categorized into two major forms viz. organic and inorganic. The leaf litter inputs contribute to most of the total S pool in soils which is composed of organic fractions. Soil sulphate may originate from atmospheric deposition, fertilizer addition or mineralization of soil organic S, which is the main sulphur fraction in soil. Replenishment of sulphur in soils was made possible through the use of indigenous sources of sulphur for achieving higher crop yield and quality in eastern states of India (Singh and Singh, 2016)

Reddy *et al.* (1988) concluded that the sulphur content of cereal plants generally falls within the range of 0.16 - 0.25 per cent where less than 0.20 per cent is considered sub optimal for most of the cereals.

2.3 Sulphur concentration in plants

The variation among sulphur requirement of different crops is dependent on the genetic character of the crops. Even within the same crop, different varieties varied greatly with respect to the sulphur content. Generally, S content was estimated to be high in oilseeds and pulses as compared to cereals and other crops. The concentration of S is higher in the grains than in straw taking the widest differences among cruciferous crops and legumes being the smallest (Aulakh *et al.,* 1985).

2.4 sulphur in rice nutrition

Sulphur is very much beneficial for increasing the production of rice and is one of the major essential nutrient elements involved in the synthesis of chlorophyll, certain amino acids like methionine, cystine, cysteine and some plant hormones such as thiamine and biotin (Rahman *et al.,* 2007).

Rice farmers usually apply high amounts of nitrogen, phosphorus and potassium leading to an imbalance between offtake and input of nutrients followed by fertility decline and increased deficiencies of nutrients like zinc and sulphur. Rice plants will continue to grow weIl only if they receive an adequate supply of sulfur and other nutrients throughout much of their growing period. This sulfur may come from the soil, irrigation or rainwater, by absorption from the atmosphere or from applied manures or fertilizers. Rice plants remove between 8 and 17 kg S ha^{-1} from a paddy soil, depending on variety, to yield between 4 and 9 tonnes of grain per hectare (Wang,1978)

Rice plants have the capacity to transmit oxygen absorbed via the stomates of leaf blades and leaf sheaths, or produced during photosynthesis, through air passages in the leaves, stems, nodes and roots to the surrounding soil or soil solution (Armstrong,1969; Barber *et al.,*1962 and Bristow,1975)

2.5 Factors affecting sulphur availability in soil

The soil organic matter acts as the primary source of plant available SO_4 in surface soil. The occurrence of most of the sulphur (>95%) as sulphate esters or as C-bonded sulphur rather than inorganic sulphates is well explained by chemical and spectroscopic studies (Kertesz and Mirleau, 2004).

Soils that are sandy, low in organic matter and found in upper to mid-slope field positions are particularly prone to S deficiency since only a small amount of SO_4 sulphur is released from organic matter which is susceptible to leaching loss.

The different soils contain varied ratio of organic carbon to organic sulphur but a value of 100:1 is often used (Tabatabai, 2005).

It was found that the soil pH was increased by application of limestone and soil mixing to the strongly acidic soil of an area. The microbial activity was assessed by measuring the dehydrogenase activity and hence the mineralizable carbon status was increased. An increase in soil pH values stimulated the diversity as well as microbial activity, resulting in an increased soil enzymatic activity and thus affecting nutrient cycling. The sulphur availability was found to decrease with increase in soil pH as both exhibit significantly negative correlation between themselves (Sarkar *et al.,* 2006).

Beena and Thampatti (2013) stated the extremely acidic nature of Kuttanad soils with a pH range varying from 2.5 to 5.2. Significant and negative correlation was drawn between S mineralization and pH (Tabatabai and Al-khafaji, 1980).

The increased electrical conductivity values can be attributed to the sea water intrusion during summer months in the Kuttanad region of Alappuzha, Kerala (Aparna *et al.,* 2020).

2.6 Sulphur interaction with other nutrients

The sulphur in soil exists both in organic and inorganic forms. However when it comes to plant nutrition, the inorganic form of sulphur i.e. sulphate is considered as the most crucial one as it is directly taken up by the plants (Tisdale *et al.,* 1985). Generally 90 – 95 per cent of soil sulphur is found to be organically bonded with organic sulphur present in upper soil horizons. The sulphate mainly exists as sulphates of Na, K, Ca and Mg in soil solution (Sutar *et al.,* 2017).

The sulphate-S has a tendency to get readily leached from the soil surface. The leaching is at its highest when the solution contains monovalent ions such as K^+ and Na^+. However leaching losses are very less in acidic soils due to the presence of good amounts of exchangeable Al^{3+} and hence do not affect plant growth to a greater extent (Erickson, 1996).

The adsorbed sulphate is an important source of sulphur with respect to the highly weathered soils in regions of high rainfall containing predominantly Al and Fe oxides (Sequioxides) (Sutar *et al.,* 2017). The nature of colloidal system, soil pH, the sulphate concentration and concentration of other ions in the solution are key factors that determine the retention of absorbed sulphates in soils (Harward and Reisenaur, 1966).

Jansen and Bettany (1984) stated the respective uptake of S and N by application of these elements but the effect of N on S uptake varied according to S application rate. Non-significant relationship between S and N in rapeseed was reported by Singh *et al.* (1980). But the N content increased significantly with the application of S. Some other plants also had the similar interaction. The synergistic effect of combined application of S and N on the uptake of these nutrients by maize and rapeseed was confirmed by various studies (Fazli *et al.,* 2008)

Calcium sulphate is obtained from calcareous soil precipitates with calcium carbonate thus forming an insoluble complex. This form of sulphur is unavailable to plants unless a solution is formed which is a tedious process. Decrease in soil pH with increase in soil moisture content increases the availability of such sulphur (Prasad, 2007).

Sulphur exists in both organic as well as inorganic forms in agricultural land with organic S accounting for > 95 per cent of the total S. Analysis of wide range of soils reveals that around 25 to 75 per cent of the organic S in soils is HIreducible, 7 to 30 per cent is C-bonded, and finally 11 to 22 per cent remains as unidentified S. Nitrogen is associated with S in soil organic matter in a ratio of about 8:1 although the extreme ratios may vary from 5:1 to 13:1 (Tabatabai ,1984).

The findings of Kannan *et al.* (2014) revealed that the organic carbon status of *Kuttanad* ranged from 2.79 to 7.70 per cent. According to them the waterlogged condition associated with rice cropping might have enhanced the accumulation of organic carbon. The hydrologic regime played a role in organic matter accumulation (Stolt *et al.,* 2000)

In major soils of South Kerala, the different forms of sulphur have significant and positive correlation with organic carbon, total nitrogen, phosphorous, calcium, magnesium and sesquioxides and negative correlation with soil pH (Sheeba, 1991).

N: S ratios greater than 10:1 may be too great for optimum canola production which typically requires an N: S ratio of 7:1. Hence it is important to estimate the plant-available S levels in soil and if the soil is found S deficient, supplemental S fertilization may be required. Thus increased S concentration leads to decreased N: S ratio (Coyle and McAleese, 1970). They also found that the N: S ratio in wheat grain and barley grain declined from 11-28 to 10-17 and 26-28 to 8-10 due to sulphur fertilization. Kowalenko and Lowe (1975) observed the reduced S mineralization with increased N: S ratio (due to addition of N).

Shivay *et al.,* 2014 concluded that the N: S ratio reduced from 9.77 to 7.79 on application of S at 45 kg S ha^{-1}.

N: S ratio determines the sulphur metabolism in plants. The N: S ratio is similar in proteins (about 15:1) present in the vegetative organs of all crop species and the total ratio of these elements is around 12:1. The sulphur deficit results in the accumulation of non-protein nitrogen compounds that affect the spike in N: S ratio above the characteristic level for proteins (Jakubus, 2006). Similar results were achieved by Benedycka *et al.,* 1983. The N: S ratio is a sensitive indicator of sulphur supply to plants (Boreczek *et al.*, 2001). Plant growth disorders resulting from sulphur deficiency are manifested by the reduced biological value of crops.

Generally low N: S ratios, adequate for the biological value are found in luxurious and highly productive plants (Uziak *et al.,* 1982, Grygierzec *et al.,* 2015).

C: S ratio in the biomass may vary rapidly depending on S availability (Niknahad *et al.,* 2008).

Generally, agronomic crops require the same amount of S as P. Although the S content of plants varies depending on the availability of supply, some crops have greater S requirements than others.

Another factor that affects the S requirement of plants is the available N. Sulphur and nitrogen are closely related in protein synthesis thus S requirements of plants may vary with the supply of N to the crop. Hence when S becomes limiting, addition of N do not cause any increase in crop yield (Dijkshoorn and Wijk, 1967). Fazli *et al.* (2008) reported the limited efficiency of added N in the absence of S, thus S addition becomes crucial to obtain the maximum output from applied nitrogenous fertilizers.

The rise in organic S content was similar to that for C but greater than that of organic N and P. The results obtained indicate that S levels can be maintained or increased even under intensive cropping when adequate quantities of crop residues are regularly returned to soil. Addition of crop residues to soil under the minimum or no-till system however may significantly reduce the plant-available S and consequently may result in the increased application of S fertilizers (Larson *et al.,* 1972).

2.7 Soil enzyme in sulphur transformations

Soil sulphur is continuously being cycled between organic and inorganic S forms. McGill and Cole (1981) explained S mineralization through biological and biochemical mineralization. The microbial community present in soil determine the rate of S cycling (Kertesz and Mirleau, 2004). Biological mineralization occurs when microorganisms use compounds containing C-bonded S as C sources and sulphate is released as the byproduct. Biochemical reaction takes place through the synthesis of arylsulphatase activity when the microbial S requirements are not met by the sulphate levels (Tabatabai and Dick, 2002).

Dick *et al.* (2000) concluded that both soil fertility as well as crop production are affected by soil pH and biological processes including enzyme activities.

The dominance of enzymatic activity in the surface soils might be owed to the abundance of microbial population in the surface layers due to the accumulation of organic matter in those layers (Kalembasa and Kuziemska, 2010). Organic S compounds are available to plants but need to be converted by biochemical or microbial mineralization to inorganic SO_4^{2-} for plant uptake (Castellano and Dick, 1991).

Sulphatases are enzymes belonging to class esterase that catalyze the hydrolysis of ester sulfates, where the linkage with sulfate is in the form of R–O–S where R represents a diverse group of organic moieties. Sulphatases occur in different forms in nature, including arylsulphatases, alkyl sulphatases, steroid sulphatases, glucosulphatases, chondrosulphatases, and mycosulphatases. Arylsulphatase catalyzes the hydrolysis of ester-bonded S by fission of the O–S linkage in them. (Germida *et al.*, 1992; Haneklaus *et al.,* 2007). Most of the studies conducted have been directed to arylsulphatase which was the first detected sulphatase in nature (Fitzgerald, 1978).

A study conducted on arylsulphatase showed that soil arylsulphatase activity increased with increase in temperature up to 57 °C but got decreased thereafter (Trasar-Cepeda *et al.,* 2007). Arylsulphatase activity gets inactivated at temperatures ranging from 60 to 70 °C (Tabatabai and Bremner, 1971). Arylsulphatase activity was significantly interrelated with soil organic matter content (Tabatabai, 1994; Klose *et al.,* 1999; Knights *et al.,* 2001).

The inhibition of arylsulphatase activity by trace elements is revealed by a study titled with Effects of trace elements on arylsulfatase activity in soils, the inhibition by MoO_4^{2-}, WO_4^{2-}, AsO_4^{3-}, and PO_4^{3-} shows competitive kinetics. At concentrations of 25 mmol g^{-1} of soil, some common soil anions like NO_2, NO_3, Cl and SO_4 are not inhibitors of this enzyme (Khafaji and Tabatabai, 1979).

It is suggested based on the studies that arylsulphatase activity is linked to S supply because the biochemical mineralization relies on the release of sulphate from the ester sulfate fraction through enzymatic hydrolysis and the majority of the mineralizable soil organic S is in the ester sulfate form (Speir and Ross, 1978).

There are lots of enzymes in soil such as oxidoreductases, hydrolases, isomerases, lyases and ligases. Each of them play an important role in biochemical functions in the overall process of material and energy conversion (Gu *et al.,* 2009).

Dehydrogenases (DHA) play a significant role in the biological oxidation of soil organic matter (OM) by transferring hydrogen from organic substrates to inorganic acceptors (Zhang *et al.,* 2010).

The higher DHA was observed in flooded soil rather than in non-flooded conditions. The higher DHA values in flooded conditions coincided with the results presented by Weaver *et al.* (2012).

The Cysteine desulphydrase (CDA) enzyme plays an important role in the catalysis of desulphydration of cysteine liberating equimolar quantities of pryruvate, hydrogen sulphide and ammonia. CDA activity is widely distributed among bacteria and fungi (Ohkishi *et al.,* 1981).

Skiba and Wainwright (1983) reported the presence of CDA in coastal sand dunes.

2.8 Sulphur fractions

Sulphur in soil can be broadly grouped into five forms - total S, organic S, non-sulphate S, available S and water soluble S. The nature and amount of various forms of S depends on variation in soil texture, pH, calcium carbonate, organic matter and other soil characteristics (Xiao et al., 2015). The influence of various soil factors on availability of sulphur and hence the variations in status of different sulphur forms based on soil types was reported by Balanagoudar and Satyanarayana (1990).

The total S content in soils is present in varied amounts depending upon its content in primary minerals, organic compounds, sulphate ions adsorbed and present in soil solution. Takkar (1988) reported the extent of S content variations among and within soil types as well as regions as far as India’s tropical climate as well as agro-ecosystems with different soils**.** The considerable variation in the total sulphur content in soils might be the result of varied cropping systems and parent materials (Aggarwal and Nayyar, 1998).

Bhatnagar *et al.* (2003) reported the significant and positive interrelation between total S and soil organic matter. Similar conclusions were drawn by Aggarwal and Nayyar (1998) and Trivedi et al. in 1998. Negative correlation between pH and total S was reported by Sharma and Gangwar (1997). Patel *and* Patel. (2008) also observed similar relationship between the same.

The tropical soils of India generally contain lower total S content compared to temperate zone soils. Since the total S content is a function of soil organic matter or organic S, lower S reservoir in tropical soils of India would have resulted from its poor organic matter content (Takkar, 1988).

The estimated total and available sulphur in some soils of Chhotanagpur area of Bihar (now in Jharkhand) showed that it was remarkably high in alkaline soils while the total S was highest in acidic soils (Mahto *et al.* 1992).

The distribution of total soil Sulphur in Indian soils experience a wide variation probably due to several soil forming factors like parent materials, climatic conditions, degree of weathering, amount of organic matter etc. In general, the soil S is highest in the top soil and decreases with depth whereas this pattern does not occur where sulphates get deposited in lower layers (Takkar, 1988).

The relative total S content in the soils of West Bengal was lower than that of soils of Uttar Pradesh despite having fine textured soils (Kanwar and Mohan, 1964; Bhan and Thripathi, 1973). The coastal saline soils of West Bengal had three times more S content when compared to normal soil due to the accumulation of sulphate salts from sea water (Mukhopadhyay and Mukhopadhyay, 1980).

The red soils of Andhra Pradesh had high S content (Prasad *et al.,* 1983). The S content was comparatively less in highly weathered lateritic soils. The total S can be correlated significantly and positively with clay content (Halder and Bharthakur, 1976). Acid soils contain comparatively higher S content than alkaline soils (Kanwar, 1976).

The cultivated soils had markedly low S content than forest soils due to decreased organic matter (PA).

The surface soils of India has the total S content ranging between 20 mg kg^{-1} to as high as 9750 mg kg^{-1}. The total S in agricultural soils varied from 50 to 300 mg kg^{-1} though an average of 576 mg kg^{-1} was observed in certain alluvial soils of Bihar (Tandon, 1991). According to Hegde (1980), more than 10 per cent of the total S gets accumulated as available-S in hilly red and alluvial paddy soils.

The significantly positive relationship of organic-S with organic carbon indicated a simultaneous increase in the status of organic-S in soil (Sharma and Gangwar, 1997). Organic S was found to exhibit significant and negative correlation with pH, $CaCO_3$, clay and CEC. It showed significant and positive relationship with organic carbon, silt and total N (Bhatnagar *et. al*. 2003). Up to 98 per cent of the total soil S is present as organic S compounds and is associated with heterogeneous plant residues, animals and soil microorganisms (Bloem, 1998).

Soils with high organic sulphur content also had high total S. The lower proportion of inorganic S compared to organic S could be due to leaching of inorganic S and its conversion to organic form by plants in hills and terai soils (Mukhopadhyay and Mukhopadhyay, 1980). Since S in Indian soils is a major constituent of organic matter, the content of S is determined by the amount and nature of organic matter in soil.

Stevenson (1986) reported that 1 - 3 per cent of the soil organic S is associated with microbiological biomass whereas more recent studies reveal that the microbiological biomass S generally accounts for 1.5 – 5 per cent of total organic S (Banarjee *et al.,* 1993).

The organic S content was interrelated significantly and positively with silt plus clay fractions in the Langarian series of Sangrur (Ahmed and Jha, 1969). The higher altitude soils had relatively higher S supplying capacity than lower altitude soils due to narrowed C: organic S ratio of the former than the latter (Joshi, 1984).

Ruhal and Palliwal (1980) stated the significant correlation among different fractions of S except total S.

Sulphate- S exhibited significantly positive interrelation with organic carbon and EC wherein a negative correlation with CaCO3 (Chaudhary and Shukla, 2002). They also concluded that an increase in soil pH resulted in increased sulphate retention by soils. In soils having high pH and those with low sulphur retention, sulphate is likely to behave more like nitrate while in acid soils and those with large amount of sesquioxides, the behavior of sulphate could be somewhat similar to that of phosphate.

Ghai (1980) reported that sulphate sulphur correlated significantly and positively with electrical conductivity in Alluvial soils of Ludhiana. Similar inference was given by Cheema and Arora (1984).

The soil pH significantly and negatively correlated with non sulphate S and total S. EC and organic carbon was found to have positive correlation with sulphate S, water soluble S, heat soluble sulphur, organic sulphur and total S (Sutaria, 2016).

Bhatnagar *et al.* (2003) reported that total S appears to be a function of soil organic matter as both are significantly and positively interrelated.

Negative relationship between pH and total S was also reported by Sharma and Gangwar (1997).

In Indian soils, organic fraction accounts for 2 to 71 per cent of total sulphur. In terms of proportion of total sulphur, this fraction is opposite to that of organic sulphur fraction. On an average, non-sulphate sulphur constituted 22 per cent of total sulphur in hill and Tarai soils but 66 per cent in alluvial soils. The total as well as non-sulphate sulphur increased with depth in several soil profiles from Northern Karnataka which was due to leaching and its subsequent precipitation as gypsum crystals (Misal *et al.,* 2017). Cicy (1989) reported that the *Kari* soils of Kuttanad had remarkably good non sulphate S content.

2.9 Sulphur adsorption in soils

The behavior of sulphate in soils of tropics has received less attention compared to temperate regions although considerable S deficiencies has been reported from several areas of humid tropics. (McClung *et al.,* 1959; Bolle-Jones, 1964; Fox *et al.,* 1965; Muller, 1965; Hasan *et al.,* 1970). Sulphate adsorption was identified to follow the order- alluvial soils <red soils <lateritic soils regardless of the concentration of sulphate solution employed (Dolui and Nandi, 1989). Sulphate got adsorbed more on subsurface horizon than surface soil (Williams and Steinbergs, 1962).

Sulphate content was high in the soils of volcanic origin from St. Vincent and Monserrate clay from Trinidad and the sorption increased with increase in sulphate concentration up to the highest concentration used (Fox, 1969). Sulphate accumulation in the lower horizons of soils high in iron and aluminium oxides was reported both in tropics (Bornemisza, 1959) and under temperate conditions (Ensminger, 1954).

Gokila *et al.* (2017) reported the irreversible nature of sulphate sorption capacity as the main reason for S deficiency which largely depends on the pH, amorphous and crystalline Fe and Al content, available phosphorus, organic carbon content, clay, Ca and Mg. They also suggested that the available sulphate content of these soils further moderated the adsorption of sulphur in soil.

The amount of sulphate adsorbed at low concentrations of dissolved sulphate was in accordance with the Langmuir equation. However, at higher concentrations this relationship broke down which could be due to differing adsorption sites (Haque and Walmsley, 1973). Haque and Walmsley (1973) stated the relation of sulphate adsorption to the percentage of NaOH-extractable aluminium in the soil and no correlation with Fe_2O_3 content. On the contrary, Biswas *et al.* (2003) reported that Fe and Al oxides were the deciding factors in the retention of sulphate in soil and they suggested the suitability of Freundlich equation to describe sulphate adsorption in soil.

The amount of sulphur that gets adsorbed is important from the point of view of sulphur storage in soil profiles as a means of avoiding losses in soils of humid area or during rainy season of sub humid areas.

The amount of sulphate adsorbed by soils increased with the raise in sulphate concentration in equilibrium solution. Similar observations were also drawn by Murthy (2004).

The sorption capacity of soils varied widely and followed the order-coarse textured soils < fine textured soils < medium textured soils (Sharma and Sankhyan, 2020). The sulphate concentration in soil solution as provided by the sorption/ desorption isotherms gives an estimation of S availability to plants (Kimsey *et al.,* 2005).

Sulphur adsorption significantly and negatively correlated with soil pH. The high S adsorption at low pH could be explained by the protonation of hydroxyl groups on the surface of iron and aluminium oxides. Sulphate ions would get attached to positive charges generated in this manner when non-specific adsorption occurs. But in the case of specific adsorption, hydroxyl ions would be displaced by sulphate ions according to the protonation mechanism proposed by Hingston *et al.,* 1968.

The sorption capacity of the soils varied widely and followed the order: medium > fine > coarse textured soils.

2.10 Desorption of sulphur

Some soils used for adsorption study of sulphur has the capacity to retain sulphate which makes it important from the agricultural point of view to know whether the adsorbed sulphate in those soils gets easily desorbed and also on its availability to plant growth. In subsurface horizon, the amount of sulphur released decreased with depth which indicated high sulphate accumulation by adsorption. In surface horizon, lower quantities were adsorbed with higher organic matter content and sulphate was readily desorbed. On the other hand, sub surface soils exhibited sulphur desorption below the amount adsorbed for all levels of adsorbed sulphur.

The major forms of S in soils based on relative extractability and plant availability includes – sulphate (SO_4 -S) ions in the soil solution, sulphate S adsorbed in inorganic colloids, inorganic compounds in insoluble forms (pyrite and marcasite (FeS_2), pyrrhotite (Fe1-xS) and chalcopyrite ($CuFeS_2$), and organic S compounds (Thiols, disulfides, polysulfides and ester sulphates). The sulphate ions get mainly adsorbed by clay minerals and Fe/Al oxides as well. The adsorption also increases with decrease in pH below 5.5 (Pigna and Violante 2003).

The smaller the constant value related to desorbed S mobility (kd), lesser is the sulphur desorption thereby suggesting a need for fertilization in soils (Dutta, 2009).

Materials and methods

3. MATERIALS AND METHODS

The present study titled 'Sulphur dynamics in major rice-growing soils of Kerala' was carried out at College of Agriculture, Kerala Agricultural University during 2016-2019. In order to carry out the research programme, major rice growing tracts of the state coming under 6 Agro-ecological units (AUE) were selected, viz; namely *Onattukara* sandy soil (AEU 3), *Poonthalppadam* (AEU 23), Black cotton soils of Chittoor (AEU 23), *Kari* soils of Kuttanad (AEU 4), *Kole* lands of Thrissur (AEU 6), *Pokkali* (AEU 5) and Low land brown hydromorphic laterite (AUE 10). The location details on soil sample collection are given in table 1.

Table 1. Soil sampling locations with soil taxonomy and agro ecological units

Soil sample No	Soil type	Location	Soil taxonomy	Agro-ecological unit
1	Black cotton (1)	Muthalamada N 10.61176 E 76.75469	*Vertic Haplustepts / Typic Hapluserts*	AEU 23
2	Black cotton (2)	Muthalamada N 10.61259 E 76.75566	*Vertic Haplustepts / Typic Hapluserts*	AEU 23
3	Black cotton (3)	Muthalamada N 10.61237 E 76.75479	*Vertic Haplustepts / Typic Hapluserts*	AEU 23
4	Black cotton (4)	Muthalamada N 10.61267 E 76.75486	*Vertic Haplustepts / Typic Hapluserts*	AEU 23
5	Black cotton (5)	Muthalamada N 10.61233 E 76.75559	*Vertic Haplustepts / Typic Hapluserts*	AEU 23

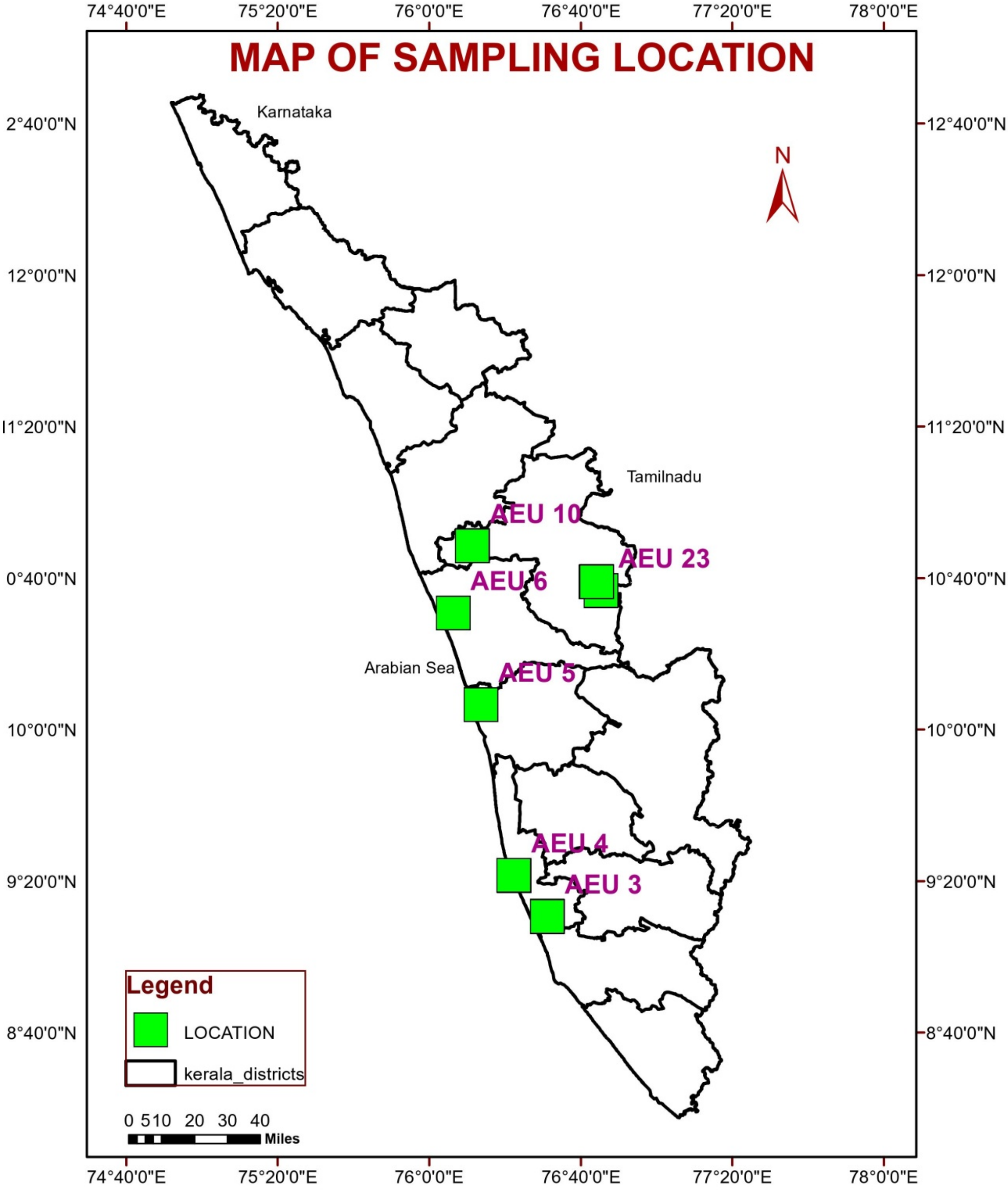
Soil sample No	Soil type	Location	Soil taxonomy	Agro-ecological unit
6	Low land brown hydromorphic laterite (1)	RARS, Pattambi N 10.80953 E 76.19020	*Typic Tropaquepts* and *Aeric Tropaquepts*	AEU 10
7	Low land brown hydromorphic laterite (2)	RARS, Pattambi N 10.80979 E 76.18974	*Typic Tropaquepts* and *Aeric Tropaquepts*	AEU 10
8	Low land brown hydromorphic laterite (3)	RARS, Pattambi N 10.81003 E 76.18941	*Typic Tropaquepts* and *Aeric Tropaquepts*	AEU 10
9	Low land brown hydromorphic laterite (4)	RARS, Pattambi N 10.80995 E 76.18893	*Typic Tropaquepts* and *Aeric Tropaquepts*	AEU 10
10	Low land brown hydromorphic laterite (5)	RARS, Pattambi N 10.80991 E 76.18811	*Typic Tropaquepts* and *Aeric Tropaquepts*	AEU 10
11	*Onattukara* sandy soil (1)	RARS, Onattukara N 9.17650 E 76.51951	*Typic Ustipsamments*	AEU 3
12	*Onattukara* sandy soil (2)	RARS, Onattukara N 09.17982 E 76.51892	*Typic Ustipsamments*	AEU 3
13	*Onattukara* sandy soil (3)	RARS, Onattukara N 09.17676 E 76.51842	*Typic Ustipsamments*	AEU 3
14	*Onattukara* sandy soil (4)	RARS, Onattukara N 09.17899 E 76.5199	*Typic Ustipsamments*	AEU 3

Soil sample No	**Soil type**	**Location**	**Soil taxonomy**	**Agro-ecological unit**
15	*Onattukara* sandy soil (5)	RARS, Onattukara N 9.17796 E 76.51888	*Typic Ustipsamments*	AEU 3
16	*Poonthalppadam* (1)	Pattanchery N 10.65133 E 76.73333	*Humic Epiaquepts*	AEU 23
17	*Poonthalppadam* (2)	Pattanchery N 10.65146 E 76.73709	*Humic Epiaquepts*	AEU 23
18	Poonthalppadam (3)	Pattanchery N 10.65159 E 76.73644	*Humic Epiaquepts*	AEU 23
19	*Poonthalppadam* (4)	Pattanchery N 10.65187 E 76.73647	*Humic Epiaquepts*	AEU 23
20	*Poonthalppadam* (5)	Pattanchery N 10.65114 E 76.73713	*Humic Epiaquepts*	AEU 23
21	*Kole* lands (1)	Chiratta kadavu N 10.51276 E 76.10497	*Typic Sulfihemists/Sulfic Epiaquepts*	AEU 6
22	*Kole* lands (2)	Chiratta kadavu N 10.51286 E 76.10537	*Typic Sulfihemists/Sulfic Epiaquepts*	AEU 6
23	*Kole* lands (3)	Chiratta kadavu N 10.51341 E 76.10544	*Typic Sulfihemists/Sulfic Epiaquepts*	AEU 6

Soil sample No	Soil type	Location	Soil taxonomy	Agro-ecological unit
24	*Kole* lands (4)	Chiratta kadavu N 10.51361 E 76.10563	*Typic Sulfihemists/Sulfic Epiaquepts*	AEU 6
25	*Kole* lands (5)	Chiratta kadavu N 10.51316 E 76.10488	*Typic Sulfihemists/Sulfic Epiaquepts*	AEU 6
26	*Pokkali* (1)	N 10.11069 E 76.22678	*Salidic Sulfaquepts*	AEU 5
27	*Pokkali* (2)	N 10.11109 E 76.22639	*Salidic Sulfaquepts*	AEU 5
28	*Pokkali* (3)	N 10.11113 E 76.22638	*Salidic Sulfaquepts*	AEU 5
29	*Pokkali* (4)	N 10.11025 E 76.22680	*Salidic Sulfaquepts*	AEU 5
30	*Pokkali* (5)	N 10.10973 E 76.22695	*Salidic Sulfaquepts*	AEU 5
31	*Kari* soils (1)	Purakkad N 09.21483 E 76.22350	*Typic Sulfohemists / Sulfic Endaquepts*	AEU 4
32	*Kari* soils (2)	Purakkad N 09.358744 E 76.37260	*Typic Sulfohemists / Sulfic Endaquepts*	AEU 4
33	*Kari* soils (3)	Purakkad N 09.358919 E 76.37152	*Typic Sulfohemists / Sulfic Endaquepts*	AEU 4

Soil sample No	Soil type	Location	Soil taxonomy	Agro-ecological unit
34	*Kari* soils (4)	Purakkad N 09.357858 E 76.37344	*Typic Sulfohemists / Sulfic Endaquepts*	AEU 4
35	*Kari* soils (5)	Purakkad N 09.358994 E 76.37187	*Typic Sulfohemists / Sulfic Endaquepts*	AEU 4

Plate 1. Map of sampling locations



3.1 Collection of soil samples and analysis

Representative soil samples were collected from seven different rice growing tracts falling under different agro-ecological units (AEU) of Kerala during first crop season, whereas the samples for initial characterisation were collected one week prior to cultivation. From each location, five representative soil samples were collected before cropping and another three samples each were collected during active tillering stage of the rice crop and after crop harvest. In addition, three plant samples each were also collected at active tillering stage of rice crop and after harvest depicting each location.

Since the present study was aimed at examining the sulphur dynamics, farmers of the experimental locations were requested to keep away from the regular practice of applying N P complex fertilizer ammonium phosphate sulphate (20: 20 : 0 : 13) in field, which was accepted and adopted by the farming community in true sprits by choosing the sulphur free fertilizer sources, di ammonium phosphate (18 : 46 : 0) to supply nitrogen and phosphorus to the rice crop. This change over encouraged a lot to arrive at much reliable values on soil sulphur status of the major rice growing tracts of the state.

Table 2. Details on rice varieties and planting time across the locations

Sl. No	Location	Varieties	Season
1	Black cotton soils of Chittoor	Ponni	April-May to Sep-Oct *(Virippu)*
2	Low land brown hydromorphic laterite	Jyothi	April-May to Sep-Oct *(Virippu)*
3	*Onattukara* sandy soil	Bhagya	April-August *(Virippu)*
4	*Poonthalppadam* -Slushy paddy land soils	Uma	April-May to Sep-Oct *(Virippu)*
5	*Kole* lands	Uma	August-Sep to Dec-Jan *(Mundakan)*
6	*Pokkali* soil	Vyttila-1	May-June to Sep-Oct *(Virippu)*
7	*Kari* soils of Kuttanad	Uma	June-July to Sep-Oct

Plate 2. An overview on soil types covering the experimental locations

3.1.1 Procedure for sampling

Soil sampling was done in a way to accurately represent the soil of the field in each locations using either a core sampler or Spade based on prevailing soil conditions, from 0-20 cm depth. In case of *Kari* soils of Kuttanad, *Pokkali* soils and *Kole* lands, utmost care was taken not to disturb the reducing condition to ensure which samples were sealed as such soon on collection. The samples thus collected were processed and stored in clean containers and used for further analysis

3.1.2 Expression of result of wet analysis

For expressing the results of wet analysis, the moisture content of the samples were estimated gravimetrically. In order to find out the moisture percentage, an initially weighed soil (W1) sample was kept in a hot air oven at 105 °C and dried to constant weight and was again weighed (W2). Percentage of moisture = [(W1-W2)/W1] x 100. This method of moisture correction can be further explained through an example- suppose a soil contains 60 per cent moisture, then the actual percentage weight of the soil on wet basis will be 40 per cent. Hence, if 5g soil is taken for analysis, the actual weight on dry weight basis will be =5x 40/100= 2 g.

3.1.3 Soil analysis

The procedure adopted for soil analysis are detailed below.

3.1.3.1 Soil pH

The pH of the soil samples were determined potentiometrically in a 1:2.5 soil water suspension using a glass electrode in the 'ELICO' pH meter (Jackson, 1958).

3.1.3.2 Electrical conductivity

Electrical conductivity was estimated using the supernatant liquid of the same soil water suspension (1:2.5) used for pH determination with the support of a glass electrode in the 'ELICO' electrical conductivity meter (Jackson, 1958).

3.1.3.3 Cation Exchange Capacity

Cation exchange capacity was measured using neutral normal ammonium acetate extraction method (Piper, 1966).

3.1.3.4 Organic carbon

Wet digestion method proposed by Walkley and Black (1934) was adopted for the determination of OC content of soil using potassium dichromate and ferrous ammonium sulphate.

3.1.3.5 Bulk density

Bulk density of the soil samples were determined using the core method (Carter and Gregorich, 2007).

3.1.3.5. Soil temperature

Soil temperature was measured at 15 cm soil depth using a soil thermometer.

3.1.3.6 Soil texture

Texture of soil samples were determined by International pipette method (Robinson, 1922). Soil sample weighing 20 g was taken in a 500 mL beaker, 10 mL of 30 per cent hydrogen peroxide solution was added to the beaker and heated on a hot plate to destroy the organic matter. The dispersion of soil particles was ensured by adding 8 mL of 1 N NaOH. The contents were then transferred to a spoutless cylinder of 1000mL capacity after proper stirring and was kept undisturbed. Nextly a quantity of 20 mL suspension was pipetted out from the undisturbed cylinder based on the sedimentation time. After oven drying the weight of clay and silt particles were found out. The sediments were washed and finally oven dried to estimate the weight of sand particles.

3.1.4 Available nutrients

3.1.4.1 Available nitrogen

The available nitrogen in the soil samples were analysed by alkaline permanganate method (Subbiah and Asija, 1956) using 0.32 per cent $KMnO_4$ and 2.5 per cent NaOH. The released ammonia was absorbed in 5 per cent boric acid containing mixed indicator and titrated against 0.02 N H_2SO_4.

3.1.4.2 Available phosphorous

The available phosphorous in collected soil samples were estimated using Bray No.1 reagent (Bray and Kurtz, 1945) for soils having pH below 6.5 and Olsen's method (Olsen *et al.*, 1954) for soils with pH above 6.5. Available phosphorus content was estimated colorimetrically by reduced molybdate ascorbic acid blue colour method (Watanabe and Olsen, 1965) using Spectrophotometer

Plate 3. Instruments used

Spectro photometer

ICP-OES

CHNS analyser

3.1.4.3 Available potassium, calcium and magnesium

The available potassium, calcium and magnesium in the soil samples were extracted using neutral normal ammonium acetate. The available potassium content in the sample was estimated using flame photometry (Jackson, 1958) whereas the available calcium and magnesium were estimated using Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES ;Model Perkin- Elmer Optima 8000).

3.1.4.4 Available sulphur

The available sulphur in soil samples were extracted using 0.15 per cent $CaCl_2$ (Williams and Steinberg, 1959; Tabatabai, 1982) and estimated by turbidimetry (Massoumi and Cornfield, 1963) using spectrophotometer (Model; Systronics 169).

3.1.4.5 Available micronutrients (Av.Fe, Av.Cu, Av. Mn and Av.Zn)

The available micronutrients in the soil samples were extracted using 0.1 M HCl (Sims and Johnson, 1991) for soils having pH below 6.5 and 0.005 M DTPA and 0.01 M $CaCl_2.2H_2O$ buffered at a pH of 7.3 by 0.1 M triethanolamine (TPA) for soils having pH greater than 6.5 (Lindsay and Norwell, 1978). The filtrate was later collected and analysed for Fe, Cu, Mn and Zn using ICP-OES (Model Perkin- Elmer Optima 8000)

3.1.4.5 Available boron

Available boron in the soil samples were extracted using hot water (Berger and Trug, 1939; Gupta, 1972) and boron content was estimated in ICP-OES (Model Perkin- Elmer Optima 8000)

3.1.5 Microbial biomass carbon (MBC)

Microbial biomass carbon was estimated by fumigation method. For this 5 sets of 10 gram soil was taken of which one set was set aside for moisture determination, two sets were kept for fumigation with ethyl alcohol free chloroform in a vacuum desiccator for 24 hrs and the remaining two sets were maintained as non fumigated samples. Soil samples were transferred to a 250 mL conical flask and 25 mL of 0.5 M K_2SO_4 was added and then shaken for 30 minutes. After shaking, the suspension was filtered through Whatman No 1 filter paper. From the filtrate, 10 mL was taken for titration in a 500 mL conical flask. To 2 mL of 0.2 N $K_2Cr_2O_7$ and 5mL of H_2SO_4 was added. A blank was made using 10 mL distilled water with all other chemicals mentioned above. The conical flasks were kept on a hot plate at 100º C for 30 minutes followed by adding 250 mL distilled water and was kept for cooling. Two or three drops of ferroin indicator was added and was titrated against 0.005 N ferrous ammonium sulphate till a brick red end point could be noticed.

3.1.6 Dehydrogenase activity

The dehydrogenase activity was estimated as per the procedure described by Casida *et al.* (1964). About 1 g of soil was weighed and taken in an air tight screw capped test tube of 15 mL capacity, to which 0.02mL of 3 per cent triphenyl tetrazolium chloride solution was added to saturate the soil. Then 0.5 mL of 1 per cent glucose solution was added in each tube. The bottom of the tube was gently tapped to drive out all trapped oxygen, and thus a water seal was formed above the soil and ensured that no air bubbles were formed in tube. Tube was incubated at 28 ± 0.5 °C for 24 h. After incubation, 10 mL methanol was added and the contents were vigorously shaken for proper mixing. Samples were allowed to stand for six hours. Clear pink coloured supernatant was removed and the reading were taken with a UV-Visible spectrophotometer at a wavelength of 485 nm.

A series of standard viz., 10, 20, 30, 40 and 50 mg kg^{-1} were used for preparing the calibration curve. The result was expressed in terms of triphenyl formazan (TPF) hydrolysed in micrograms per gram of soil per day.

3.1.7 Aryl sulphatase activity assay

In a 50 mL volumetric flask ,1 g of soil was taken and added with 0.25 mL of toluene, 4mL of acetate buffer and 1mL of 0.5 M p-Nitrophenyl sulphate solution. Swirled the flask and kept in an incubator at 37°C for one hour. Similarly a set of control was made without adding NPS solution

After 1 hr, 1 mL of 0.5 M $CaCl_2$ and 4mL of 0.5 M NaOH solutions were added, swirled the flask for few seconds and filtered the soil suspension through a

Whatman No. 2 filter paper. In control set 1mL of PNS solution was added just before the filtration.

A series of standards viz 0.2, 0.4, 0.6, 0.8 and 1 mg kg^{-1} of PNS were used for preparing the calibration curve. The intensity was measured at 440nm. Intensity of control was deducted from samples and expressed as mg p-nitrophenyl released g soil hr^{-1} time.

3.1.8 Cysteine desulfhydrase activity (CDA)

- Soil samples weighing 1g each and toluene (0.5 mL) taken in three universal bottles closed with screw caps and left for 15 min
- Tris HCl buffer (3 mL, 0.2 M, pH 8.3) and pyridoxal phosphate (0.2 mM, 1 mL) added to the three bottles to initiate enzyme reaction whereas one bottle was devoid of L-cysteine (5 mM, 1 mL)
- The contents in bottles were thoroughly mixed and incubated at 37 °C
- Two sets of controls were included containing a) Reaction mixture that lack L-cysteine b) Trichloroacetic acid (TCA 10 %) that was added immediately to the bottle containing L-cysteine to arrest enzyme reaction
- Trichloroacetic acid (TCA 10 %) was added to the reaction mixture (sample) containing L-cysteine after 2 hours of incubation
- Filtered the soil suspensions through Whatman No.1 filter paper
- Trichloroacetic acid (0.3 mL (of 50 % w/v solution), distilled water (2.2 mL) and 2,4-dintrophenylhydrazine (1 mL, of a 1 % solution in 2 M HCl) added to 0.5 mL of filtrate. The contents were thoroughly mixed and left at room temp for 10 min
- Sodium hydroxide (5 mL of a 2.5 N solution) added after 10 min incubation at room temperature, the pyruvate formed was measured at 445 nm

3.2 Sulphur fractionation procedure

The sulphur fractions included in this research are sulphate sulphur, total water soluble sulphur, heat soluble sulphur, sulphate soluble after ignition, total organic sulphur and total sulphur. Total sulphur was estimated using CHNS analyser. The other fractions were determined using the procedure of Williams and Steinbergs (1958) and S in the extracts was estimated by turbidimetry (Massoumi and Cornfield, 1963) using a spectrophotometer (Model: Systronics169)

3.2.1 Sulphate sulphur

Five gram of soil was extracted with 25 mL of 0.15 per cent calcium chloride. After 30 minutes of shaking filtered through Whatman no. 42 filter and paper sulphate sulphur was determined with barium chloride

3.2.2 Water soluble sulphur

Five gram soil was extracted with 33 mL of 1 per cent sodium chloride. After centrifuging and filtering a 25 mL aliquot was pipetted into a silica basin and evaporated to dryness with 2mL of 5 percent hydrogen peroxide. The basin was then heated in a hot air oven at 102 °C for 60 minutes to remove excess hydrogen peroxide. After cooling the residue was taken up in 25 mL of distilled water, transferred to centrifuge tube and centrifuged to remove suspended matter. Sulphur was determined using barium chloride.

3.2.3 Heat soluble sulphur

Five gram soil was taken into a silica basin and 20 mL distilled water was added. The basin was then placed on a boiling water bath and evaporated to dryness. It was then kept in a hot air oven at 102°C for 2 hrs. After cooling, the soil was transferred to a 50mL centrifuge tube and extracted with 33mL 1 percent sodium chloride. Sulphur was estimated by barium chloride method.

3.2.4 Total organic sulphur

Five gram of soil samples were leached first with distilled water, then with 1 per cent hydrochloric acid and finally with distilled water until the leachate was free of chloride. The soil was transferred to a beaker and oxidised with hydrogen peroxide and extracted with 1 per cent sodium chloride. Estimation was done using barium chloride method.

3.2.5 Total sulphur

Total sulphur was determined using CHNS analyser (Model: Elementar’s vario EL cube).

3.3 Adsorption study

Adsorption studies were conducted for selected soil samples (low and higher range of available sulphur) at two temperature (25 °C and 40 °C). Five gram soil sample was equilibrated with 25 mL different concentration of sulphur solutions (0, 5, 25, 50, 100, and 200 mg L^{-1}). This suspension were shaken for one hour and kept idle for over night and next morning another one hour shaking was done (Chao et al., 1962).

Plate 4. Incubation for adsorption

3.4 Plant analysis

3.4.1 Collection of Plant samples

Plant samples were collected randomly from the field at three fields per location at tillering and harvest stage. Grain samples were also collected at harvest stage for determining the nutrient content both in plant and grain samples were first air dried (after thorough washing in case of plant sample), transferred to clean paper bags, dried in oven set at 70 – 80 °C powdered in stainless steel grinder and stored in clean containers for further analysis.

3.4.2 Plant nutrient analysis

From the powdered sample, 0.5 g was taken and digested using a micro digester in nitric acid medium and made up to 100 mL and used for analysing total content of total phosphorus, potassium, calcium, magnesium, sulphur, iron, manganese, zinc, copper and boron.

Table 3. Methodology of plant total nutrient analysis

Sl. No	Element	Method
1	Nitrogen	Kjeldhal's digestion method (Jackson, 1973)
2	Phosphorus	Vanadomolybdate phosphoric yellow colour in nitric acid (Piper, 1966)
3	Potassium	Flame photometry (Jackson, 1973)
4	Calcium and Magnesium	ICP-OES (Model: Optima 8x00 series)
5	Sulphur	Barium chloride – turbidimetry
6	Iron, manganese, zinc, copper and boron	ICP-OES (Model: Optima 8x00 series)

3.5 Statistical analysis

One way ANOVA analysis for comparison of means were done in Grapesagri1 package (Gopinath *et al*., 2021). Correlation analysis of data generated from different experiments was carried out using the method suggested by Cox, 1987 using SPSS package. Path analysis in sulphur fractions and the adsorption isotherm were fitted using R statistical package (R version 3.2.3)

Results

4. RESULTS

The study titled ‘Sulphur dynamics in major rice-growing soils of Kerala was undertaken to understand the sulphur dynamics in major rice soils of Kerala and to assess its relationship with that of carbon, nitrogen and phosphorous. Unfolding the antagonism/synergism between sulphur and other nutrients was also envisaged at. These objectives were accomplished through four experiments namely collection and characterisation of soil Sample 2) fractionation of sulphur 3) an adsorption study and 4) by assessing the effect of sulphur on adsorption of other nutrients. The results generated are presented in this chapter.

4.1. Characterisation of soil samples

Representative geo referenced samples (35 Nos.) collected from major rice growing soils of Kerala (Table 1) viz; 1. *Onattukara* sandy soil- Coastal sandy soil (AEU 3); 2. *Poonthalppadam* -Slushy paddy land soils (AEU 23); 3. black cotton soils of Chittoor - (AEU 23); 4. *Kari* soils of Kuttanad -Acid sulphate soils (AEU 4); 5. *Kole* lands of Thrissur-Potential acid sulphate soils (AEU 6); 6. Acid saline soils (*Pokkali* and/or *Kaipad*) (AEU 5) and 7. Low land brown hydromorphic laterite (AEU 10) were analysed to study the electro-chemical and physical properties along with available nutrient status . The results are given in tables 4, 5, 6 and 7.

4.1.1. Physico- chemical properties and available nutrient status

4.1.1.1. Soil pH

The pH of the soils ranged from 3.35 to 8.26. The lowest pH was recorded in the *Kari* soils of Kuttanad and highest in black cotton soil. All other soils except black cotton soil were acidic in nature.

4.1.1.2. Electrical conductivity

The lowest electrical conductivity 0.043 dS m^{-1} was recorded in *Poonthalpadam* soils (Sample No. 18) and the highest 1.92 dSm^{-1} in *Pokkali* soil (Sample No. 27). EC values were less than 1 in all soils except *Pokkali* soil. Of the total samples characterised, above 50 per cent recorded EC less than 0.1dS m^{-1}.

4.1.1.3. Cation exchange capacity (CEC)

It was observed that the CEC ranged from 1.09 to 13.84 (cmol (+) kg^{-1}). The highest CEC was reported from *Kari* soil (Sample No.33) and the lowest from *Onattukara* sandy soil (Sample No. 15)

4.1.1.4. Organic carbon

The organic carbon status of soil varied from 0.037 to 7.80 per cent. Sandy soil of *Onattukara* (Sample No. 14) recorded the lowest organic carbon (0.037per cent) whereas *Kari soil* (Sample No. 33) recorded the highest (7.80 per cent) organic carbon. Forty per cent of soil samples had more than 1.5 percentage organic carbon. Fourteen per cent of the samples analysed had low (< 0.75%) organic carbon. The organic carbon content of *Kari* soils ranged from 3.53 to 7.8 per cent.

4.1.1.5. Soil temperature

The soil temperature ranged from 28 to 37°C, lowest temperature was recorded in *Pokkali* soils (Sample No. 27 and 30) and highest in *Kari* soil (Sample No. 31 and 33).

4.1.1.6. Bulk density

The bulk density of soils extended between 1.23 to 1.59 gcm^{-3}. The lowest bulk density was observed in black cotton soils (Sample No. 5) and highest in *Onattukara* sandy soils (Sample No. 13). Of all the soil samples analysed, about 29 per cent of the soils had a bulk density more than 1.5 gcm^{-1}.

4.1.1.7. Soil texture

Sand fraction in the soils ranged from 25.2 to 83 per cent. The maximum sand per cent was observed in *Onattukara* sandy soil (Sample No. 12) and minimum in *Kole* land (Sample No. 23). The silt fraction ranged from 3.6 per cent in *Pokkali* soil (Sample No. 26 and 30) to 39.8 per cent in *Kole* land soils (Sample No. 23). The lowest clay content of 6 per cent was recorded in *Onattukara* sandy soils ((Sample No. 15) and highest in laterite soil 45.3 % (Sample No. 7). Sandy clay, Sandy clay loam, clay loam and loamy sand were the major textural classes identified representing 25.71, 20, 25.71, and 28.57 percentage on apportioning.

Table 4. Physico-chemical properties of soils

Sample No	pH	EC (dS m^{-1})	CEC (cmol(+) kg^{-1})	OC (%)	Temperature (°C)	Bd (Mg m^{-3})	Sand (%)	Silt (%)	Clay (%)	Textural class
1	8.22	0.14	9.20	0.90	29.00	1.24	50.30	10.00	39.70	Sandy clay
2	8.18	0.17	9.60	1.07	29.00	1.25	47.00	12.00	41.00	Sandy clay
3	8.26	0.30	10.90	1.10	33.00	1.31	50.50	13.20	36.30	Sandy clay
4	8.22	0.38	11.50	1.06	33.00	1.27	48.80	12.60	38.60	Sandy clay
5	8.20	0.25	10.20	0.88	32.00	1.23	50.00	13.20	36.80	Sandy clay
6	5.03	0.05	1.81	0.90	33.00	1.32	43.00	19.00	38.00	Clay loam
7	5.01	0.05	1.76	1.22	33.00	1.34	29.70	25.00	45.30	Clay loam
8	5.20	0.06	1.82	1.06	33.50	1.32	33.00	24.70	42.30	Clay loam
9	5.26	0.05	1.74	0.88	34.00	1.40	34.20	27.00	38.80	Clay loam
10	5.25	0.06	1.78	0.97	33.00	1.38	40.00	21.60	38.40	Clay loam
11	5.77	0.07	1.14	0.52	28.00	1.53	80.40	12.00	7.60	loamy sand
12	5.30	0.09	1.16	0.46	28.00	1.58	83.00	9.30	7.70	loamy sand
13	4.83	0.11	1.18	0.48	29.10	1.59	76.80	13.20	10.00	loamy sand
14	5.77	0.07	1.13	0.37	30.00	1.54	78.30	14.00	7.70	loamy sand
15	5.43	0.05	1.09	0.38	29.00	1.57	79.70	14.30	6.00	loamy sand
16	5.31	0.09	8.31	0.91	30.00	1.38	50.00	20.60	29.40	Sandy clay loam
17	5.48	0.09	8.14	0.86	32.00	1.38	57.00	14.00	29.00	Sandy clay loam
18	5.66	0.04	7.94	1.05	32.00	1.41	48.00	18.70	33.30	Sandy clay loam
19	5.34	0.05	9.12	0.79	32.00	1.39	46.50	16.50	37.00	Sandy clay loam
20	5.23	0.16	8.51	0.85	31.00	1.43	50.00	14.70	35.30	Sandy clay loam
21	6.80	0.05	7.16	2.28	29.00	1.44	49.00	20.60	30.40	Sandy clay loam
22	6.63	0.04	6.38	1.99	29.10	1.40	27.00	35.00	38.00	Clay loam

Table 4. Continued

Sample No	pH	EC (dS m^{-1})	CEC (cmol(+) kg^{-1})	OC (%)	Temperature (°C)	Bd (Mg m^{-3})	Sand (%)	Silt (%)	Clay (%)	Textural class
23	6.41	0.04	5.29	2.27	29.10	1.39	25.20	39.80	35.00	Clay loam
24	6.68	0.04	6.52	1.75	29.00	1.41	29.00	37.30	33.70	clay loam
25	6.47	0.06	7.23	1.49	29.20	1.39	26.20	38.60	35.20	clay loam
26	5.82	1.21	11.05	1.81	29.00	1.35	59.10	7.40	33.50	Sandy clay loam
27	6.61	1.92	12.23	1.76	28.00	1.38	57.00	3.60	39.40	sandy clay
28	6.42	1.48	11.18	2.48	28.10	1.36	50.50	6.30	43.20	sandy clay
29	5.73	1.57	11.57	2.49	28.30	1.39	52.40	7.00	40.60	sandy clay
30	2.00	1.64	11.86	2.00	28.00	1.39	55.00	3.60	41.40	sandy clay
31	4.95	0.81	13.12	4.95	37.00	1.50	74.40	17.00	8.60	loamy sand
32	4.25	0.98	13.64	4.25	36.00	1.54	80.00	7.80	12.20	loamy sand
33	7.80	1.42	13.84	7.80	37.00	1.50	81.50	6.00	12.50	loamy sand
34	4.60	0.40	12.08	4.60	36.50	1.52	81.00	9.30	9.70	loamy sand
35	3.53	0.81	12.87	3.53	36.00	1.54	80.50	9.00	10.50	loamy sand
Min.	0.37	0.04	1.09	0.22	28.00	1.23	25.20	3.60	6.00	
Max.	7.80	1.92	13.84	7.80	37.00	1.59	83.00	39.80	45.30	

4.1.2. Soil biological properties

Soil biological properties (Microbial biomass carbon, dehydrogenase activity, Aryl sulphatase activity) were analysed and are provided in table 5.

4.1.2.1. Microbial biomass carbon (MBC)

Microbial biomass carbon of analysed soils ranged from 11.54 to 402.45 mg kg^{-1}. The highest Microbial biomass carbon was observed in *Kari* soils (Sample No. 33) and lowest in *Onattukara* sandy soil (Sample No. 11). The *Kari* and *Kole* land soils had relatively higher Microbial biomass carbon content in comparison to other soils.

4.1.2.2. Dehydrogenase activity

The dehydrogenase activity of soils differed from 0.08 to 8.63 µg TPF g^{-1} soil 24 hr^{-1}. The lowest dehydrogenase activity (0.08 µg TPF g^{-1}soil 24 hr^{-1}) was recorded in *Onattukara* sandy soils (Sample No. 12) and highest (8.63 µg TPF g^{-1} soil 24 hr^{-1}) in *Pokkali* soils (Sample No. 29).

4.1.2.3 Aryl sulphatase activity

Aryl sulphatase activity ranged between 0.38 to 58.66 mg p- nitrophenol released g^{-1} soil h^{-1}. The lowest activity was reported from *Onattukara* sandy soil (Sample No. 15) and highest from *Kari* soils (Sample No. 32). The enzyme activity was more than 10 in *Kole* land, *Pokkali* soils and *Kari* soils.

Table 5. Soil biological properties

Sample No.	MBC (mg kg^{-1})	Dehydrogenase activity (µg TPF g^{-1}soil)	Aryl sulphatase activity(mg p-nitrophenol released g^{-1}soil h^{-1})	Cysteine desulfhydrase (µ moles pyruvate formed g^{-1} 2 h^{-1})
1	39.56	0.22	4.67	Not detected
2	41.71	0.31	2.69	Not detected
3	39.11	2.30	2.15	Not detected
4	42.00	0.19	8.65	Not detected
5	45.47	1.61	5.54	Not detected
6	86.60	5.24	2.74	Not detected
7	103.63	5.77	3.45	Not detected
8	72.36	5.10	4.56	Not detected
9	36.46	6.39	3.45	Not detected
10	109.70	4.17	2.74	Not detected
11	11.54	1.54	0.80	Not detected
12	24.34	0.08	6.96	Not detected
13	33.45	2.28	3.24	Not detected
14	19.33	0.38	6.52	Not detected
15	28.56	1.43	0.38	Not detected
16	37.42	0.49	5.91	Not detected
17	43.56	5.31	5.43	Not detected
18	40.21	7.32	2.41	Not detected
19	50.23	5.75	5.74	Not detected
20	48.72	2.82	4.55	Not detected
21	260.74	1.43	16.33	Not detected
22	284.42	0.61	29.00	Not detected
23	179.63	1.21	36.11	Not detected
24	225.60	0.30	15.72	Not detected

Table 5. Continued

Sample No.	MBC (mg kg^{-1})	Dehydrogenase activity (µg TPF g^{-1}soil)	Aryl sulphatase activity (mg p-nitrophenol released g^{-1}soil h^{-1})	Cysteine desulfhydrase (µ moles pyruvate formed g^{-1} 2 h^{-1})
25	243.67	1.00	10.40	Not detected
26	156.45	1.16	10.25	Not detected
27	145.67	1.91	11.34	Not detected
28	178.54	1.74	11.57	Not detected
29	267.86	8.63	10.23	Not detected
30	254.65	1.68	10.23	Not detected
31	339.43	5.82	58.56	Not detected
32	309.18	4.23	58.66	Not detected
33	402.45	1.17	49.87	Not detected
34	357.34	0.77	50.87	Not detected
35	393.45	0.42	53.40	Not detected
Min.	11.54	0.08	0.38	
Max.	402.45	8.63	58.66	

4.1.3. Available nutrient status

The data on available nutrient status estimated prior to rice cultivation in the major soils covered are furnished in table 6.

4.1.3.1Available nitrogen (Av. N)

The available nitrogen extended from 122.89 to 773.31 kg ha^{-1}. A very low available nitrogen was observed in samples from *Onattukara* sandy soils (Sample No.14) whereas the highest value was observed in *Kole* land soil (Sample No. 21). Of all the soil samples analysed 48.57 per cent of soils were low in available nitrogen (<280 kg ha-1) whereas 17.14 per cent were high in terms of nitrogen content (>560 kg ha-1).

4.1.3.2. Available phosphorus (Av. P)

The available phosphorus extended from 10.15 to 110.73 kg ha^{-1}. The lowest value for available P was reported from *Kole* land soils (Sample No.25) and the highest value from *Poonthalpadam* soils (Sample No. 19). Of all the 35 samples, analysed 71.42 per cent of soils were high in available phosphorous (>24 kg ha^{-1}). None of the samples analysed were found deficient (<10 kg ha^{-1}) in available phosphorous.

4.1.3.3. Available potassium (Av. K)

The available potassium fluctuated between 38.53 kg to 1980.16 kg ha^{-1}. The lowest available K was observed in *Onattukara* sandy soils (Sample No.15) and highest in *Pokkali* soil (Sample No. 26). Categorising further it could be seen that 17.14 per cent analysed soil samples were low in available potassium (<108 kg $ha^{-1)}$ whereas 51.42 per cent of soil samples contained high potassium (>280kg ha $^{-1}$).

4.1.3.4 Available calcium (Av. Ca)

The available calcium content of soil samples extended from 108.85 to 2121.27 mg kg^{-1}. Among the samples analysed 37.14 percent were deficient (< 300 mg kg^{-1}) in available calcium. Another major observation was that all the samples collected from *Onattukara* region were deficient in available calcium. The lowest available Ca status was observed in *Kari* soils of Kuttanad

Table 6. Available nutrient status of soil before cultivation

Sample No	Av. N	Av.P	Av. K	Av. Ca	Av. Mg	Av. S	Av. Fe	Av. Mn	Av. Cu	Av. Zn	Av. B
	kg ha^{-1}			mg kg^{-1}							
1	206.41	68.20	229.22	1578.38	348.55	132.51	80.78	35.78	6.77	13.73	0.85
2	243.19	59.07	238.58	2121.27	412.83	54.80	70.56	43.79	6.05	10.74	0.91
3	318.15	61.35	293.15	1820.24	467.52	140.38	52.42	66.41	4.99	4.94	0.66
4	220.46	51.50	313.85	1976.62	487.63	35.16	30.85	27.82	5.36	5.16	0.98
5	282.45	48.15	338.95	1709.16	460.69	113.54	54.67	27.89	7.51	5.08	0.99
6	257.41	41.23	202.60	658.00	392.78	7.73	278.00	17.28	8.20	5.33	0.78
7	253.88	52.60	203.36	577.00	403.56	13.31	307.65	18.88	6.05	4.75	0.79
8	315.29	36.76	185.69	538.00	396.40	8.69	255.65	14.08	8.25	4.01	0.64
9	253.77	38.16	164.90	567.00	300.68	9.68	196.65	17.26	8.20	2.64	0.80
10	371.67	22.94	224.28	466.24	278.00	12.91	189.75	12.97	9.35	2.71	0.68
11	203.19	27.27	102.45	139.95	15.07	6.07	45.53	8.27	3.75	3.72	0.31
12	214.89	36.41	51.28	175.45	14.68	8.73	54.00	11.05	3.33	3.15	0.27
13	177.45	59.43	64.34	161.75	13.94	18.97	27.80	10.93	2.83	3.08	0.36
14	122.89	26.28	81.71	259.40	28.02	10.24	34.41	9.18	3.51	3.53	0.28
15	174.51	21.56	38.53	139.85	14.24	14.48	23.98	8.98	2.36	3.12	0.24
16	251.87	37.65	205.79	623.50	200.99	176.76	157.40	27.29	8.76	9.36	0.70
17	238.24	52.17	228.09	505.00	242.76	72.54	149.80	24.58	8.31	10.47	0.46
18	230.11	37.79	283.04	492.85	259.11	36.45	146.85	25.45	8.31	6.66	0.78
19	227.00	110.73	339.68	584.00	207.38	45.62	143.75	31.11	7.47	6.06	0.69
20	215.32	39.34	208.87	489.25	280.50	47.57	159.65	36.11	7.80	6.69	0.95
21	773.31	10.16	409.79	212.25	60.14	194.32	431.45	97.09	15.40	5.10	0.73

Table 6. Continued

Sample No	Av. N	Av.P	Av. K	Av. Ca	Av. Mg	Av. S	Av. Fe	Av. Mn	Av. Cu	Av. Zn	Av. B
	kg ha^{-1}			mg kg^{-1}							
22	459.95	11.90	323.71	277.35	60.77	239.43	310.90	86.27	12.73	7.10	0.76
23	587.27	10.21	366.42	353.60	147.94	120.77	387.20	93.90	10.65	5.50	0.92
24	429.87	14.45	284.95	204.30	71.46	142.35	261.15	92.48	7.45	4.50	1.24
25	453.30	10.15	338.06	248.20	55.81	151.99	628.00	96.74	12.89	11.00	0.89
26	654.36	38.98	1980.16	651.19	591.09	2125.89	365.15	15.38	11.78	13.60	4.26
27	250.20	41.35	1191.81	551.06	496.83	1619.90	487.30	16.64	20.65	14.30	3.66
28	395.96	52.43	1592.89	676.21	372.13	2027.15	334.25	20.16	17.90	12.35	7.36
29	464.90	47.13	1788.91	626.87	269.26	2255.26	472.20	19.11	6.12	3.90	6.07
30	621.52	65.49	1758.26	614.59	379.82	2121.84	390.75	21.74	3.18	3.45	4.32
31	699.31	34.01	47.32	543.50	495.50	691.96	369.15	20.64	6.36	4.51	1.07
32	386.10	39.25	309.94	108.85	81.75	1147.19	921.60	17.20	5.39	4.21	0.70
33	652.29	14.40	836.08	123.10	116.25	2004.35	459.65	15.19	5.07	4.34	1.54
34	525.55	13.62	390.77	128.05	92.90	1122.16	321.20	16.73	5.18	4.28	0.81
35	369.88	37.80	194.85	121.40	97.45	860.79	754.92	15.30	9.25	3.13	0.95
Min	122.89	10.15	38.53	108.85	13.94	6.07	23.98	8.27	2.36	2.64	0.24
Max	773.31	110.73	1980.16	2121.27	591.09	2255.26	921.60	97.09	20.65	14.30	7.36

(Sample No. 32) whereas black *cotton* soils reported the highest available calcium (Sample No.2).

4.1.3.5 Available magnesium (Av. Mg)

The available magnesium ranged from 13.94 to 591.09 mg kg^{-1}. About 37.14 per cent of the samples analysed were found to be deficient in available magnesium (<120 mg kg^{-1}). The lowest available magnesium status was observed in *Onattukara* sandy soils (Sample No. 13) and highest in *Pokkali* soils (Sample No. 26).

4.1.3.6 Available sulphur (Av. S)

The available sulphur extended between 6.07 to 2255.26 mg kg^{-1}. None of the analysed soil samples were deficient in available sulphur (<5 mg kg^{-1}). The lowest sulphur status was associated with *Onattukara* sandy soils (Sample No. 11) wherein the *Pokkali* soil (Sample No. 29) recorded the highest value of available sulphur.

4.1.3.7 Available iron (Av. Fe)

The available iron content of soil varied from 23.98 to 921 mg kg^{-1}. The lowest value of available Fe was reported from *Onattukara* sandy soils (Sample No. 15) and the highest value from *Kari* soils (Sample No.32).

4.1.3.8 Available manganese (Av Mn)

The available manganese differed from 8.27 to 97.09 mg kg^{-1}. The maximal value for available Mn was reported from *Kole* land soils (Sample No.21) whereas the minimal value from *Onattukara* sandy soils (Sample No. 11).

4.1.3.9 Available zinc (Av. Zn)

The available zinc in soil samples ranged from 2.64 to 14.3 mg kg^{-1}. The highest value for available Zn was observed in *Pokkali* soils (Sample No.27) and the lowest value was obtained in laterite soils (Sample No.9). None of the soil samples were found deficient in available zinc.

4.1.3.10 Available copper (Av. Cu)

The available copper status ranged between 2.63 to 20.65 mg kg^{-1}. The lowest available copper (2.63 mg kg^{-1}) was recorded from *Onattukara* sandy soils

(Sample No. 15) and the highest (20.65 mg kg^{-1}) from *Pokkali* soils (Sample No. 27).

4.1.3.11 Available boron (Av. B)

The hot water extractable boron was found to vary between 0.24 to 7.36 mg kg^{-1}. All the soil samples analysed from *Onattukara* region were deficient in available boron (<0.5 mg kg^{-1}) wherein the *Pokkali* soils were relatively higher with respect to available boron content.

4.1.4. Summary statistics of initial characterization

Agroecological unit based values of electrochemical properties, physical properties, biological properties and available nutrients status are presented in the table 7, 8 and 9.

4.1.4.1. Electrochemical properties

4.1.4.1.1. Soil pH

The black cotton soil recorded significantly higher pH value (8.21) whereas the lowest pH (4.37) was recorded from *Kari* soil.

4.1.4.1.2. Electrical conductivity

The AEU based electrical conductivity ranged from 0.0542 to 1.565. The *Pokkali* soil reported significantly higher value for electrical conductivity while the lowest value was reported from laterite soil which is on par with *Onattukara* sandy soil as well as *Poonthalpadam* soil.

4.1.4.1.3. Cation exchange capacity

The significantly highest CEC was reported from *Kari* soil (13.11cmol (+) kg^{-1}) whereas lowest value was reported from *Onattukara* sandy soil (1.14cmol (+) kg^{-1}) which is on par with laterite soil.

4.1.4.1.4. Organic carbon

The organic carbon values extended between 0.442 to 5.026 percent. The *Kari* soils of Kuttanad had significantly highest value for organic carbon and lowest value was observed to be from *Onattukara* sandy soil which is on par with *Poonthalpadam* soil, black cotton soil as well as laterite soil.

4.1.4.2. Physical properties

4.1.4.2.1. Soil temperature

The *Kari* soil of Kuttanad recorded significantly highest soil temperature (36.5°C) whereas the lowest value was recorded from *Pokkali* soil (28.28 °C) which is on par with *Onattukara* sandy soil as well as *Kole* land.

4.1.4.2.2. Bulk density

The values for bulk density extended between 1.26 to 1.562 gcm^{-3}. The *Onattukara* sandy soil reported significantly higher value and lowest value was reported from black cotton soil.

4.1.4.2.3. Soil texture

The sand fractions in the soils ranged from 31.28 to 79.64 per cent. The *Onattukara* sandy soil had significantly higher value of sand fractions which is on par with *Kari* soil whereas lowest was observed to be from *Kole* land which is on par with laterite soil.

The *Kole* land recorded significantly highest value for silt fraction (34.26 per cent) while *Pokkali* soil recorded the lowest value (5.58 per cent).

The significantly highest value for clay fraction was observed to be from laterite soil (40.56 per cent) which is on par with *Pokkali* soil as well as black cotton soil and lowest value was observed in sandy soils of *Onattukara* (7.8 per cent) which is on par with *Kari* soil.

Table 7. Physico-chemical properties of soils on before cropping

Soil type	pH	EC (dS m^{-1})	CEC (cmol(+) kg^{-1})	OC (%)	Temperature (°C)	Bd (Mg m^{-3})	Sand (%)	Silt (%)	Clay (%)	Textural class
black cotton soils of Chittoor	8.216	0.247	10.28	1.002	31.2	1.26	49.32	12.2	38.48	Sandy clay
Low land brown hydromorphic laterite	5.15	0.054	1.782	1.006	33.3	1.352	35.98	23.46	40.56	Clay loam
Onattukara sandy soil	5.42	0.08	1.14	0.442	28.82	1.562	79.64	12.56	7.8	loamy sand
Poonthalppadam -Slushy paddy land soils	5.404	0.088	8.404	0.892	31.4	1.398	50.3	16.9	32.8	Sandy clay loam
Kole lands	6.598	0.464	6.516	1.956	29.08	1.406	31.28	34.26	34.46	clay loam
Pokkali	6.034	1.565	11.578	2.108	28.28	1.374	54.8	5.58	39.62	sandy clay
Kari soils of Kuttanad	4.376	0.885	13.11	5.026	36.5	1.52	79.48	9.82	10.7	loamy sand
C.D.	0.625	0.23	0.765	0.848	1.24	0.033	6.48	5.07	3.561	

4.1.4.3. Biological properties

4.1.4.3.1. Microbial Biomass Carbon (MBC)

The *Kari* soil reported significantly higher value for MBC (360.37mg kg^{-1}) whereas lowest value was reported from *Onattukara* sandy soil (23.444 mg kg^{-1}) which is on par with black cotton and *Poonthalpadam* soil.

4.1.4.3.2. Dehydrogenase activity

The values of dehydrogenase activity extended between 0.910 to 5.334µg TPF g^{-1}soil 24 hr^{-1}. The laterite soil had significantly highest value which is on par with *Poonthalpadam* soil and *Pokkali* soil whereas *Kole* land had the lowest value which is on par with black cotton soil, *Onattukara* sandy soil as well *Pokkali* soil.

4.1.4.3.3. Aryl sulphatase activity

The *Kari* soil recorded significantly higher value for aryl sulphatase activity (54.272 mg p- nitrophenol released g^{-1}soil h^{-1}) whereas laterite soil recorded the lowest value (3.388) which is on par with *Onattukara* sandy soil, black cotton soil as well as *Poonthalpadam* soil.

Table 8. Summary statistics of biological properties in before cropping

Location	MBC (mg kg^{-1})	Dehydrogenase activity (µg TPF g^{-1}soil)	Aryl sulphatase activity (mg p-nitrophenol released g^{-1}soil h^{-1})
Black cotton soils of Chittoor	41.57cd	0.926c	4.74cd
Low land brown hydromorphic laterite	81.75c	5.334a	3.388d
Onattukara sandy soil	23.444d	1.142c	3.58d
Poonthalppadam -Slushy paddy land soils	44.028cd	4.338ab	4.808cd
Kole lands	238.812b	0.91c	21.512b
Pokkali	200.634b	3.024abc	10.724c
Kari soils of Kuttanad	360.37a	2.482bc	54.272a
CD	41.655	2.475	5.996

4.1.4.4. Summary statistics of available nutrients status

4.1.4.4.1Available nitrogen (Av. N)

The available nitrogen status ranged from 178.56 to 540.74 kg ha^{-1}. The *Kole* land reported significantly higher value for Av. N which is on par with *Kari* soil as well as *Pokkali* soil. The lowest value was reported from *Onattukara* sandy soils which is on par with *Poonthalpadam* soil, black cotton soil and laterite soil.

4.1.4.4.2 Available phosphorus (Av. P)

The available phosphorus content extended between11.37 to 57.65 kg ha^{-1}. The significantly highest value for Av. Pwas observed to be from black cotton soils which is on par with *Poonthalpadam* soil and the lowest value was observed in *Kole* land which is on par with *Kari* soil.

4.1.4.4.3. Available potassium (Av. K)

The *Pokkali* soil had significantly higher value for Av. K (1662.40 kg ha^{-1}) whereas the lowest was observed in *Onattukara* sandy soil (67.66 kg ha^{-1}) which is on par with laterite soil and *Poonthalpadam* soil.

4.1.4.4.4. Available calcium (Av. Ca)

The available calcium content of soil samples extended between175.28 to 1841.13 mg kg^{-1}. The significantly highest value for Av. Ca was recorded from black cotton soil whereas lowest value was recorded from *Onattukara* sandy soil which is on par with *Kari* soil as well as *Kole* land.

4.1.4.4.5. Available magnesium (Av. Mg)

The available magnesium status of soils ranged from 17.19 to 435.44 mg kg^{-1}. The black cotton soil had significantly highest value which is on par with *Pokkali* soil while lowest value was observed in *Onattukara* sandy soil which is on par with *Kole* land.

4.1.4.4.6. Available sulphur (Av. S)

The available sulphur content extended between10.46 to 2030 mg kg^{-1}. The significantly higher value for Av. S was reported from *Pokkali* soil whereas lowest sulphur status was associated with laterite soils which is on par with *Onattukara* sandy soil, *Poonthalpadam* soil, black cotton and *Kole* land.

Table 9. Summary statistics of available nutrients status before cropping

Soil type	Av.N	Av.P	AvK	Av S	Av Ca	Av Mg	Av Fe	Av Mn	Av Cu	Av Zn	Av B
	kg ha^{-1}			mg kg^{-1}							
black cotton soils of chittoor	254.132b	57.654a	282.75b	95.278c	1841.134a	435.444a	57.856d	40.338b	6.136bc	7.93a	0.878b
Low land brown hydromorphic laterite	290.404b	38.338abc	196.166bc	10.464c	561.248b	354.284ab	245.54c	16.094de	8.01ab	3.888b	0.736b
Onattukara sandy soil	178.586b	34.19bc	67.662c	11.698c	175.28c	17.19e	37.144d	9.682e	3.156c	3.32b	0.294b
Poonthalppadam -Slushy paddy land soils	232.508b	55.536a	253.094bc	75.788c	538.92b	238.148bc	151.49cd	28.908c	8.13ab	7.848a	0.715b
Kole lands	540.74a	11.374d	344.586b	169.772c	259.14c	79.224de	403.74b	93.296a	11.824a	6.64ab	0.906b
Pokkali	477.388a	49.076ab	1662.406a	2030.008a	623.984b	421.826a	409.93b	18.606d	11.926a	9.52a	5.135a
Kari soils of Kuttanad	526.626a	27.816cd	355.792b	1165.29b	204.98c	176.77cd	565.304a	17.012de	6.25bc	4.094b	1.014b
CD	135.952	20.016	211.045	278.188	153.783	116.645	151.55	8.717	4.11	3.73	0.785

4.1.4.4.7. Available iron (Av. Fe)

The available iron content of soils varied between 37.14 to 565.30 mg kg^{-1}. The significantly highest value was obtained from *Kari* soil and lowest value from *Onattukara sandy* soils which is on par with black cotton soil as well as *Poonthalpadam* soil.

4.1.4.4.8. Available manganese (Av Mn)

The available manganese extended between9.68 to 93.30mg kg^{-1}. The *Kole* land had significantly highest value for Av. Mn while *Onattukara* sandy soil had the lowest value which is on par with laterite soil and *Kari* soil.

4.1.4.4.9. Available zinc (Av. Zn)

The available zinc ranged between 3.32 to 9.52 mg kg^{-1}. The significantly highest value for Av. Zn was observed in *Pokkali* soils which is on par with black cotton soil, *Poonthalpadam* soil as well as *Kole* land. The lowest value was obtained from *Onattukara* sandy soil which is on par with laterite soil, *Kari* soil and *Kole* land.

4.1.4.4.10. Available copper (Av. Cu)

The available copper status ranged between 3.16 to 11.93 mg kg $^{-1}$. The *Pokkali* soil reported significantly higher value for Av. Cu which is on par with *Kole* land, *Poonthalpadam* soil as well as laterite soil. The lowest value was reported from *Onattukara* sandy soils which is on par with black cotton soil and *Kari* soil.

4.1.4.4.11. Available boron (Av. B)

The Av. B status was found to vary between 0.29 to 5.14 mg kg^{-1}. The significantly highest value for Av. B was observed to be from *Pokkali* soil whereas all other soils do not exhibit any significant differences among them.

4.1.4.5. Relationship between physico-chemical properties and available nutrients before cultivation

The correlation between soil physico-chemical properties and available nutrients are provided in table 10. The pH correlated significantly and positively with Av. Ca (0.728**) and negatively with temperature sand Av. Fe (-0.389*). Electrical conductivity (EC) was significantly and positively correlated with OC

(0.543**) Av. N (0.418*), Av. K (0.825**), Av. S (0.945**), Av. Mg (0.343*), Av. Fe (0.526**), Av. B (0.804**)

Cation exchange capacity (CEC) had given a significant positive correlation with OC (0.628**), Av. N (0.460**), Av. K (0.488**), Av. S (0.643**), Av. Mg (0.353*), Av. Fe (0.484**), Av. Zn (352*), Av. B (0.442**). Organic carbon had shown significant and positive correlation with temperature (0.575*), Av. N (0.689**), Av. S (0.604**), Av. Fe (0.637**).

Bulk density had significantly and positively correlated with sand (0.701**) and negatively with clay (-0.872**), Av. P (-0.358*), Av. Ca (-0.793**), Av. Mg (-0.734**) and Av. Zn (-0.487**)

Sand content had given a negative correlation with Av. Mn (-0.602**), Av. Cu (-0.432**).

Clay content had a significant positive correlation with pH, Av. K (0.349*), Av. Ca (0.514**), Av. Mg (0.611**), Av. Cu (0.466**), Av. Zn (0.415*), Av. B (0.368*).

Table 10. Correlation between physico - chemical properties and available nutrients

	pH	EC	CEC	OC	BD	Sand	Clay
Ph							
EC							
CEC		0.668**					
OC	-0.364*	0.543**	0.628**				
Temperature				0.575**			
Av. N		0.418*	0.460**	0.689**			
Av. P					-0.358*		
Av. K		0.825**	0.488**				0.349*
Av. S		0.945**	0.643**	0.604**			
Av. Ca	0.728**				-0.793**		0.514**
Av. Mg		0.343*	0.353*		-0.734**		0.611**
Av. Fe	-0.389*	0.525**	0.484**	0.637**			
Av. Mn	0.450**					-0.602**	
Av. Cu						-0.432**	0.466**
Av. Zn	0.399*		0.352*		-0.487**		0.415*
Av. B		0.804**	0.442**				0.368*

4.1.4.6. Relationship between biological properties and physico chemical properties

The correlation between soil biological properties and physico-chemical properties are provided in table 11. Microbial biomass carbon (MBC) had significant positive correlation with aryl sulphatase activity (0.848**), EC (0.519**), CEC (0.572**), OC (0.867**), temperature (0.377*). Dehydrogenase activity had shown a negative correlation with pH (-400*). Aryl sulphatase activity seemed to be significantly and positively correlated with EC (0.347*), CEC (0.544**), OC (0.872**), temperature (0.594**), and negatively correlated with pH (-0.411*)

Table 11. Correlation between soil biological properties and physico chemical properties

	MBC	Dehydrogenase activity	Aryl sulphatase activity
MBC			
Dehydrogenase activity			
Aryl sulphatase activity	0.848^{**}		
pH	-0.345^{*}	-0.400^{*}	-0.411^{*}
EC	0.519^{**}		0.347^{*}
CEC	0.572^{**}		0.544^{**}
OC	0.867^{**}		0.872^{**}
Temperature	0.377^{*}		0.594^{**}

Table 12. Correlation between biological properties and available N, P, and S

	Av.N	Av.P	Av. S
MBC	0.786^{**}	-0.408^{*}	0.606^{**}
Aryl sulphatase activity	0.589^{**}	-0.357^{*}	0.385^{*}

4.1.4.7. Relationship between biological properties, available status of N, P and S

The correlation coefficient arrived at between biological properties and Av.N, Av.P, Av. S are given in table 12. Microbial biomass carbon was significantly and positively correlated with Av. N (0.786**), Av. S (0.606**) and negatively correlated with Av. P(-0.408*). Aryl sulphatase had a significant and positive correlation with Av. N (0.589**) , Av. S (0.385*) as well as negative correlation with Av. P(-0.357*).

4.1.4.8. Relationship between available nutrients

The results on correlation done between available nutrients are furnished in table 13. Available nitrogen had shown significantly positive correlation with Av. S Av. Fe (0.565**),and Av. B (0.337*). Available potassium significantly and positively correlated with Av. S (0.892**), Av. Mg (0.388*), Av. Fe (0.343*), Av. Cu (0.355*), Av. Zn (0.368*) and Av. B (0.923**).

Available sulphur was found to have significant positive correlation with Av. Fe (0.548**) and Av. B (0.833**). Available calcium had shown significant and positive correlation with Av. Mg (0.682**) and negative correlation with Av. Fe (-0.413*). Available magnesium was significantly and positively correlated with Av. Zn (0.401*) and Av. B (0.388*).

Available iron was significantly and positively correlated with Av. Cu (0.386*). Available manganese had shown a significant and positivel correlation with Av. Cu (0.363*). Available copper exhibited a significant positive correlation with Av. Zn (0.621**) and Av. B (0.420*). A significant and positive correlation was reported between available Zn and Av. B (0.370*).

Table 13. Correlation between available nutrients

	Av. N	Av. K	Av. S	Av. Ca	Av. Mg	Av. Fe	Av. Mn	Av. Cu	Av. Zn
Av. K	0.463^{**}								
Av. S	0.550^{**}	0.892^{**}							
Av. Mg		0.388^{*}		0.682^{**}					
Av. Fe	0.565^{**}	0.343^{*}	0.548^{**}	-0.413^{*}					
Av. Cu		0.355^{*}				0.386^{*}	0.363^{*}		
Av. Zn		0.368^{*}			0.401^{*}			0.621^{**}	
Av. B	0.337^{*}	0.923^{**}	0.833^{**}		0.388^{*}			0.420^{*}	0.370^{*}

4.2. ACTIVE TILLERING STAGE

4.2.1. Electro chemical properties and available nutrient content of soil

The soil samples were collected at active tillering stage of the crop under wet condition, analysed as such (without drying) and the results were then expressed on dry weight basis. The data on electro chemical properties and available nutrient content are furnished in table 14 and 15.

4.2.1.1. Soil pH

The soil pH analysed at active tillering stage ranged from 5.23 to 7.92. The highest value was reported from black cotton soil (Sample No.3) and lowest from *Kari* soil (Sample No.21).

4.2.1.2. Electrical conductivity

The electrical conductivity varied from 0.029 to 0.675 dS m^{-1}. The maximum value was recorded for *Pokkali* soil (Sample No.18) and minimum value for laterite soil (Sample No.5).

4.2.1.3. Organic carbon

The values for organic carbon extended between 0.056 to 6.53 per cent. The *Kari* soil (Sample No.21) reported the highest value for organic carbon whereas *Onattukara* sandy soil (Sample No.8) reported the lowest value.

4.2.1.4. Available nitrogen

The available nitrogen ranged from 75.26 to 288.51 kg ha^{-1}. The highest value was recorded from *Kari* soils (Sample No. 21) and lowest from *Onnatukara* sandy soils (Sample No. 8).

4.2.1.5. Available phosphorus

It was observed that the available phosphorus ranged between 30.54 to 82 kg ha^{-1}. The lowest Av. Pwas reported from *Kari* soils of Kuttanad (Sample No. 19) and highest from laterite soils (Sample No. 4). At active tillering stage all the samples were high in terms of available P content.

4.2.1.6. Available potassium

The available potassium content ranged from 25.51 to 685.68 kg ha^{-1}. The lowest Av. K was identified to be from *Pokkali* soils (Sample No. 17) and highest sufficient or high potassium when compared to other soils.

Table 14. Electro chemical properties of soil at active tillering stage

Sample No	pH	EC (dS m^{-1})	OC (%)
1	7.85	0.098	0.75
2	7.91	0.101	0.86
3	7.92	0.185	0.97
4	5.35	0.036	0.98
5	5.41	0.030	1.20
6	5.62	0.042	1.15
7	6.12	0.043	0.62
8	5.52	0.062	0.56
9	5.23	0.088	0.59
10	5.45	0.058	1.15
11	5.62	0.070	1.33
12	5.52	0.039	1.02
13	6.91	0.050	2.03
14	6.82	0.039	1.77
15	6.62	0.031	2.02
16	5.96	0.548	2.87
17	6.25	0.687	2.39
18	6.62	0.688	2.45
19	5.42	0.354	4.14
20	5.62	0.488	5.03
21	5.52	0.624	6.53
Min	5.23	0.030	0.56
Max	7.92	0.688	6.53

4.2.1.7. Available calcium

The available calcium varied from 128.94 to 2489.35mgkg^{-1}. The *Onnatukara* sandy soils reported the lowest Av. Ca value (Sample No.8) whereas *Pokkali* soils reported the highest value for Av. Ca (Sample No.18).

4.2.1.8. Available magnesium

The available magnesium content ranged from 13.39 to 1366.23 mg kg^{-1}. The highest Av. Mg was recorded in *Pokkali* soils (Sample No.17) and lowest in *Onnatukara* soils (Sample No.8).

4.2.1.9. Available sulphur

The available sulphur ranged from 2.61 to 1632.46 mg kg^{-1}. The laterite soils (Sample No.6) had the lowest Av. S whereas *Pokkali* soils (Sample No.16) reported the highest value for the same.

4.2.1.10. Available iron

The available iron in analysed samples extended from 8.98 to 182.78 mg kg^{-1}. The minimal value for Av. Fe was associated with black *cotton* soils (Sample No.3) whereas the maximal value for the same was reported from *Kari* soils (Sample No.20).

4.2.1.11. Available manganese

The available Mn in analysed samples extended between 7.28 to 32.98 mg kg^{-1}. The minimal value for Av. Mn was reported from *Onnatukara sandy* soils (Sample No.8) and maximal value from black *cotton* soils (Sample No.3).

4.2.1.12. Available zinc

The available zinc ranged from 2.65 to 16.87 mg kg$^{-1.}$ The highest value for Av. Zn was reported from *Pokkali* soils (Sample No.17) and the lowest value from *Onnatukara sandy* soils (Sample No.8).

4.2.1.13. Available copper

The available copper varied from 2.71 to 18.76 mg kg^{-1}. The value for Av. Cu was highest in *Pokkali* soils (Sample No.17) and lowest in *Onnatukara* sandy soils (Sample No.9).

Table 15. Available nutrient status at active tillering stage

Sample No	Av.N	Av.P	Av. K	Av. Ca	Av. Mg	Av. S	Av. Fe	Av. Mn	Av. Cu	Av. Zn	Av. B
	kg ha^{-1}			mg kg^{-1}							
1	87.80	68.97	500.17	1482.55	325.27	40.84	15.16	28.98	5.78	6.61	1.01
2	93.81	74.09	300.82	1983.25	395.84	32.21	14.02	21.67	4.98	5.32	0.74
3	101.81	60.56	499.32	1760.64	396.24	80.24	8.98	32.98	4.08	5.02	0.56
4	87.81	82.00	90.14	329.99	57.32	7.26	30.87	13.26	6.83	7.32	0.58
5	112.90	80.16	64.27	462.27	72.13	2.72	49.76	12.38	6.12	5.67	0.43
6	125.44	76.07	153.13	367.83	50.61	2.61	58.98	21.76	7.23	7.58	0.32
7	77.81	55.67	70.59	165.46	22.00	7.64	60.89	8.13	3.86	3.57	0.32
8	75.26	66.92	64.47	128.94	13.39	3.23	40.56	7.28	2.65	2.87	0.20
9	83.81	70.77	119.25	160.00	13.54	3.68	45.87	14.23	3.01	2.71	0.28
10	90.81	76.11	101.54	1396.00	491.39	80.36	28.98	13.45	6.95	7.45	0.43
11	100.35	65.51	100.87	2268.46	780.07	46.03	22.67	16.78	7.38	7.25	0.13
12	112.90	65.05	122.24	2226.58	763.59	49.70	21.45	27.34	6.92	6.94	0.26
13	125.44	62.50	277.76	354.00	128.00	120.00	80.54	21.28	13.87	13.76	0.54
14	115.87	57.98	484.83	298.32	108.65	155.47	59.45	12.34	10.73	11.32	0.63
15	112.90	58.33	424.32	524.00	108.57	130.95	73.76	11.98	7.47	7.65	0.77
16	118.56	40.32	88.34	2235.64	1354.45	1632.46	93.45	13.45	9.23	9.87	3.24
17	94.81	61.46	25.51	2199.64	1366.23	863.66	75.08	8.43	16.87	18.76	3.12
18	112.90	39.23	85.65	2489.35	1309.68	1353.25	90.12	10.43	13.76	15.87	5.89

Table 15. Continued

Sample No	Av.N	Av.P	Av. K	Av. Ca	Av. Mg	Av. S	Av. Fe	Av. Mn	Av. Cu	Av. Zn	Av. B
	kg ha^{-1}			mg kg^{-1}							
19	137.98	30.54	685.68	648.22	451.25	583.85	70.23	18.76	5.87	5.78	0.96
20	112.90	71.92	235.14	165.80	96.35	766.87	182.78	11.43	4.98	4.98	0.48
21	288.51	62.36	303.52	243.40	135.84	818.65	73.43	13.50	3.87	4.87	1.29
Min	75.26	30.54	25.51	128.94	13.39	2.61	8.98	7.28	2.65	2.71	0.13
Max	288.51	82.00	685.68	2489.35	1366.23	1632.46	182.78	32.98	16.87	18.76	5.89

4.2.1.14. Available boron

The reported values for available boron ranged from 0.13 to 5.89 mg kg^{-1}. The *Pokkali* soils recorded the highest value for Av. B (Sample No.18) whereas *Poonthalppadam* soils recorded the lowest value for the same (Sample No.11).

4.2.2. Total plant nutrient content

Plant samples were collected at tillering stage and analysed for total nutrients. The data on total nutrient content at tillering stage is given in table 16.

4.2.2.1. Total nitrogen

The content ranged from 1.29 to 3.11 percent. The rice crop raised in black cotton soil (Sample No.2) reported the highest total N whereas the *Poonthalpadam* soil (Sample No.11) reported the lowest value for the same.

4.2.2.2. Total Phosphorus

The total phosphorus content at tillering stage was identified to be with in the range of 0.21 to 0.7 percent. The highest value for total P was reported from laterite soils (Sample No.5) and lowest from *Kari* soils (Sample No.20).

4.2.2.3. Total Potassium

The total potassium content extended from 0.86 to 1.31 percent. The *Onattukara* soils reported the highest K content (Sample No.7) whereas *Kari* soils reported the lowest K content (Sample No.19).

4.2.2.4. Total Calcium

The total calcium content for analysed samples ranged from 0.09 to 0.35 percent. The total calcium content was the highest in black cotton soils (Sample No.1) and lowest in *Onnatukara* sandy soil (Sample No. 9).

4.2.2.5. Total Magnesium

The total magnesium content ranged from 0.011 to 0.013 per cent. The maximal value was identified to be from *Pokkali* soils (Sample No.16) and the minimal value from *Onnatukara* sandy soils (Sample No.7).

4.2.2.6. Total Sulphur

The values for total sulphur ranged from 0.03 to 0.149 percent**.** The highest S content was reported from *Pokkali* soils (Sample No.18) and the lowest from *Onnatukara sandy* soil (Sample No. 7).

Table 16. Plant nutrient content at active tillering stage

Sample No	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	Total S (%)	Total Fe(mg kg^{-1})	Total Mn (mg kg^{-1})	Total Zn (mg kg^{-1})	Total Cu (mg kg^{-1})	Total B (mg kg^{-1})
1	2.38	0.45	1.11	0.351	0.0128	0.0846	432.05	535.00	79.00	9.375	6.50
2	3.11	0.42	1.17	0.210	0.0121	0.0930	239.55	548.00	51.50	11.246	13.50
3	2.32	0.40	0.96	0.318	0.0125	0.1049	373.25	367.00	25.50	9.548	9.00
4	1.76	0.48	1.27	0.122	0.0126	0.1046	1224.88	602.00	65.00	12.150	18.50
5	1.57	0.70	1.11	0.141	0.0121	0.1215	1485.00	430.00	90.50	11.449	22.50
6	1.54	0.24	1.21	0.098	0.0123	0.0911	1835.00	463.50	70.00	10.047	4.50
7	1.71	0.42	1.31	0.191	0.0112	0.0300	919.50	336.50	80.00	18.578	9.00
8	1.65	0.47	0.97	0.115	0.0124	0.1140	1685.50	240.00	34.50	15.246	15.50
9	1.68	0.53	1.27	0.089	0.0117	0.1005	1613.00	282.00	51.50	17.325	29.50
10	1.88	0.33	1.10	0.301	0.0126	0.0846	659.62	728.00	28.50	20.249	9.00
11	1.29	0.33	1.08	0.276	0.0123	0.0792	511.79	593.00	18.50	22.245	5.50
12	1.60	0.33	0.91	0.281	0.0121	0.0914	781.35	941.50	11.00	24.358	4.50
13	2.21	0.41	1.03	0.175	0.0127	0.1159	1075.32	340.00	107.00	17.145	17.50
14	2.32	0.50	0.91	0.156	0.0128	0.1154	2511.22	1051.00	142.00	14.923	21.50
15	2.38	0.42	0.94	0.119	0.0126	0.1259	1236.38	442.00	102.50	16.288	19.50
16	1.76	0.32	0.87	0.128	0.0131	0.1360	974.35	146.50	70.50	17.145	12.50
17	1.82	0.32	0.97	0.179	0.0128	0.0900	1188.93	246.00	42.00	14.314	16.50
18	1.79	0.30	0.88	0.113	0.0125	0.1488	1467.22	295.00	49.50	14.712	17.50

Table 16. Continued

Sample No	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	Total S (%)	Total Fe (mg kg^{-1})	Total Mn (mg kg^{-1})	Total Zn (mg kg^{-1})	Total Cu (mg kg^{-1})	Total B (mg kg^{-1})
19	2.24	0.24	0.86	0.124	0.0122	0.0907	1185.44	82.00	113.00	21.246	30.50
20	2.18	0.21	1.13	0.152	0.0127	0.0922	1037.43	38.00	111.50	19.287	27.00
21	1.57	0.26	0.98	0.118	0.0121	0.1201	912.46	63.50	109.00	22.459	18.00
Min	1.29	0.21	0.86	0.09	0.0112	0.030	239.55	38.00	11.00	9.38	4.50
Max	3.11	0.70	1.31	0.35	0.0131	0.149	2511.22	1051.00	142.00	24.36	30.50

4.2.2.7. Total Iron

The analysed values for total iron ranged from 239.55 to 2511.22 mg kg^{-1}. The value for total Fe was at its maximum in *Kole* land soils (Sample No.14) whereas minimum in black cotton soils (Sample No.2).

4.2.2.8. Total Manganese

The total Mn content ranged from 38 to 1051 percent. The maximal value for total Mn was reported from *Kole* land soils (Sample No.14) the minimal value from *Kari* soils (Sample No.20).

4.2.2.9. Total Zinc

The total zinc content ranged between 11 and 142 percent. The total Zn was highest in soils of *Kole* land (Sample No.14) and lowest in soils of *Poonthalpadam* (Sample No.12).

4.2.2.10. Total Copper

The analysed values for total copper extended from 9.38 to 24.36 percent. The highest value for total Cu was reported from soils of *Poonthalpadam* (Sample No.14) whereas the lowest value was from black cotton soils (Sample No.1).

4.2.2.11. Total Boron

The total boron content ranged between 4.5 to 30.5 percent. The *Kari* soils recorded the highest total B (Sample No.19) and laterite soils recorded the lowest value for the same. (Sample No.6).

4.2.3. Summary statistics of electro chemical properties and available nutrient status

The mean values of electro chemical properties and available nutrient status at active tillering stage are furnished in table 17 and 18.

4.2.3.1. Soil pH

The mean soil pH at active tillering stage ranged from 5.46 to 7.89. The significantly highest value was reported from black cotton soil and lowest from laterite soil which is on par with *Kari* soil, *Poonthalpadam* as well as *Onattukara* sandy soil.

4.2.3.2. Electrical conductivity

The mean electrical conductivity varied between 0.036 to 0.641 dS m^{-1}. The *Pokkali* soil reported significantly higher value for electrical conductivity whereas laterite soil reported the lowest value which is on par with *Kole* land, *Poonthalpadam* soils, *Onattukara* sandy soil and black cotton soil.

Table 17. Summary statistics of electro-chemical properties of soils at active tillering stage

Soil type	pH	EC (dS m^{-1})	OC (%)
black cotton soils of chittoor	7.893^{a}	0.128^{c}	0.86^{d}
Low land brown hydromorphic laterite	5.46^{d}	0.036^{c}	1.11^{cd}
Onattukara sandy soil	5.623^{d}	0.064^{c}	0.59^{d}
Poonthalppadam -Slushy paddy land soils	5.53^{d}	0.056^{c}	1.167^{cd}
Kole lands	6.783^{b}	0.04^{c}	1.94^{bc}
Pokkali	6.277^{c}	0.641^{a}	2.57^{b}
Kari soils of Kuttanad	5.52^{d}	0.489^{b}	5.233^{a}
CD	0.406	0.111	0.837

4.2.3.3. Organic carbon

The mean values for organic carbon extended between 0.59 to 5.23 per cent. The *Kari* soil reported the significantly highest value for organic carbon whereas *Onattukara* sandy soil reported the lowest value which is on par with black cotton soil, laterite soil as well as *Poonthalpadam* soil.

4.2.3.4. Available nitrogen

The mean available nitrogen ranged from 78.96 to 179.80 kg ha^{-1}. The significantly highest value was recorded from *Kari* soils and lowest from *Onnatukara* sandy soils.

4.2.3.5. Available phosphorus

It was observed that the mean values for available phosphorus ranged between 47.00 to 79.41 kg ha^{-1}. The laterite soils recorded significantly highest value for Av. P which is on par with *Poonthalpadam* soil, black cotton soil as well as *Onattukara* sandy soil. The lowest value for Av. P was reported from *Pokkali* soil which is on par with *Kari* soil, *Onattukara* sandy soil as well as *Kole* land.

4.2.3.6. Available potassium

The mean values of available potassium content ranged from 66.50 to 433.44 kg ha^{-1}. It was found that black cotton soil had significantly highest value which is on par with *Kari* soil and *Kole* land. The lowest value was identified to be from *Pokkali* soils which is on par with *Onattukara* sandy soil, laterite soil as well as *Poonthalpadam* soil.

4.2.3.7. Available calcium

The *Pokkali* soil recorded significantly higher value for Av. Ca (2308.21 mg kg^{-1}) which is on par with *Poonthalpadam* soil whereas *Onattukara* sandy soil recorded the lowest value *Onnatukara* sandy soils (151.47) which is on par with *Kari* soil, laterite soil as well as *Kole* land.

4.2.3.8. Available magnesium

The mean available magnesium content extended between 16.31 to 1343.45 kg ha^{-1}. The significantly highest value was observed to be from *Pokkali* soil while *Onnatukara* sandy soil reported the lowest value which is on par with laterite soil and *Kole* land.

4.2.3.9. Available sulphur

The significantly highest value for Av. S was identified to be from *Pokkali* soil (1283.12 mg kg^{-1}) and lowest value from laterite soil (4.20 mg kg^{-1}) which is on par with *Onattukara* sandy soil, black cotton soil , *Kole* land as well as *Poonthalpadam* soil.

4.2.3.10. Available Iron

The mean values for available iron extended between 12.72 to 108.81 mg kg^{-1}. The significantly highest value was observed to be from *Kari* soil which is on par with *Pokkali* soil as well as *Kole* land while the lowest value was associated with black *cotton* soils which is on par with *Poonthalpadam* soil, laterite soil as well as *Onattukara* sandy soil.

4.2.3.11. Available manganese

The mean Av. Mn content ranged between 9.88 to 27.88mg kg^{-1}. The black cotton soil recorded significantly higher value for Av. Mn which is on par with *Poonthalpadam* soil whereas *Onattukara* sandy soil recorded the lowest value which is on par with *Pokkali* soil, *Kari* soil, *Kole* land as well as laterite soil.

4.2.3.12. Available zinc

The significantly highest mean value for Av. Zn was obtained from *Pokkali* soils (13.29 mg kg^{-1}) which is on par with *Kole* land whereas the lowest value was reported from *Onnatukara sandy* soils (3.17 mg kg^{-1}) which is on par with *Kari* soil as well as black cotton soil.

4.2.3.13. Available copper

The mean available copper extended between3.05 to 14.83mg kg^{-1}. The significantly highest value for Av. Cu was reported from *Pokkali* soils and lowest from *Onnatukara* sandy soils which is on par with *Kari* soil as well as black cotton soil.

4.2.3.14. Available boron

The reported mean values for available boron ranged from 0.276to 4.083mg kg^{-1}. The *Pokkali* soils recorded the significantly highest value for Av. B whereas all other soils do not exhibit any significant differences among them.

Table 18. Summary statistics of available nutrients status at active tillering stage

Soil type	Av. N	Av. P	Av. K	Av. Ca	Av. Mg	Av. S	Av. F	Av. Mn	Av. Zn	Av. Cu	Av. B
	kg ha^{-1}			mg kg^{-1}							
black cotton soils of chittoor	94.47	67.87^{ab}	433.43^{a}	1742.14^{b}	372.45^{c}	51.09^{c}	12.72^{c}	27.87^{a}	4.94^{bc}	5.65^{cd}	0.770^{b}
Low land brown hydromorphic laterite	108.72	79.41^{a}	102.51^{b}	386.69^{c}	60.02^{de}	4.19^{c}	46.53^{bc}	15.80^{bc}	6.72^{b}	6.85^{c}	0.443^{b}
Onattukara sandy soil	78.96	64.453^{abc}	84.77^{b}	151.46^{c}	16.31^{e}	4.85^{c}	49.10^{bc}	9.88^{c}	3.17^{c}	3.05^{d}	0.267^{b}
Poonthalppadam -Slushy paddy land soils	101.35	68.89^{ab}	108.21^{b}	1963.68^{ab}	678.35^{b}	58.69^{c}	24.36^{c}	19.19^{ab}	7.08^{b}	7.21^{bc}	0.273^{b}
Kole lands	118.07	59.60^{bc}	395.63^{a}	392.10^{c}	115.07^{de}	135.47^{c}	71.25^{ab}	15.20^{bc}	10.69^{a}	10.91^{b}	0.647^{b}
Pokkali	108.76	47.00^{c}	66.50^{b}	2308.21^{a}	1343.45^{a}	1283.12^{a}	86.21^{ab}	10.77^{bc}	13.28^{a}	14.83^{a}	4.083^{a}
Kari soils of Kuttanad	179.80	54.94^{c}	408.11^{a}	352.47^{c}	227.81^{cd}	723.12^{b}	108.81^{a}	14.56^{bc}	4.90^{bc}	5.21^{cd}	0.910^{b}
CD	N/A	18.59	196.21	426.88	171.25	271.31	45.19	8.759	3.471	3.76	1.093

4.2.4. Summary statistics of total plant nutrient content

The data on mean total plant nutrient content at active tillering stage is given in table 19

4.2.4.1. Total nitrogen

The mean total nitrogen content ranged from 1.59 to 2.60 percent. The rice crop raised in black cotton soils reported significantly highest total N content which is on par with *Kole* land whereas the *Poonthalpadam* soil reported the lowest value which is on par with laterite soil, *Onattukara* sandy soil, *Pokkali* soil as well as *Kari* soil.

4.2.4.2. Total Phosphorus

The mean total phosphorus content was identified to be within the range of 0.237 to 0.473 percent. The significantly highest value for total P was reported from laterite soils which is on par with *Onattukara* sandy soil, *Kole* land, black cotton soil, *Poonthalpadam* soil as well as *Pokkali* soil. The lowest value was observed in *Kari* soil which is on par with *Pokkali* soil and *Poonthalpadam* soil.

4.2.4.3. Total Potassium

The laterite soils reported significantly highest value (1.197 per cent) which is on par with *Onattukara* sandy soil, black cotton soil and *Poonthalpadam* soil. The *Pokkali* soil reported the lowest value (0.907 per cent) for total K content which is on par with *Kole* land, *Kari* soils, *Poonthalpadam* soil as well as black cotton soil.

4.2.4.4. Total Calcium

The mean total calcium content for analysed samples ranged from 0.12 to 0.293 percent. The total calcium content was significantly highest in black cotton soils which is on par with *Poonthalpadam* soil and lowest in laterite soil which is on par with *Kari* soil, *Onattukara* sandy soil, *Pokkali* soil as well as *Kole* land.

4.2.4.5. Total Magnesium

The mean total magnesium content extended between 0.012 to 0.013 per cent. The *Pokkali* soils recorded significantly higher mean total Mg wherein the *Onnatukara sandy* soils had the lowest value.

Table 19. Summary statistics of total plant nutrient content at active tillering stage

Soil type	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	Total S (%)	Total Fe(mg kg^{-1})	TotalMn (mg kg^{-1})	Total Zn (mg kg^{-1})	Total Cu (mg kg^{-1})	Total B (mg kg^{-1})
black cotton soils of Chittoor	2.60a	0.42a	1.08^{abc}	0.293^{a}	0.013	0.094	348.28^{c}	483.33^{ab}	52.00^{b}	10.05^{c}	9.66^{bc}
Low land brown hydromorphic laterite	1.62c	0.47a	1.19^{a}	0.12^{b}	0.012	0.106	1514.96^{a}	498.50^{ab}	75.16^{b}	11.21^{c}	15.16^{abc}
Onattukara sandy soil	1.68c	0.47a	1.18^{ab}	0.132^{b}	0.012	0.081	1406.00^{a}	286.16^{bc}	55.33^{b}	17.05^{b}	18.00^{ab}
Poonthalppadam - Slushy paddy land soils	1.59c	0.33ab	1.03^{abc}	0.286^{a}	0.012	0.085	650.92^{bc}	754.16^{a}	19.33^{c}	22.28^{a}	6.33^{c}
Kole lands	2.30ab	0.44a	0.96^{c}	0.150^{b}	0.013	0.119	1607.64^{a}	611.00^{a}	117.17^{a}	16.11^{b}	19.50^{ab}
Pokkali	1.79c	0.31ab	0.91^{c}	0.140^{b}	0.013	0.125	1210.16^{ab}	229.16^{bc}	54.00^{b}	15.39^{b}	15.50^{abc}
Kari soils of Kuttanad	1.99bc	0.23b	0.99b^{c}	0.131^{b}	0.012	0.101	1045.11^{ab}	61.167^{c}	111.17^{a}	20.99^{a}	25.16^{a}
CD	0.44	0.16	0.19	0.07	NA	NA	661.592	300.23	31.00	2.60	10.87

4.2.4.6. Total Sulphur

The values for mean total sulphur content varied from 0.081 to 0.125 percent**.** The significantly highest S content was reported from *Pokkali* soils and the lowest from *Onnatukara sandy* soil.

4.2.4.7. Total Iron

The significantly highest value for total Fe content (1607.64 mg kg^{-1}) was identified to be from *Kole* land which is on par with laterite soil, *Onattukara* sandy soils, *Pokkali* soil as well as *Kari* soil. The lowest value (348.28 mg kg^{-1}) was recorded from black cotton soil which is on par with *Poonthalpadam* soil.

4.2.4.8. Total Manganese

The mean total Mn content ranged from 61.17 to 754.17mg kg^{-1}. The significantly highest value was reported from *Poonthalpadam* soils which is on par with *Kole* land, laterite soil as well as black cotton soil. The minimal value was obtained from *Kari* soils which is on par with *Pokkali* soils and *Onattukara* sandy soils.

4.2.4.9. Total Zinc

The mean total zinc content ranged between 19.33 and 117.17mg kg^{-1}. The significantly highest value was identified to be from *Kole* land which is on par with *Kari* soil and lowest value from *Poonthalpadam* soil.

4.2.4.10. Total Copper

The mean total copper extended from 10.06 to 22.28mg kg^{-1}. The *Poonthalpadam* soils reported significantly higher value for total Cu content (22.28 mg kg^{-1}) which is on par with *Kari* soil. The minimal value was obtained black cotton soils (10.06 mg kg^{-1}) which is on par with laterite soil.

4.2.4.11. Total Boron

The mean total boron content ranged between 6.33to 25.17mg kg^{-1}. The *Kari* soils recorded the significantly highest value for total B content which is on par with *Kole* land, *Onattukara* sandy soil, *Pokkali* soil as well as laterite soil. The *Poonthalpadam* soils recorded the lowest value which is on par with black cotton soil, laterite soil and *Pokkali* soil.

4.2.5.1. Relationship between electrochemical parameters and available nutrients at active tillering stage

The data on correlation between electro chemical properties and available nutrient content of soil at active tillering stage is provided in table 20

The soil pH at active tillering stage significantly and positively correlated with Av. K (0.486*), Av. Mn (0.511*). Electrical conductivity had shown a significant and positive correlation with OC (0.719*), Av. N (0.447*), Av. Mg (0.633**), Av. S (0.911**), Av. Fe (0.571**), Av. Cu (0.458*), Av. B (0.777**) and negative correlation with Av. P(-0.522*).

Organic carbon was found to have a significant and positive correlation with Av. N (0.797**), Av. S (0.638**) and Av. Fe (0.682**). Available phosphorous significantly and negatively correlated with Av. Mg (-0.510*) and Av. S (-0.646**). Available potassium recorded a significant and positive correlation with Av. Mn (0.494*).

Available calcium had a significant and positive correlation with Av. Mg (0.878**), Av. Cu (0.450*), Av. B (0.543*). Available magnesium had shown a significant and positive correlation with Av. S (0.700**),Av. Zn (0.612**), Av. Cu (0.653**) and Av. B (0.771**). Available sulphur had a significant and positive correlation with Av. Fe (0.610**), Av. Zn (0.434*), Av. Cu (0.484*) and Av. B (0.830**).

Available zinc was found to have a significant and positive correlation with Av. Cu (0.991**) and Av. B (0.619**). Available copper exhibited significant and positive correlation with Av. B (0.866**).

Table 20. Correlation between electro chemical properties and available nutrients at active tillering stage

	Av.N	Av.P	Av. K	Av. Ca	Av. Mg	Av. S	Av. Fe	Av. Mn	Av. Cu	Av. Zn	Av. B
pH			0.486*					0.511*			
EC	0.447*	-0.522*			0.633**	0.911**	0.571**			0.458*	0.777**
OC	0.797**					0.638**	0.682**				
Av.P					-0.510*	-0.646**					
Av. K								0.494*			
Av. Ca					0.878**					0.450*	0.543*
Av. Mg		-0.510*		0.878**		0.700**			0.612**	0.653**	0.771**
Av. S		-0.646**			0.700**		0.610**		0.434*	0.484*	0.830**
Av. Fe						0.610**					
Av. Mn			0.494*				-0.484*				
Av. Cu					0.612**	0.434*				0.991**	0.619**
Av. Zn				0.450*	0.653**	0.484*			0.991**		0.686**

4.2.5.2. Relationship between electrochemical properties and total plant nutrient content at active tillering stage

The correlation coefficient of electrochemical properties with total plant nutrient content at tillering stage is given in table 21

Table 21. Correlation coefficient of electrochemical properties with total plant nutrient content at tillering stage

	pH	EC	OC
Total N	0.756**		
Total P		-0.558**	-0.586**
Total K		-0.450*	
Total Ca	0.465*		
Total Mn		-0.619**	
Total Zn			0.519*
Total Cu	-0.555**		0.448*
Total B			0.439*

The soil pH had a significant and positive correlation with total N (0.756**), total Ca (0.465*) and negative correlation with total Cu (-0.555**). A significant and negative correlation was reported for electrical conductivity with total P (-0.558**), total K (-0.450*) and total Mn (-0.619**). Organic carbon was found to have a significant and positive correlation with total Zn (0.519*), total Cu (0.448*), total B (0.439*) and negative correlation with total P (-0.586**).

4.3. HARVEST STAGE

4.3.1. Electro chemical properties and available nutrients

The data on electro chemical properties and available nutrient content of soil at harvest stage is provided in table 22 and 23

4.3.1.1 Soil pH

The soil pH at harvest stage ranged from 5.05 to 7.35. The highest value was recorded for black cotton soil (Sample No.3) and lowest for *Kari* soil (Sample No.21).

4.3.1.2. Electrical conductivity

The values for electrical conductivity extended between 0.038 to 1.002 dS m^{-1}. The *Pokkali* soil (Sample No.17) reported the highest value while *Kole* land soil reported the lowest value (Sample No.15).

4.3.1.3. Organic carbon

The organic carbon ranged from 0.047 to 5.32 per cent. The maximum value was observed for *Kari* soil (Sample No.21) and minimum for *Onattukara* sandy soil (Sample No.9).

4.3.1.4. Available nitrogen

The available nitrogen content ranged from 62.72 to 163.07 kg ha $^{-1}$. The *Onattukara* sandy soils were identified to possess the lowest value for Av. N (Sample No.8) whereas *Kole* land soils exhibited the highest value for the same (Sample No.14).

4.3.1.5. Available phosphorous

The values for available phosphorous Differed from 41.60 to 91.76 kg ha^{-1},The highest values for Av. P was reported from *Onnatukara sandy* soils (Sample No.9) whereas the lowest was from *Kari* soils (Sample No.19)

4.3.1.6. Available potassium

The recorded available potassium status of the analysed samples extended between 68.89 to 1504.75 kg ha^{-1}. The lowest Av. K was identified to be from *Onnatukara sandy* soils (Sample No.7) whereas the highest was from *Pokkali* soils (Sample No.18).

4.3.1.7. Available calcium

The available calcium ranged from 152.46 to 2441.03 mg kg^{-1}. The value for Av. Ca was maximum in *Poonthalpadam* soils (Sample No.11) and minimum in *Kari* soils (Sample No.20).

4.3.1.8. Available magnesium

The values for available magnesium was identified to be within the range of 9.32 to 1025.35 mg kg^{-1}. The maximal value for Av. Mg was reported from *Pokkali* soils (Sample No.18) whereas the minimal value was registered in *Onnatukara* soils (Sample No.9).

Table 22. Electro chemical properties of soil at harvest stage

Sample No	pH	EC (dS m^{-1})	OC (%)
1	7.21	0.101	0.77
2	7.32	0.135	1.11
3	7.35	0.198	1.08
4	5.23	0.040	1.01
5	5.24	0.387	1.09
6	5.32	0.499	0.96
7	5.98	0.051	0.57
8	5.5	0.080	0.50
9	5.12	0.102	0.47
10	5.21	0.062	1.03
11	5.51	0.078	0.92
12	5.62	0.039	0.69
13	6.65	0.052	3.56
14	6.21	0.040	2.14
15	6.15	0.038	2.42
16	5.76	0.954	1.77
17	6.32	1.002	1.58
18	6.26	0.987	2.81
19	5.21	0.548	4.29
20	5.21	0.658	3.47
21	5.05	0.988	5.32
Min	5.05	0.038	0.47
Max	7.35	1.002	5.32

4.3.1.9. Available sulphur

The values for available sulphur ranged between 3.45 to 935.87 mg kg^{-1}. The *Onnatukara* sandy soils reported the lowest value for Av. S (Sample No.8) while *Pokkali* soils reported the maximal value (Sample No.16).

4.3.1.10. Available iron

The values for available iron extended from 9.21 to 178.97 mg kg^{-1}. The highest value for Av. Fe was observed in *Kari* soils (Sample No.20) and lowest was in black *cotton* soils (Sample No.3).

4.3.1.11. Available manganese

The values for available Mn ranged from 7.90 to 26.54 mg kg^{-1}. It was maximum in black cotton soils (Sample No.3) and minimum in *Onnatukara* sandy soils (Sample No.8).

4.3.1.12. Available zinc

The values for available zinc was revealed to be within the range of 1.78 to 12.87 mg kg^{-1}.The maximal value for Av. Zn was reported from *Pokkali* soils (Sample No.17) and the minimal value from *Onattukara* as well as black *cotton* soils (Sample No.7 &Sample No.3).

4.3.1.13. **Available copper**

The available copper ranged from 2.09 to 16.57 mg kg^{-1}. The *Pokkali* soils reported the highest value for Av. Cu (Sample No.17) whereas *Onnatukara* soils reported the lowest value in terms of Av. Cu (Sample No.8).

4.3.1.14. **Available boron**

The values for available boron extended between 0.09 and 5.95 mg kg^{-1}. The highest value for Av. B was reported from *Pokkali* soils (Sample No.18) and the lowest value from both black *cotton* as well as laterite soils (Sample No.1&Sample No.6).

Table 23. Available nutrient status at harvest stage

Sample No	Av.N	Av.P	Av. K	Av. Ca	Av. Mg	Av. S	Av. Fe	Av. Mn	Av. Cu	Av. Zn	Av. B
	kg ha^{-1}			mg kg^{-1}							
1	75.26	78.04	456.39	1401.23	298.45	43.21	13.78	20.98	5.98	4.23	0.09
2	87.81	86.39	420.04	2003.28	284.75	54.91	18.45	22.64	3.78	4.70	0.32
3	100.35	61.34	580.03	1662.16	304.27	35.24	9.21	26.54	1.78	5.20	0.85
4	112.90	76.79	224.61	315.01	51.18	5.62	40.76	18.76	4.81	6.43	0.14
5	137.98	78.34	248.75	190.13	29.68	4.13	66.98	13.10	6.43	4.58	0.26
6	137.98	74.80	276.99	501.84	49.86	4.60	54.32	8.97	3.76	5.98	0.09
7	75.26	86.17	68.89	183.65	15.72	8.32	41.23	8.04	1.78	2.98	0.29
8	62.72	82.56	89.53	203.12	20.83	3.45	47.21	7.90	2.03	2.09	0.15
9	75.64	91.76	69.57	170.71	9.32	9.37	24.86	16.40	2.18	2.13	0.10
10	100.35	74.89	140.58	1813.27	541.11	33.58	23.54	17.54	4.25	5.48	0.40
11	90.52	71.30	153.94	2441.03	682.73	29.54	30.76	12.76	4.38	5.98	0.12
12	97.21	62.27	618.70	1370.60	295.88	55.40	17.32	20.87	2.22	4.98	0.14
13	137.98	64.97	398.21	1122.04	230.87	158.77	91.34	20.23	8.65	7.65	0.54
14	163.07	63.22	402.15	2076.08	214.65	182.93	50.65	14.32	7.35	8.32	0.38
15	150.18	71.16	434.41	593.46	547.58	132.25	67.65	9.94	4.76	5.34	0.53
16	67.89	45.56	1327.29	1534.56	993.87	935.87	100.34	8.76	5.93	7.89	3.05
17	75.26	62.52	1243.25	1313.98	931.70	854.05	83.65	14.76	12.87	16.57	2.92
18	62.72	53.66	1504.75	1916.53	1025.35	755.48	71.43	9.20	9.36	13.87	5.95

Table 23. Continued

Sample No	Av.N	Av.P	Av. K	Av. Ca	Av. Mg	Av. S	Av. Fe	Av. Mn	Av. Cu	Av. Zn	Av. B
	kg ha^{-1}			mg kg^{-1}							
19	118.78	41.60	503.42	650.24	425.32	620.82	93.45	16.36	3.65	5.18	0.56
20	112.90	71.75	235.72	152.46	97.45	364.97	178.97	9.03	3.34	4.28	0.52
21	87.81	78.82	183.30	227.51	144.73	292.69	66.21	11.10	4.04	3.91	0.92
Min	62.72	41.60	68.89	152.46	9.32	3.45	9.21	7.90	1.78	2.09	0.09
Max	163.07	91.76	1504.75	2441.03	1025.35	935.87	178.97	26.54	12.87	16.57	5.95

4.3.2. Total plant nutrient content

Plant samples collected at harvest stage were analysed and the values are given in table 19.

4.3.2.1. Total Nitrogen

The total nitrogen extended between 0.53 to 1.57 percent. It was highest in black *cotton* soils (Sample No.3) and lowest in *Kole* land soils (Sample No.13).

4.3.2.2. Total Phosphorous

The total phosphorous content ranged from 0.15 to 0.35 percent. The maximum value for total P was observed in *Kole* land soils (Sample No.15) and minimum in *Kari* soils (Sample No.19).

4.3.2.3. Total Potassium

The values for total potassium ranged between 0.95 to 1.39 percent. The highest value for total K was observed in laterite soils (Sample No.4) and lowest was in *Pokkali* soils (Sample No.16).

4.3.2.4. Total Calcium

The values for total calcium ranged from 0.117 to 0.327 percent. The maximal value for total Ca was reported from black cotton soils (Sample No.1) and the minimal value from laterite soils (Sample No.6).

4.3.2.5. Total Magnesium

The values for total Mg ranged from 0.011 to 0.014 percent. The maximal value was observed in *Pokkali* soils (Sample No.16) whereas minimal value was associated with *Onnatukara* sandy soils (Sample No.7).

4.3.2.6. Total Sulphur

The values for total sulphur extended from 0.012 to 0.119 percent. The highest value for S was reported from black cotton soils (Sample No.1) and the lowest from *Poonthalpaadam* soils (Sample No.10).

4.3.2.7. Total Iron

The total iron content ranged from 118.90 to 1005.19 mg kg^{-1}. The *Kole* land soils reported the highest value for total Fe (Sample No.14) and black cotton soils the lowest (Sample No.1).

4.3.2.8. Total Manganese

The total Mn content ranged between 109 to 705.5 mg kg^{-1}. The maximal value for Mn was identified to be from *Kole* land soils (Sample No.14) while *Kari* soils (Sample No.20) were minimal in respect to total Mn content.

4.3.2.9. Total Zinc

The values for total zinc ranged from 8.53 to 24.31 mg kg^{-1}. The value for total Zn was maximum in *Onattukara* soils (Sample No.9) and minimum n black cotton soils (Sample No.2).

4.3.2.10. Total Copper

The total copper content ranged from 18.22 to 31.55 mg kg^{-1}in the samples analysed. The highest value for total Cu was reported from *Poonthalpaadam* soils (Sample No.12) and lowest was from black cotton soils (Sample No.2).

4.3.2.11. Total Boron

The analysed values for total boron content varied between 2.90 to 5.42 percent. The *Kari* soils reported the highest B content (Sample No.19) whereas laterite soils reported the lowest (Sample No.4).

Table 24. Plant nutrient content at harvest stage

Sample No	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	Total S (%)	Total Fe (mg kg^{-1})	Total Mn (mg kg^{-1})	Total Zn (mg kg^{-1})	Total Cu (mg kg^{-1})	Total B (mg kg^{-1})
1	1.37	0.27	1.23	0.327	0.013	0.119	118.90	378.00	10.62	19.16	2.99
2	1.18	0.25	1.31	0.273	0.012	0.112	134.74	529.00	8.53	18.22	3.12
3	1.57	0.24	1.05	0.304	0.012	0.095	298.90	689.50	13.28	20.55	4.94
4	0.76	0.30	1.39	0.158	0.013	0.067	777.99	345.54	9.12	21.58	2.90
5	0.78	0.35	1.21	0.130	0.012	0.078	755.34	234.44	10.12	18.95	3.73
6	0.78	0.18	1.31	0.117	0.013	0.083	770.37	412.23	14.30	18.46	3.52
7	0.76	0.25	1.35	0.182	0.011	0.054	794.95	266.00	13.49	23.55	4.00
8	0.87	0.27	1.02	0.138	0.013	0.094	814.14	144.00	19.19	25.31	3.96
9	1.29	0.34	1.32	0.123	0.012	0.085	985.35	513.00	24.31	22.55	3.71
10	0.92	0.23	1.20	0.294	0.013	0.012	576.38	591.00	11.13	26.58	4.38
11	1.12	0.22	1.21	0.238	0.012	0.094	237.87	580.50	22.86	30.26	3.62
12	0.78	0.22	0.99	0.251	0.013	0.098	336.33	639.50	14.93	31.55	4.95
13	0.53	0.25	1.13	0.165	0.013	0.064	903.07	685.00	17.72	23.58	3.84
14	0.76	0.28	1.02	0.138	0.013	0.091	1005.19	705.50	21.27	21.55	4.44
15	0.73	0.35	1.03	0.132	0.013	0.065	928.24	698.34	19.89	19.33	3.05
16	0.62	0.22	0.95	0.134	0.014	0.073	295.78	158.27	19.27	21.96	4.47
17	0.73	0.21	1.05	0.164	0.013	0.097	696.51	187.25	10.97	19.99	4.38
18	0.64	0.18	0.99	0.150	0.013	0.109	658.75	190.00	13.85	20.37	3.61

Table 24. Continued

Sample No	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	Total S (%)	Total Fe (mg kg^{-1})	Total Mn (mg kg^{-1})	Total Zn (mg kg^{-1})	Total Cu (mg kg^{-1})	Total B (mg kg^{-1})
19	1.54	0.15	0.96	0.144	0.012	0.115	665.04	215.50	19.69	25.97	5.42
20	0.92	0.17	1.23	0.129	0.013	0.100	761.47	109.00	16.43	23.69	3.83
21	1.06	0.18	1.10	0.131	0.012	0.107	604.55	140.50	14.79	29.99	3.43
Min	0.53	0.15	0.95	0.117	0.011	0.012	118.902	109.000	8.529	18.225	2.895
Max	1.57	0.35	1.39	0.327	0.014	0.119	1005.189	705.500	24.310	31.548	5.424

4.3.3. Summary statistics of electro chemical properties and available nutrients in soil

The data on mean electro chemical properties and available nutrient content of soil at harvest stage is provided in table 25 and 26

Table 25. Summary statistics of electro-chemical properties of soils at harvest stage

Soil type	pH	EC (ds m^{-1})	OC (%)
Black cotton soils of Chittoor	7.293^{a}	0.145^{cd}	0.987^{c}
Low land brown hydromorphic laterite	5.263^{c}	0.309^{c}	1.02^{c}
Onattukara sandy soil	5.533^{c}	0.078^{d}	0.513^{c}
Poonthalppadam -Slushy paddy land soils	5.447^{c}	0.06^{d}	0.88^{c}
Kole lands	6.337^{b}	0.043^{d}	2.707^{b}
Pokkali soil	6.113^{b}	0.981^{a}	2.053^{b}
Kari soils of Kuttanad	5.157^{c}	0.731^{b}	4.36^{a}
CD	0.427	0.223	0.921

4.3.3.1 Soil pH

The mean soil pH at harvest stage ranged between 5.16 to 7.29. The significantly highest value was recorded for black cotton soil and lowest for *Kari* soil which is on par with *Poonthalpadam* soil, laterite soil as well as *Onattukara* sandy soil.

4.3.3.2. Electrical conductivity

The mean electrical conductivity extended varied between 0.043 to 0.981 dS m^{-1}. The *Pokkali* soil reported the significantly highest value while *Kole* land soil reported the lowest value which is on par with *Poonthalpadam* soil and *Onattukara* sandy soil.

4.3.3.3. Organic carbon

The *Kari* soil was found to have significantly highest value (4.36 per cent) whereas the *Onattukara* sandy soil had the lowest value 0.513 per cent which is on par with *Poonthalpadam* soil, black cotton as well as laterite soil.

4.3.3.4. Available nitrogen

The mean available nitrogen content ranged from 68.62 to 150.41 kg ha $^{-1}$. The *Kole lands* were identified to possess significantly highest value for mean Av. N whereas *Pokkali* soils exhibited the lowest value which is on par with *Onattukara* sandy soil and black cotton soil.

4.3.3.5. Available phosphorous

The significantly highest values for mean Av. P was reported from *Onnatukara* sandy soils (86.83 kg ha^{-1}) which is on par with laterite soil, black cotton soil as well as *Poonthalpadam* soil whereas the lowest value was from *Pokkali* soils (53.91 kg ha^{-1}) which is on par with *Kari* soil, *Kole* land and *Poonthalpadam* soil.

4.3.3.6. Available potassium

The mean available potassium status of the analyzed samples extended between 76.00 to 1358.43 kg ha^{-1}. The significantly highest value was identified to be from *Pokkali* soils while the lowest from *Onattukara* sandy soil which is on par with laterite soil, *Poonthalpadam* soil and *Kari* soil.

4.3.3.7. Available calcium

The mean Av. Ca was significantly higher in *Poonthalpadam* soils (1847.97 kg ha^{-1}) which is on par with black cotton soil, *Pokkali* soil as well as *Kole* land. The lowest value was observed in *Onattukara sandy* soils (185.82 kg ha^{-1}) which is on par with laterite soil and *Kari* soil .

4.3.3.8. Available magnesium

The mean available magnesium was identified to be within the range of 15.29 to 983.64 mg kg^{-1}. The significantly higher value for mean Av. Mg was reported from *Pokkali* soils whereas the minimal value was reported in *Onattukara* sandy soils which is on par with laterite soil as well as *Kari* soils.

Table 26. Summary statistics of available nutrients status at harvest stage

Sample No	Av.N	Av.P	Av. K	Av. Ca	Av. Mg	Av. S	Av. Fe	Av. Mn	Av. Cu	Av. Zn	Av. B
	kg ha^{-1}			mg kg^{-1}							
black cotton soils of chittoor	87.807^{cd}	75.25^{ab}	485.48^{b}	1688.89^{a}	295.82^{bc}	44.45^{cd}	13.81^{d}	23.39^{a}	3.85^{bc}	4.71^{bc}	0.42^{b}
Low land brown hydromorphic laterite	129.62^{b}	$76.64a^{b}$	$250.11b^{c}$	335.66^{b}	43.57^{d}	4.78^{d}	54.02^{bcd}	13.61^{b}	5.00^{bc}	5.663^{b}	0.16^{b}
Onattukara sandy soil	71.207^{d}	86.83^{a}	76.00^{c}	185.82^{b}	15.29^{d}	7.04^{d}	37.767^{cd}	10.78^{b}	2.00^{c}	2.4^{c}	0.18^{b}
Poonthalppadam -Slushy paddy land soils	96.027^{c}	69.487^{abc}	304.40^{bc}	1874.97^{a}	506.57^{b}	39.50^{cd}	23.87^{3d}	17.06^{ab}	3.62^{c}	5.48^{bc}	0.22^{b}
Kole lands	150.41^{a}	66.45^{bc}	411.59^{b}	1263.86^{a}	331.03^{bc}	157.98^{c}	69.88^{abc}	14.83^{b}	6.92^{ab}	7.103^{b}	0.48^{b}
Pokkali	68.62^{d}	53.91^{c}	1358.43^{a}	1588.35^{a}	983.64^{a}	848.47^{a}	85.14^{ab}	10.91^{b}	9.39^{a}	12.78^{a}	3.97^{a}
Kari soils of Kuttanad	106.497^{c}	64.05^{bc}	307.48^{bc}	343.40^{b}	222.50^{cd}	426.16^{b}	112.88^{a}	12.16^{b}	3.68^{c}	4.46^{bc}	0.67^{b}
CD	20.01	17.633	238.363	705.135	217.021	130.426	44.215	7.393	3.23	3.261	1.181

4.3.3.9. Available sulphur

The *Pokkali* soils reported the significantly highest value for mean Av. S (848.47 mg kg^{-1}) while laterite soils reported the lowest value (4.78 mg kg^{-1}) which is on par with *Onattukara* sandy soil, *Poonthalpadam* soil and black cotton soils.

4.3.3.10. Available iron

The mean available iron extended between 13.81 to 112.88 mg kg^{-1}. The significantly highest value for mean Av. Fe was observed in *Kari* soils which is on par with *Pokkali* soil as well as *Kole* land. The lowest value was reported in black *cotton* soils which is on par with *Poonthalpadam* soil, *Onattukara* sandy soils as well as laterite soils.

4.3.3.11. Available manganese

The mean available Mn ranged from 10.78 to 23.39 mg kg^{-1}. The mean value was significantly higher in black cotton soils which is on par with *Poonthalpadam* soils and lower in *Onattukara sandy* soils which is on par with all other soil types except black cotton soils.

4.3.3.12. Available zinc

The mean available zinc was identified to be within the range of 2.40 to 12.78mg kg^{-1}. The significantly highest value was reported in *Pokkali* soils and the lowest in *Onattukara* sandy soil which is on par with *Kari* soil, black cotton soil as well as *Poonthalpadam* soil.

4.3.3.13. Available copper

The mean available copper ranged from 2.00 to 9.39mg kg^{-1}. The *Pokkali* soils reported significantly highest value for mean Av. Cu (9.39 mg kg^{-1}) which is on par with *Kole* land. The *Onnatukara sandy* soils reported the lowest value (2.00 mg kg^{-1}) which is on par with *Poonthalpadam* soil, *Kari* soils, black cotton soil as well as laterite soil.

4.3.3.14. Available boron

The mean available boron extended between 0.163 and 3.97mg kg^{-1}. The significantly highest value for Av. B was reported from *Pokkali* soils and the lowest value laterite soils which is on par with all other soil types except *Pokkali* soils.

4.3.4. Summary statistics of total plant nutrient content

The mean total plant nutrient status at harvest stage is given in table 27

4.3.4.1. Total Nitrogen

The mean total nitrogen content extended between 0.663 to 1.373 percent. It was significantly higher in black *cotton* soils which is on par with *Kari* soil and lowest in *Pokkali* soils which is on par with *Kole* land, laterite soil, *Poonthalpadam* soils as well as *Onattukara* sandy soils.

4.3.4.2 Total Phosphorous

The mean total phosphorous content ranged from 0.167 to 0.293 percent. The *Kole* land reported significantly highest value which is on par with *Onattukara* sandy soil, laterite soil, black cotton soil as well as *Poonthalpadam* soil. The lowest value was observed in *Kari* soils which is on par with *Pokkali* soil and *Poonthalpadam* soils.

4.3.4.3 Total Potassium

The mean total potassium ranged between 0.997 to 1.303 percent. The significantly highest value for total K was observed in laterite soils and lowest in *Pokkali* soils.

4.3.4.4 Total Calcium

The significantly highest value for total Ca was recorded in black cotton soils (0.301 percent) and lowest in *Kari* soils (0.135 per cent) which is on par with laterite soil, *Kole* land, *Onattukara* sandy soil as well as *Pokkali* soils.

4.3.4.5. Total Magnesium

The mean total Mg content ranged between 0.012 to 0.013 per cent. The mean total Mg content for all the soil types were observed to be the same as far as the variations among the highest as well as lowest values of total magnesium is considered negligible (0.001 per cent).

4.3.4.6. Total Sulphur

The total sulphur content extended between 0.068 to 0.109 percent. The significantly highest value was reported from black cotton soils and lowest from *Poonthalpaadam* soils.

Table 27. Summary statistics of total plant nutrient content at harvest stage

Sample No	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	Total S (%)	Total Fe (mg kg^{-1})	Total Mn (mg kg^{-1})	Total Zn (mg kg^{-1})	Total Cu (mg kg^{-1})	Total B (mg kg^{-1})
black cotton soils of Chittoor	1.37^{a}	0.253^{ab}	1.197	0.301^{a}	0.012	0.109	184.18^{e}	532.167^{a}	10.81	19.31^{d}	3.683
Low land brown hydromorphic laterite	0.77^{c}	0.277^{ab}	1.303	0.135^{c}	0.013	0.076	767.90^{abc}	330.737^{b}	11.18	19.66^{d}	3.383
Onattukara sandy soil	0.97^{bc}	0.287^{a}	1.23	0.148^{c}	0.012	0.078	867.81^{ab}	307.667^{b}	18.997	23.80^{bc}	3.89
Poonthalppadam - Slushy paddy land soils	0.94^{bc}	0.223^{abc}	1.133	0.261^{b}	0.013	0.068	383.52^{de}	603.667^{a}	16.307	29.46^{a}	4.317
Kole lands	0.67^{c}	0.293^{a}	1.06	0.145^{c}	0.013	0.073	945.50^{a}	696.28^{a}	19.627	21.49^{cd}	3.777
Pokkali	0.66^{c}	0.203^{bc}	0.997	0.149^{c}	0.013	0.093	550.35^{cd}	178.507^{b}	14.697	20.77^{cd}	4.153
Kari soils of Kuttanad	1.17^{ab}	0.167^{c}	1.097	0.135^{c}	0.012	0.107	677.02^{bc}	155.00^{b}	16.97	26.55^{ab}	4.227
CD	0.34	0.077	N/A	0.04	N/A	N/A	218.95	177.699	N/A	3.538	N/A

4.3.4.7. Total Iron

The mean total iron content varied between 184.18 to 945.50 mg kg^{-1}. The *Kole* land soils reported significantly higher value which is on par with *Onattukara* sandy soils and laterite soil. The lowest value was recorded in black cotton soils which is on par with *Poonthalpadam* soil.

4.3.4.8. Total Manganese

The significantly higher value for mean total Mn was identified to be from *Kole* land (696.28 mg kg^{-}1) which is on par with *Poonthalpadam* soils and black cotton soils. The *Kari* soils had the lowest value 155.00 (mg kg^{-1}) which is on par with *Pokkali* soil, *Onattukara* sandy soil as well as laterite soils .

4.3.4.9. Total Zinc

The total zinc content ranged between 10.81 to 19.627 mg kg^{-1}. The value for mean total Zn was significantly high in *Kole* land and minimum in black *cotton* soils.

4.3.4.10. Total Copper

The total copper content ranged from 19.31 to 29.46 mg kg^{-1}. The significantly highest value for total Cu was reported from *Poonthalpaadam* soils which is on par with *Kari* soil. The lowest value was recorded in black cotton soils which is on par with laterite soil, *Pokkali* soil and *Kole* lands.

4.3.4.11. Total Boron

The mean total boron content varied between 3.683 to 4.317mg kg^{-1}. The *Poonthalpaadam* soils reported the highest total B content whereas laterite soils reported the lowest.

4.3.5.1. Relationship between electrochemical parameters and available nutrients at harvest stage

The correlation between soil physico-chemical properties and available nutrients are provided in table 28

The soil pH had a significant and positive correlation with Av. Ca (0.527*) and. Electrical conductivity had shown a significant and positive correlation with OC (0.530*), Av. K (0.646**), Av. Mg (0.505*), Av. S (0.830**), Av. Fe

(0.573**), Av. Zn (0.454*), Av. Cu (0.547*), Av. B (0.723**) and negative correlation with Av. P(-0.460*).

Organic carbon reported significant and positive correlation with Av. S (0.472*) and Av. Fe (0.629**).

Table 28. Correlation coefficient of electrochemical properties with available nutrients at harvest stage

	Av.P	Av. K	Av. Ca	Av. Mg	Av. S	Av. Fe	Av. Cu	Av. Zn	Av. B
pH			0.527^{*}						
EC	-0.460^{*}	0.646^{**}		0.505^{*}	0.830^{**}	0.573^{**}	0.454^{*}	0.547^{*}	0.723^{**}
OC					0.472^{*}	0.629^{**}			

4.3.5.2. Relationship between electrochemical properties and total plant nutrient content at harvest stage

The correlation coefficient of electrochemical properties with total plant nutrient content at harvest stage is given in table 29

The soil pH was found to have a significant and positive correlation with total Ca (0.572**) and negative correlation with total Cu (-0.481*). Electrical conductivity significantly and negatively correlated with total P (-0.583**) and total Mn (-0.702**). A significant and negative correlation was observed between organic carbon and total P (-0.475*).

Table 29. Correlation coefficient of electrochemical properties with total plant nutrient content at harvest stage

	Total P	Total Ca	Total Mn	Total Cu
pH		0.572**		-0.481*
EC	-0.583**		-0.702**	
OC	-0.475*			

4.4.1. Total nutrient content in grain

The grain samples were collected after harvest and analysed using standard procedures to estimate total nutrient content. The data is furnished in table 30.

4.4.1.1. Total Nitrogen

The values for total grain nitrogen content ranged from 1.33 to 1.96 percent. The maximal value was identified to be from *Kari* soils (Sample No.21) whereas minimal value was from *Kole* land soils (Sample No.13).

4.4.1.2. Total Phosphorous

The grain phosphorous content extended between 0.2 to 0.41 percent. The phosphorous content was maximum in laterite soils (Sample No.4) and minimum in *Kole* land soils (Sample No.15).

4.4.1.3. Total Potassium

The total potassium content varied from 0.23 to 0.44 percent. The highest K content was observed in *Kole* land soils (Sample No.14) and lowest in *Kari* soils (Sample No.19).

4.4.1.4. Total Calcium

The total grain calcium content ranged from 0.01 to 0.027 percent. It was the highest for samples from black *cotton* soils (Sample No.1) and lowest from *Kole* land soils (Sample No.15).

4.4.1.5. Total Magnesium

The total magnesium content varied from 0.0107 to 0.0134 percent. The maximal value was reported from *Kole* land soils (Sample No.14) and minimal from *Onattukara* soils (Sample No.7).

4.4.1.6. Total Sulphur

The values for grain sulphur content varied between 0.01 to 0.112 percent. The highest value for total S was recorded from *Kari* soils (Sample No.19) and the lowest value from *Poonthalpaadam* soils (Sample No.10).

4.4.1.7. Total Iron

The total Iron content extended between 30.53 to 219.35 percent. The *Kole* land soils (Sample No.19) reported the highest value for Fe contained in paddy grain whereas the samples collected from black *cotton* soils showed the lowest Fe content in rice grain (Sample No.1)

4.4.1.8. Total Manganese

The grain manganese content ranged from 21.26 to 78.77 percent. The highest Mn content was identified to be from black cotton soils (Sample No.3) and the lowest from *Kari* soils (Sample No.20).

4.4.1.9. Total Zinc

The analytical value on total Zn contained in grain ranged between 26 to 119 percent. The maximal value for Zn was reported from *Onnatukara* sandy soils (Sample No.9) while the minimal value was from black *cotton* soils (Sample No.2).

Table 30. Nutrient content in grain

Sample No	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	Total S (%)	Total Fe (mg kg^{-1})	Total Mn (mg kg^{-1})	Total Zn (mg kg^{-1})	Total Cu (mg kg^{-1})	Total B (mg kg^{-1})
1	1.924	0.39	0.42	0.027	0.0123	0.091	30.53	43.19	37.00	9.68	14.00
2	1.824	0.38	0.41	0.022	0.0117	0.092	34.59	60.44	26.00	11.53	15.00
3	1.95	0.40	0.38	0.025	0.0119	0.080	76.74	78.77	52.00	10.07	21.00
4	1.71	0.41	0.25	0.017	0.0131	0.054	165.83	39.48	50.00	13.17	16.06
5	1.58	0.32	0.27	0.014	0.0122	0.071	161.73	34.56	66.50	11.20	15.87
6	1.68	0.38	0.32	0.013	0.0122	0.064	164.95	47.10	61.87	9.97	14.98
7	1.65	0.33	0.36	0.020	0.0107	0.033	165.53	30.39	47.00	17.38	17.03
8	1.83	0.33	0.39	0.015	0.0125	0.078	171.55	25.03	65.50	14.28	16.87
9	1.81	0.33	0.38	0.014	0.0118	0.068	204.73	58.61	119.00	16.25	15.77
10	1.75	0.37	0.43	0.025	0.0122	0.010	120.46	67.52	38.00	19.01	23.00
11	1.83	0.32	0.43	0.019	0.0117	0.074	54.16	53.98	102.50	22.96	19.00
12	1.61	0.31	0.39	0.021	0.0120	0.087	73.32	54.41	50.00	24.97	26.00
13	1.33	0.39	0.39	0.015	0.0120	0.055	196.34	78.26	60.50	18.08	17.10
14	1.47	0.35	0.44	0.014	0.0134	0.070	219.35	60.03	73.00	16.17	20.34
15	1.48	0.20	0.40	0.012	0.0126	0.060	203.31	64.94	67.89	15.94	16.00
16	1.79	0.32	0.35	0.015	0.0130	0.054	65.02	24.66	66.00	17.02	19.00
17	1.44	0.25	0.30	0.015	0.0125	0.091	153.69	36.52	37.50	13.39	23.00
18	1.44	0.25	0.30	0.014	0.0121	0.106	145.90	28.14	45.00	13.78	18.98

Table 30. Continued

Sample No	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	Total S (%)	Total Fe (mg kg^{-1})	Total Mn (mg kg^{-1})	Total Zn (mg kg^{-1})	Total Cu (mg kg^{-1})	Total B (mg kg^{-1})
19	1.81	0.25	0.23	0.014	0.0122	0.112	141.76	27.80	67.50	19.92	28.50
20	1.71	0.26	0.26	0.014	0.0126	0.080	163.04	21.26	56.50	18.11	20.12
21	1.96	0.31	0.29	0.015	0.0122	0.104	129.44	25.20	51.45	22.51	18.00
Min	**1.33**	**0.20**	**0.23**	**0.012**	**0.0107**	**0.010**	**30.527**	**21.26**	**26.000**	**9.676**	**14.000**
Max	**1.96**	**0.41**	**0.44**	**0.027**	**0.0134**	**0.112**	**219.347**	**78.77**	**119.000**	**24.974**	**28.500**

4.4.1.10. Total Copper

The grain copper content varied from 9.68 to 24.97 percent. The highest value for Cu was recorded from *Poonthalpadam* soils (Sample No.12) and the lowest value from black cotton soils (Sample No.1).

4.4.1.11. Total Boron

The analysed grain boron content extended from 14 to 28.5 percent and was maximum in *Kari* soils (Sample No.19) and minimum in black *cotton* soils (Sample No.1).

4.4.2. Summary statistics of nutrient content in grain

4.4.2.1. Total Nitrogen

The mean total N content extended between 1.427 to 1.899 per cent. The black cotton soil reported significantly higher value which is on par with *Kari* soils, *Onattukara* sandy soils and *Poonthalpadam* soils. The lowest value was reported in *Kole* land which is on par with *Pokkali* soil.

4.4.2.2. Total Phosphorous

The total grain phosphorous content varied between 0.273 to 0.390 percent. The significantly highest value was observed to be from black cotton soil and lowest from *Pokkali* as well as *Kari* soils.

4.4.2.3. Total Potassium

The *Poonthalpadam* soils reported significantly highest value (0.417 per cent) which is on par with *Kole* land, black cotton soil and *Onattukara* sandy soils. The lowest value (0.26 per cent) was obtained from *Kari* soils which is on par with laterite soils.

4.4.2.4. Total Calcium

The mean values were found to extend between 0.014 to 0.025 per cent. The significantly higher value was identified to be from black cotton soils which is on par with *Poonthalpadam* soil and the lowest value from *Kole* land which is on par with *Kari* soil, *Pokkali* soil, laterite soil as well as *Onattukara* sandy soils.

Table 31. Summary statistics of total nutrient content in grain

Soil type	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)	Total S (%)	Total Fe (mg kg^{-1})	Total Mn (mg kg^{-1})	Total Zn (mg kg^{-1})	Total Cu (mg kg^{-1})	Total B (mg kg^{-1})
black cotton soils of Chittoor	1.899^{a}	0.39	0.403^{a}	0.025^{a}	0.012	0.088	47.287^{e}	60.800^{a}	38.333	10.427^{d}	16.667
Low land brown hydromorphic laterite	1.657^{bc}	0.37	0.28b^{c}	0.015^{b}	0.013	0.063	164.17^{abc}	40.380^{bc}	59.457	11.447^{cd}	15.637
Onattukara sandy soil	1.763^{ab}	0.33	0.377^{a}	0.016^{b}	0.012	0.06	180.603^{ab}	38.010^{c}	77.167	15.97^{b}	16.557
Poonthalppadam - Slushy paddy land soils	1.73^{abc}	0.333	0.417^{a}	0.022^{a}	0.012	0.057	82.647^{de}	58.687^{ab}	63.5	22.313^{a}	22.667
Kole lands	1.427^{d}	0.313	0.41^{a}	0.014^{b}	0.013	0.062	206.333^{a}	67.743^{a}	67.13	16.73^{b}	17.813
Pokkali	1.557^{cd}	0.273	0.317^{b}	0.015^{b}	0.013	0.084	121.537^{cd}	29.773^{c}	49.5	14.73b^{c}	20.327
Kari soils of Kuttanad	1.827^{ab}	0.273	0.26^{c}	0.014^{b}	0.012	0.099	144.747^{bc}	24.753^{c}	58.483	20.18^{a}	22.207
CD	0.204	N/A	0.046	0.004	N/A	N/A	47.306	19.615	N/A	3.339	N/A

4.4.2.5. Total Magnesium

The total magnesium content varied between 0.0117 to 0.0127 percent. The maximal value was reported from *Kole* land soils and minimal from *Onattukara* sandy soils.

4.4.2.6. Total Sulphur

The values for total grain sulphur content ranged between 0.057 to 0.099 percent. The highest value for total S was recorded from *Kari* soils and the lowest from *Poonthalpaadam* soils.

4.4.2.7. Total Iron

The significantly higher value (206.33 mg kg^{-1}) for total iron was reported in *Kole* land which is on par with *Onattukara* sandy soil and laterite soil. The lowest value (47.287 mg kg^{-1}) was observed to be from black cotton soil which is on par with *Poonthalpadam* soil.

4.4.2.8. Total Manganese

The significantly higher value (67.743 mg kg^{-1}) for total Mn was identified to be from *Kole* land which is on par with black cotton soil and *Poonthalpadam* soils. The lowest value (24.753 mg kg^{-1}) was obtained from *Kari* soil which is on par with *Pokkali* soil, *Onattukara* sandy soil and laterite soils.

4.4.2.9. Total Zinc

The total grain Zn content varied between (38.333 to 77.167 mg kg^{-1}). The highest value was observed for *Onattukara* sandy soil whereas lowest value for black cotton soil.

4.4.2.10. Total Copper

The P*oonthalpadam* soils reported significantly higher value (22.313 mg kg^{-1}) which is on par with *Kari* soil. The lowest value (10.427mg kg^{-1}) was recorded in black cotton soil which is on par with laterite soil.

4.4.2.11. Total Boron

The mean values for total B extended between (15.637 to 22.667 mg kg^{-1}). The *Poonthalapadam* soils reported the highest value whereas laterite soils reported the lowest value.

4.5. Antagonism of S with nutrients

Available S at active tillering stage had shown significant as well as negative correlation with plant P (-0.507*), plant K (-0.536*) and plant Mn (-0.529*). Available S at harvest stage significantly and negatively correlated with total P (-505*), total plant K (-0.591**) and plant Mn (-0.515*).

Table 32 Correlation coefficient between available sulphur and nutrients

	Total P content in plant	Total K content in plant	Total Mn content in plant
Available S at active tillering stage	-0.507*	-0.536*	-0.529*
Available S at harvest stage	-0.505*	-0.591**	-0.515*

4.6. SULPHUR FRACTIONS

4.6.1. Sulphur fractions before cultivation

The data on sulphur fractions analysed in the 35 soil samples collected are furnished in table 32.

The sulphate S fraction was found in the range from 6.07 mg kg^{-1} to 2255.26 mg kg^{-1}. Lowest value was reported in *Onattukara* sandy soil (Sample No. 11) and highest was in *Pokkali* soil (Sample No. 29). In case of *Pokkali* soils, all the samples showed >1500 mg kg^{-1} of sulphate sulphur and similar was the trend in *Kari*soils also where all the samples registered high amount of sulphate S.

The total water soluble S ranged from 10.25 mg kg^{-1} to 2035.25 mg kg^{-1}. The lowest was observed in low land brown laterite soil (Sample No.6) and the highest was in *Pokkali* soil (Sample No.29). The samples from low land brown laterite and *Onattukara* sandy soil contained < 20 mg kg^{-1} of total water soluble S whereas *Pokkali* and *Kari* soil contained > 500 mg kg^{-1} of total water soluble S.

The lowest content (11.23 mg kg^{-1}) of heat soluble sulphate was observed in *Onattukara* sandy soil (Sample No.13) and the highest (2089.17 mg kg^{-1}) was in *Kari* soil (Sample No.33). Samples from *Pokkali* and *Kari* soil contained > 800 mg kg^{-1} of heat soluble sulphate. The lowest content of heat soluble sulphate in *Pokkali* soil was 1606.98 mg kg^{-1}.

The sulphate soluble after ignition ranged from 59.00 to 5715.31 mg kg^{-1}. The *Onattukara* sandy soil (Sample No.13) contained lowest amount of sulphate soluble after ignition and the highest content was in *Pokkali* soil (Sample No.30). All samples from *Pokkali* and *Kari* soil contained > 2000 mg kg^{-1} of sulphate soluble after ignition, where as the samples from low land laterite and *Onattukara* sandy soils contained <120 mg kg^{-1} of sulphate soluble after ignition.

The total organic sulphur ranged from 140.69 mg kg^{-1} to 8269.67. The lowest total organic sulphur content was observed in *Onattukara* sandy soil (Sample No. 11) and highest was in *Kari* soil (Sample No.33). All other soil samples except low land brown laterite and *Onattukara* sandy soils had > 280 mg kg^{-1} of total organic sulphur.

Total sulphur content ranged from 226.33 mg kg^{-1} to 9336.45 mg kg^{-1}. The lowest content was observed in *Onattukara* sandy soil (Sample No.11) and the highest in *Kari* soil (Sample No.33). Samples from *Onattukara* sandy soils and low land brown laterite contained < 400 mg kg^{-1} of total S whereas samples from *Pokkali* and *Kari* soil contained > 4500 mg kg^{-1} of total S.

Table 33. Fractions of sulphur before cropping

Sample No.	Sulphate S	Total Water soluble S	Heat soluble S	Sulphate soluble after ignition	Total organic S	Total S
	mg kg $^{-1}$					
1	132.51	137.25	166.87	874.58	961.71	1274.27
2	54.80	68.21	109.58	403.82	741.97	1002.57
3	140.38	143.55	182.81	593.86	1018.40	1276.31
4	35.16	33.25	53.41	173.11	430.96	600.30
5	113.54	112.55	151.02	490.50	1050.80	1295.89
6	7.73	10.25	14.68	104.57	179.77	351.60
7	13.31	13.58	19.44	120.75	202.86	375.20
8	8.69	12.55	17.96	113.37	215.24	350.05
9	9.68	14.27	20.42	104.65	226.35	356.88
10	12.91	16.24	23.25	114.21	274.25	383.74
11	6.07	12.54	19.17	66.77	140.69	226.33
12	8.73	14.25	18.90	87.30	194.02	235.21
13	9.12	19.25	11.23	59.00	201.91	251.25
14	10.02	14.25	20.34	86.56	206.93	257.54
15	10.63	17.28	19.40	76.73	210.96	290.24
16	176.76	178.25	266.05	1394.37	2692.88	3568.07
17	72.54	78.25	133.14	490.67	1830.53	2473.45
18	36.45	45.25	68.70	223.16	1029.08	1289.70
19	45.62	50.12	74.67	242.02	1242.46	1730.66
20	47.57	55.25	87.34	283.66	1438.15	1773.59
21	194.32	231.24	264.12	1384.27	1019.36	1348.94
22	239.43	251.24	283.72	1045.58	1226.99	1610.22
23	120.77	162.25	180.77	587.24	812.14	1057.68
24	142.35	182.55	212.79	689.67	1056.85	1398.56
25	151.99	188.35	215.14	698.74	1101.26	1457.32
26	2125.89	1999.25	2036.05	4377.51	6642.33	8994.38
27	1619.90	1602.35	1606.98	4419.20	5527.83	7713.58
28	2027.15	1865.25	1896.62	2683.72	5701.26	7898.59
29	2255.26	2035.25	2061.11	4431.39	6144.45	8266.80
30	2121.84	1985.24	1987.73	5715.31	4906.65	6748.65
31	691.96	552.25	803.86	2605.32	3797.16	4518.62
32	1147.19	1024.25	1303.34	3499.78	5718.75	6570.85
33	2004.35	2003.25	2089.17	3102.63	8269.67	9336.45
34	1122.16	1112.25	1619.00	2143.72	5594.76	6372.43
35	860.79	784.25	1231.15	2123.48	4314.69	5130.16
Min	6.07	10.25	11.23	59.00	140.69	226.33
Max	2255.26	2035.25	2089.17	5715.31	8269.67	9336.45

4.6.2. Summary statistics of sulphur fractions before cultivation

The data on mean values of sulphur fractions are furnished in table 33.

The mean sulphate S fraction ranged between 8.91 to 2030.01 mg kg^{-1}. The significantly highest value was recorded in *Pokkali* soils while the lowest in *Onattukara* sandy soil which is on par with laterite soil, black cotton soils, *Poonthalpadam* soils and *Kole* land.

The *Pokkali* soils reported significantly higher value for total water soluble S (1897.47 mg kg^{-1}) whereas laterite soils had the lowest value (13.38 mg kg^{-}) which is on par with black cotton soils, *Poonthalpadam* soils, *Onattukara* sandy soils and *Kole* land.

The significantly highest value for heat soluble sulphate was observed in *Pokkali* soil (1917.70mg kg^{-1}) and the lowest value was recorded in *Onattukara* sandy soil (17.81 mg kg^{-1}) which is on par with laterite soil, black cotton soils, *Poonthalpadam* soils and *Kole* land.

Table 34. Summary statistics of sulphur fractions before crop cultivation

Locations	Sulphate S	Total Water soluble S	Heat soluble S	Sulphate soluble after ignition	Tota l organic S	Total S
	mg kg $^{-1}$					
Black cotton soils of Chittoor	95.28^{c}	98.96^{c}	132.74^{c}	507.17^{cd}	840.77^{bc}	1089.87^{cde}
Low land brown hydromorphic laterite	10.46^{c}	13.38^{c}	19.15^{c}	111.51^{d}	219.69^{c}	363.50^{de}
Onattukara sandy soil	8.91^{c}	15.52^{c}	17.81^{c}	75.27^{d}	190.90^{d}	252.11^{e}
Poonthalppadam -Slushy paddy land soils	75.79^{c}	81.43^{c}	125.98^{c}	526.78^{cd}	1646.62^{b}	2167.10^{c}
Kole lands	169.77^{c}	203.13^{c}	231.31^{c}	881.10^{c}	1043.32^{bc}	1374.54^{cd}
Pokkali	2030.01^{a}	1897.47^{a}	1917.70^{a}	4325.43^{a}	5784.50^{a}	7924.40^{a}
Kari soils of Kuttanad	1165.29^{b}	1095.25^{b}	1409.31^{b}	2694.98^{b}	5539.01^{a}	6385.70^{b}
CD	278.18	286.91	256.45	683.38	973.74	1100.14

The mean values for sulphate soluble after ignition ranged between 75.27 to 4325.43 mg kg^{-1}. The *Pokkali* soil had significantly highest value while the lowest value was obtained from *Onattukara* sandy soil which is on par with black cotton soils, *Poonthalpadam* soils, laterite soils.

The *Pokkali* soils had significantly highest value (5784.50 mg kg^{-1}) for total organic sulphur which is on par with *Kari* soil. The lowest value was reported in *Onattukara* sandy soil (190.90 mg kg^{-1}).

The mean total sulphur content extended between 252.11 mg kg^{-1} to 7924.40 mg kg $^{-1}$. The significantly highest value was observed to be from *Pokkali* soils whereas the lowest from *Onattukara* sandy soils which is on par with laterite soils as well as black cotton soils.

4.6.3. Relationship among the sulphur fractions

All the sulphur fractions had very high significant and positive correlation among them (table 34). Sulphate S was significantly and positively correlated with water soluble S (0.998**), heat soluble S (0.988**), sulphate soluble after ignition (0.938**), organic S (0.937**), and total S (0.960**). The water soluble S had shown significant and positive correlation with heat soluble S (0.988**), sulphate soluble after ignition (0.934**), organic S (0.939**) and total S (0.960**).

Heat soluble S was significantly and positively correlated with sulphate soluble after ignition (0.932**), organic S (0.966**) and total S (0.976**). The sulphate soluble after ignition was significantly and positively correlated with organic S (0.892**) and total S (0.918**). Organic S had significant and positive correlation with total S (0.993**).

Table 35. Correlation between sulphur fractions

	Sulphate S	water soluble S	Heat soluble S	Sulphate soluble after ignition	The total organic S	Total S
water soluble S	0.998**					
Heat soluble S	0.988**	0.988**				
Sulphate soluble after ignition	0.938**	0.934**	0.932**			
The total organic S	0.937**	0.939**	0.966**	0.892**		
Total S	0.960**	0.960**	0.976**	0.918**	0.993**	

4.6.4. Relationship between sulphur fractions and physico chemical properties of soil

Correlation coefficients of sulphur fractions with physico-chemical properties of soil are given in the table 35. All the fractions of S had significant and positive correlation with EC and organic carbon. Sulphate S was significantly and positively correlated with EC (0.945**), CEC (0.644**) and OC (0.604**).

Water soluble S had a significant and positive correlation with EC (0.941**), CEC (0.642**) and OC (0.612**) Heat soluble S was significantly and positively correlated with EC (0.924**), CEC (0.690**) and OC (0.679**). Sulphate soluble after ignition showed a significant and positive correlation with EC (0.923**), CEC (0.689**) and OC (0.563**).

Total organic sulphur had a significant and positive correlation with EC (0.880**), CEC (0.762**) and OC (0.762). Total S was significantly and positively correlated with EC (0.909**), CEC (0.750**) and OC (0.694**)

Table 36. Correlation between sulphur fractions and physico chemical properties

	Sulphate S	water soluble S	Heat soluble S	Sulphate soluble after ignition	The total organic S	Total S
EC	0.945^{**}	0.941^{**}	0.924^{**}	0.923^{**}	0.880^{**}	0.909^{**}
CEC	0.644^{**}	0.642^{**}	0.690^{**}	0.689^{**}	0.762^{**}	0.750^{**}
OC	0.604^{**}	0.612^{**}	0.679^{**}	0.563^{**}	0.762^{**}	0.694^{**}

4.6.5. Relationship between sulphur fractions and biological properties of soil

Relationship between sulphur fractions and organic properties of soil are furnished in table 36. Microbial biomass carbon and aryl sulphatase revealed significant and positive correlation with all the fractions. Dehydrogenase activity did not exhibit any significant correlation with sulphur fractions.

Microbial biomass carbon was significantly and positively correlated with sulphate S (0.606**), water soluble S (0.610**), heat soluble (0.680**), sulphate soluble after ignition (0.629**), total organic S (0.695**) and total S (0.652**).

Table 37. Correlation between sulphur fractions and biological properties of soil

	Sulphate S	water soluble S	Heat soluble S	Sulphate soluble after ignition	The total organic S	Total S
MBC	0.606^{**}	0.610^{**}	0.680^{**}	0.629^{**}	0.695^{**}	0.652^{**}
Aryl sulphatase activity	0.386^{*}	0.384^{*}	0.492^{**}	0.429^{*}	0.583^{**}	0.510^{**}

Aryl sulphatase activity was found to have a significant and positive correlation with water soluble S (0.384*), sulphate S (0.386*), heat soluble S (0.492**), sulphate soluble after ignition (0.429*), total organic S (0.583**) and total S (0.510**).

4.6.6. Sulphur fraction at active tillering stage

Soil samples were collected at active tillering stage and data on sulphur fractions are furnished in table 37.

The values for sulphate S ranged from 2.61 to 1632.46 mg kg^{-1}. The highest value was recorded from *Pokkali* soil (Sample No.16) and lowest from laterite soil (Sample No.6).

The total water soluble S extended between 3.98 to 1558.67 mg kg^{-1}. The *Pokkali* soils reported the highest value for total water soluble S (Sample No.16) whereas laterite soils reported the lowest value (Sample No.6).

The heat soluble sulphate ranged from 4.54 to 1563.47 mg kg^{-1}. The maximum value was identified to be from *Pokkali* soil (Sample No.16) and minimum value from *Onattukara* sandy soil (Sample No.9).

The values for sulphate soluble after ignition ranged from 25.19 to 3244.51 mg kg^{-1}. The highest value for sulphate soluble after ignition was reported from *Pokkali* soil (Sample No.16) and lowest value from laterite soil (Sample No.5).

The total organic sulphur extended between 115.24 to 5875.25 mg kg^{-1}. The *Kari* soils showed the maximum value for total organic S (Sample No.21) whereas *Onattukara* sandy soil showed the minimum value (Sample No.9).

The values for total sulphur ranged from 189.35 to 6795.25 mg kg^{-1}. The *Kari* soil recorded the highest value for total S (Sample No.21) and *Onattukara* sandy soil recorded the lowest value (Sample No.8).

Table 38. Sulphur fractions at active tillering stage

Sample No.	Sulphate S	Total Water soluble S	Heat soluble S	Sulphate soluble after ignition	Total organic S	Total S
	mg kg^{-1}					
1	40.84	42.88	51.43	245.47	503.25	648.38
2	32.21	38.81	35.34	225.79	436.12	578.33
3	80.24	90.30	10.66	420.54	590.08	1033.09
4	7.26	9.93	13.77	81.67	168.70	478.33
5	2.72	4.46	6.02	25.19	201.24	298.32
6	2.61	3.98	5.39	37.17	214.25	310.25
7	7.64	10.89	24.14	78.35	177.10	284.55
8	3.23	5.33	6.99	29.86	152.24	189.35
9	3.68	6.02	4.54	26.99	115.24	197.36
10	80.36	87.23	120.96	599.33	1685.24	1796.39
11	46.03	51.13	84.49	297.26	1458.25	1635.13
12	49.70	60.07	54.61	305.47	1001.25	1198.25
13	120.00	157.50	163.10	810.93	1031.25	1278.35
14	155.47	175.88	184.23	780.72	1198.21	1303.25
15	130.95	161.23	196.00	653.09	880.56	1008.25
16	1632.46	1558.67	1563.47	3244.51	5100.62	6312.73
17	863.66	833.84	856.77	2171.23	3875.25	5103.35
18	1353.25	1238.88	1266.12	1973.04	3805.96	5112.01
19	583.85	522.82	678.26	1841.63	3196.07	3921.74
20	766.87	668.67	863.06	1672.96	3929.88	4752.24
21	818.65	651.22	839.47	1076.88	5875.25	6795.25
Min	**2.61**	**3.98**	**4.54**	**25.19**	**115.24**	**189.35**
Max	**1632.46**	**1558.67**	**1563.47**	**3244.51**	**5875.25**	**6795.25**

4.6.7. Summary statistics of sulphur fractions at active tillering stage

Soil samples were collected at active tillering stage and the data on mean sulphur fractions are furnished in table 38.

The mean values for sulphate S ranged between 4.20 to 1283.12 mg kg^{-1}. The significantly highest value was recorded from *Pokkali* soil and lowest from laterite soil which is on par with black cotton soil, *Onattukara* sandy soils, *Poonthalpadam* soils and *Kole* lands.

The mean total water soluble S extended between 6.12 to 1210.46 mg kg^{-1}. The *Pokkali* soils reported significantly highest value for total water soluble S whereas laterite soils reported the lowest value which is on par with black cotton soil, *Onattukara* sandy soils, *Poonthalpadam* soils and *Kole* lands.

The significantly higher value for heat soluble S was identified to be from *Pokkali* soil (1228.79 mg kg^{-1}) and lowest value from laterite soil (8.39 mg kg^{-1})

Table 39. Summary statistics of sulphur fraction at active tillering stage

Soil type	Sulphate S	Total Water soluble S	Heat soluble S	Sulphate soluble after ignition	Total organic S	Total S
	mg kg^{-1}					
Black cotton soils of Chittoor	95.28[c]	98.96[c]	132.74[c]	507.17[cd]	840.77[bc]	1089.87[cde]
Low land brown hydromorphic laterite	10.46[c]	13.38[c]	19.15[c]	111.51[d]	219.69[c]	363.50[de]
Onattukara sandy soil	8.91[c]	15.52[c]	17.81[c]	75.27[d]	190.90[d]	252.11[e]
Poonthalppadam -Slushy paddy land soils	75.79[c]	81.43[c]	125.98[c]	526.78[cd]	1646.62[b]	2167.10[c]
Kole lands	169.77[c]	203.13[c]	231.31[c]	881.10[c]	1043.32[bc]	1374.54[cd]
Pokkali	2030.01[a]	1897.47[a]	1917.70[a]	4325.43[a]	5784.50[a]	7924.40[a]
Kari soils of Kuttanad	1165.29[b]	1095.25[b]	1409.31[b]	2694.98[b]	5539.01[a]	6385.70[b]
CD value	278.18	**286.91**	**256.45**	**683.38**	**973.74**	**1100.14**

which is on par with black cotton soil, *Onattukara* sandy soils, *Poonthalpadam* soils and *Kole* lands.

The mean values for sulphate soluble ranges between (45.07 to 2462.93 mg kg^{-1}). The *Pokkali* soil reported significantly highest value for sulphate soluble after ignition while the *Onattukara* sandy soils had the lowest value which is on par with black cotton soil, laterite soils and *Poonthalpadam* soils.

The *Kari* soils showed significantly higher value for total organic sulphur (433.73 mg kg^{-1}) which is on par with *Pokkali* soils whereas the *Onattukara* sandy soils had the lowest value (148.19 mg kg^{-1}) which is on par with laterite soils, black cotton soils and *Kole* lands.

The mean values for total sulphur ranged between 223.75 to 5156.41 mg kg^{-1}. The *Pokkali* soil recorded significantly highest value for total S which is on par with *Kari* soils while the *Onattukara* sandy soils recorded the lowest value which is on par with laterite soils, black cotton soils and *Kole* lands.

4.6.8. *Relationship among the sulphur fractions at active tillering stage*

All the sulphur fractions had very high significant and positive correlation among them (table 39). Sulphate S was significantly and positively correlated with water soluble S (0.997**), heat soluble S (0.996**), sulphate soluble after ignition (0.941**), organic S (0.896**) and total S (0.922**). The water soluble S had shown significant and positive correlation with heat soluble S (0.991**), sulphate soluble after ignition (0.952**), organic S (0.874**) and total S (0.902**).

Heat soluble S was significantly and positively correlated with sulphate soluble after ignition (0.951**), organic S (0.917**) and total S (0.938**). The sulphate soluble after ignition was significantly and positively correlated with organic S (0.859**) and total S (0.881**). Organic S had significant and positive correlation with total S (0.996**).

Table 40. Correlation between sulphur fractions at active tillering stage

	Sulphate S	water soluble S	Heat soluble S	Sulphate soluble after ignition	The total organic S
Sulphate S					
water soluble S	0.997**				
Heat soluble S	0.996**	0.991**			
Sulphate soluble after ignition	0.941**	0.952**	0.951**		
The total organic S	0.896**	0.874**	0.917**	0.859**	
Total S	0.922**	0.902**	0.938**	0.881**	0.996**

4.6.9. ***Relationship between electro chemical properties, available N, P, and sulphur fractions at active tillering stage***

The correlation coefficients of above relationship are shown in table 40.

The electrical conductivity significantly and positively correlated with sulphate S (0.911**), water soluble S (0.892**), heat soluble S (0.911**), sulphate soluble after ignition (0.835**), total organic S (0.911**) and total S (0.939**).

The organic carbon was found to have a significant and positive correlation with sulphate S (0.638**), water soluble S (0.596**), heat soluble S (0.686**), sulphate soluble after ignition (0.613**), total organic S (0.862**) and total S (0.838**).

The Av. N had significant and positive correlation with total organic S (0.626**) and total S (0.586**). The Av. Psignificantly and negatively correlated with sulphate S (-0.646**), water soluble S (-0.656**), heat soluble S (-0.649**), sulphate soluble after ignition (-0.694**), total organic S (-0.532*) and total S (-0.552**).

Table 41. Correlation between sulphur fractions, electro chemical properties, available N and P at active tillering stage

	Sulphate S	water soluble S	Heat soluble S	Sulphate soluble after ignition	The total organic S	Total S
EC	0.911**	0.892**	0.911**	0.835**	0.911**	0.939**
OC	0.638**	0.596**	0.686**	0.613**	0.862**	0.838**
Av.N					0.626**	0.586**
Av.p	-0.646**	-0.656**	-0.649**	-0.694**	-0.532*	-0.552**

4.6.10. Sulphur fractions at harvest stage

The data on sulphur fraction at harvest stage are shown in table 41. The values for sulphate S extended between 3.45 to 935.87 mg kg^{-1}. The highest value was observed in *Pokkali* soil (Sample No.16) and lowest in *Onattukara* sandy soil (Sample No.8).

The total water soluble S content ranged from 5.33 to893.57 mg kg^{-1}. The *Pokkali* soil (Sample No.16) reported the maximum value for total water soluble S whereas *Onattukara* sandy soil reported the lowest value (Sample No.8).

The heat soluble sulphate ranged from 6.04 to 896.32 mg kg^{-1}. The maximum value for heat soluble sulphate was recorded from *Pokkali* soil (Sample No.16) and minimum value from laterite soil (Sample No.5).

The values for sulphate soluble after ignition extended between 33.25 to 1915.25 mg kg^{-1}. The highest value was identified to be from *Kari* soil (Sample No.19) and lowest from *Onattukara* soil (Sample No.8).

Table 42. Sulphur fractions at harvest stage

Sample No.	Sulphate S	Total Water soluble S	Heat soluble S	Sulphate soluble after ignition	Total organic S	Total S
	mg kg^{-1}					
1	43.21	45.37	54.41	261.24	512.33	650.87
2	54.91	66.16	109.79	385.25	525.79	628.54
3	35.24	39.66	62.87	251.10	489.15	622.35
4	5.62	7.69	10.67	63.25	130.99	363.46
5	4.13	6.76	6.04	35.96	165.33	253.79
6	4.60	7.01	9.50	68.25	196.33	278.35
7	8.32	11.86	26.29	83.25	124.54	253.79
8	3.45	5.33	7.48	33.25	143.25	208.55
9	9.37	6.02	11.54	69.55	112.33	183.46
10	33.58	36.45	50.55	241.35	704.25	1145.24
11	29.54	32.81	54.21	192.35	935.73	1278.25
12	55.40	66.95	60.87	341.24	1115.82	1335.83
13	158.77	208.39	215.80	1075.35	1324.54	1691.43
14	182.93	206.94	216.77	919.99	1409.35	1533.72
15	132.25	162.83	197.95	657.99	889.37	1018.43
16	935.87	893.57	896.32	1862.01	2945.79	3619.49
17	854.05	824.57	847.24	844.33	3814.33	5046.61
18	755.48	691.62	706.83	1102.35	2124.88	2853.46
19	620.82	555.93	721.22	1915.25	3397.90	4170.96
20	364.97	318.24	414.65	1032.02	2758.95	4148.66
21	292.69	232.83	305.08	725.24	4265.79	5698.55
Min	**3.45**	**5.33**	**6.04**	**33.25**	**112.33**	**183.46**
Max	**935.87**	**893.57**	**896.32**	**1915.25**	**4265.79**	**5698.55**

The total organic sulphur ranged from 112.33 to 4265.79 mg kg^{-1}. The *Kari* soil had shown the highest value for total organic sulphur (Sample No.21) whereas *Onattukara* sandy soil reported the lowest value (Sample No.9).

The values for total sulphur extended between 183.46 to 5698.55 mg kg^{-1}. The highest value was observed in *Kari* soil (Sample No.21) and lowest in *Onattukara* sandy soil (Sample No.9).

4.6.11. Summary statistics of sulphur fractions at harvest stage

The data on mean sulphur fraction values at harvest stage are shown in table 42.

The mean sulphate S extended between 4.78 to 848.47 mg kg^{-1}. The significantly highest value was observed in *Pokkali* soil and lowest in laterite soil which is on par with black cotton soils, *Onattukara* sandy soils as well as *Poonthalpadam* soils.

The mean total water soluble S content ranges between7.16 to803.25 mg kg^{-1}. The *Pokkali* soil reported significantly higher value for total water soluble S whereas laterite soils reported the lowest value which is on par with black cotton soils, *Onattukara* sandy soils as well as *Poonthalpadam* soils.

The *Pokkali* soils had significantly highest mean heat soluble sulphate (816.80 mg kg^{-1}) while the laterite soils recorded the lowest value (8.73 mg kg^{-1}) which is on par with black cotton soils, *Onattukara* sandy soils and *Poonthalpadam soils.*

The mean values for sulphate soluble after ignition extended between 55.82 to 1269.56 mg kg^{-1}. The significantly highest value was identified to be for *Pokkali* soils which is on par with *Kari* soils and *Kole* lands. The lowest value was reported from laterite soil which is on par with black cotton soils, *Onattukara* sandy soils as well as *Poonthalpadam* soils.

The *Kari* soil had significantly highest mean total organic sulphur (3474.21mg kg^{-1}.) which is on par with *Pokkali* soils whereas *Onattukara* sandy soil reported the lowest value (126.71 mg kg^{-1}) which is on par with laterite soils and black cotton soils.

Table 43. Summary statistics of sulphur fraction at harvest stage

Locations	Sulphate S	Total Water soluble S	Heat soluble S	Sulphate soluble after ignition	Total organic S	Total S
	mg kg^{-1}					
Black cotton soils of Chittoor	44.45^{cd}	50.40^{d}	75.69^{cd}	299.20^{b}	509.09^{bcd}	633.92^{bcd}
Low land brown hydromorphic laterite	4.78^{d}	7.16^{d}	8.73^{d}	55.82^{b}	164.21^{cd}	298.53^{cd}
Onattukara sandy soil	7.05^{d}	7.74^{d}	15.10^{d}	62.01^{b}	126.71^{d}	215.26^{d}
Poonthalppadam -Slushy paddy land soils	39.50^{cd}	45.40^{d}	55.21^{cd}	258.32^{b}	918.60^{bc}	1253.11^{bc}
Kole lands	157.98^{c}	192.72^{c}	210.18^{c}	884.44^{a}	1207.76^{b}	1414.52^{b}
Pokkali	848.47^{a}	803.25^{a}	816.80^{a}	1269.56^{a}	2961.66^{a}	3839.85^{a}
Kari soils of Kuttanad	426.16^{b}	369.00^{b}	480.31^{b}	1224.17^{a}	3474.21^{a}	4672.72^{a}
CD value	130.43	132.04	158.48	561. 02	785.34	974.25

The mean values for total sulphur extended between 215.26 to 4672.72 mg kg^{-1}. The significantly highest value was observed in *Kari* soil which is on par with *Pokkali* soils and lowest in *Onattukara* sandy soils which is on par with laterite soils as well as black cotton soils.

4.6.12. *Relationship among the sulphur fractions at harvest stage*

A significant and positive correlation was observed among the sulphur fractions and the correlation coefficients are furnished in table 43. Sulphate S had significant and positive correlation with water soluble S (0.997**), heat soluble S (0.994**), sulphate soluble after ignition (0.835**), organic S (0.813**) and total S (0.793**). The water soluble S significantly and positively correlated with heat soluble S (0.992**), sulphate soluble after ignition (0.838**), organic S (0.793**) and total S (0.769**).

Heat soluble S was found to have a significant and positive correlation with sulphate soluble after ignition (0.873**), organic S (0.834**) and total S

(0.812**). The sulphate soluble after ignition significantly and positively correlated with organic S (0.771**) and total S (0.732**). Organic S recorded significant and positive correlation with total S (0.994**).

Table 44. Correlation between sulphur fractions at harvest stage

	Sulphate S	water soluble S	Heat soluble S	Sulphate soluble after ignition	Total organic S
water soluble S	0.997**				
Heat soluble S	0.994**	0.992**			
Sulphate soluble after ignition	0.835**	0.838**	0.873**		
Total organic S	0.813**	0.793**	0.834**	0.771**	
Total S	0.793**	0.769**	0.812**	0.732**	0.994**

4.6.13. ***Relationship between electro chemical properties, Av.P, and sulphur fractions at harvest stage***

The correlation coefficients of above relationship are furnished in table 44.

The electrical conductivity significantly and positively correlated with sulphate S (0.830**), water soluble S (0.800**), heat soluble S (0.805**), sulphate soluble after ignition (0.573**), total organic S (0.804**) and total S (0.815**). The organic carbon had shown significant and positive correlation with sulphate S

Table 45. Correlation between electro chemical properties, available P, and sulphur fractions at harvest stage

(0.472*), water soluble (0.452*), heat soluble S (0.524*), sulphate soluble after ignition (0.692**), total organic S (0.774**) and total S (0.772**).

	EC	OC	P
Sulphate S	0.830**	0.472*	-0.733**
water soluble S	0.800**	0.452*	-0.743**
Heat soluble S	0.805**	0.524*	-0.752**
Sulphate soluble after ignition	0.573**	0.692**	-0.817**
Total organic S	0.804**	0.774**	-0.578**
Total S	0.815**	0.772**	-0.529*

The Av. Psignificantly and negatively correlated with sulphate S (-0.733**), water soluble S (-0.743**), heat soluble S (-0.752**), sulphate soluble after ignition (-0.817**), total organic S (-0.578**) and total S (-0.529*).

4.7. Contribution of different sulphur fractions to available pool

The correlation as well as path coefficients of sulphur fractions on available pool are furnished in table 46 The sulphate sulphur considered as the available S was excluded from the correlation study and path analysis. All the fractions exhibited significantly high correlation with available S.

Water soluble S significantly and positively correlated with available S (0.998**). The direct effect of total water soluble S (0.839) on available S was positive. Indirect effect of water soluble S on available S through total S (0.177), heat soluble S (0.142) and sulphate soluble after ignition (0.024) was found to be positive whereas organic sulphur exerts a negative indirect effect (-0.183) on available S.

Table 46. Coefficients of correlation and path coefficients of different fractions of S on available pool

	Total Water soluble S	Heat soluble S	Sulphate soluble after ignition	Total organic S	Total S	
Total Water soluble S	0.838	0.142	0.023	-0.183	0.177	0.998**
Heat soluble S	0.828	0.143	0.023	-0.188	0.180	0.988**
Sulphate soluble after ignition	0.783	0.134	0.025	-0.173	0.169	0.938**
Total organic S	0.788	0.139	0.022	-0.195	0.183	0.938**
Total S	0.806	0.140	0.023	-0.193	0.184	0.961**

Heat soluble S had significant and positive correlation with available S (0.988**). The direct effect of heat soluble S (0.144) on available S was positive. Heat soluble S had an indirect positive effect on available S through water soluble S (0.829), sulphate soluble after ignition (0.023), total S (0.180) and had negative indirect effect through organic S (-0.189) on available S.

Sulphate soluble after ignition exhibited significant as well as positive correlation with available S (0.938). Sulphate soluble after ignition had direct positive effect on available S (0.025) whereas the indirect effect of sulphate soluble after ignition on available S through water soluble S (0.784), heat soluble S (0.134), total S (0.169) was positive. Sulphate soluble after ignition exhibited negative indirect effect on available S through organic S (-0.174).

Organic S was found to have significantly positive correlation with available S (0.938**). The direct effect of organic S (-0.195) on available S was negative. The indirect effect of organic S on available S through water soluble (0.788), heat soluble S (0.139), sulphate soluble after ignition (0.022) and total S (0.183) was positive.

Total S was found to have significantly positive correlation with available S (0.961**). The direct effect of total S on available S was positive (0.183). Indirect effect of total S on available S through total water soluble S (0.807), heat soluble S (0.141), sulphate soluble after ignition (0.023) was positive. Total S had negative indirect effect on available S through organic S (-0.194).

4.8. TOTAL C, N, P, S, C:S AND N:S RATIO

4.8.1. Before cultivation

The data on total C, N, P, S content estimated prior to rice cultivation are furnished in table 45.

4.8.1.1. Total carbon

The values for total C ranged from 0.456 to 8.485 per cent. The highest value for total C was reported from *Kari* soils (Sample No.33) and lowest from *Onattukara* sandy soils (Sample No.14).

4.8.1.2. Total nitrogen

The total N content varied from 0.097 to 0.732 per cent. The maximal value for total N was identified to be from *Kole* land (Sample No.21) whereas minimal from *Onattukara* sandy soils (Sample No.14).

4.8.1.3. Total phosphorous

The values for total P extended between 0.012 and 0.310 per cent. The *Poonthalpadam* soils reported the highest value for total P (Sample No.19) and *Onattukara* sandy soils reported the lowest value (Sample No.12).

4.8.1.4. Total sulphur

The values for total S ranged from 0.023 to 0.934 per cent. The highest value for total S was recorded from *Kari* soil (Sample No.33) and lowest from *Onattukara* sandy soil (Sample No.11).

4.8.1.5. Total carbon: Total sulphur ratio (C:S ratio)

The values for C:S ratio ranged from 2.717 to 38.605. The laterite soil (Sample No.7) reported the maximum value for C:S ratio whereas *Pokkali* soil (Sample No.26) reported the minimum value.

4.8.1.6. Total nitrogen:Total sulphur ratio (N:S ratio)

The N:S ratio extended between 0.341 and 8.473. The highest ratio was recorded for *Onattukara* sandy soil (Sample No.11) and lowest for *Pokkali* soil (Sample No.27).

Table 47. Total C, N, P, S, C:S Ratio and N :S ratio before cultivation

Sample No	TC %	TN %	TP %	TS %	C:S Ratio	N :S ratio
1	1.074	0.156	0.026	0.127	8.424	1.228
2	1.222	0.183	0.019	0.100	12.193	1.822
3	1.315	0.239	0.023	0.128	10.305	1.876
4	1.266	0.167	0.019	0.060	21.086	2.784
5	1.020	0.214	0.014	0.130	7.871	1.652
6	1.080	0.245	0.091	0.035	30.720	6.972
7	1.448	0.194	0.096	0.038	38.605	5.182
8	1.233	0.258	0.081	0.035	35.214	7.357
9	1.045	0.178	0.084	0.036	29.270	4.993
10	1.107	0.298	0.051	0.038	28.849	7.772
11	0.631	0.192	0.015	0.023	27.882	8.473
12	0.571	0.175	0.012	0.024	24.277	7.437
13	0.605	0.169	0.039	0.025	24.097	6.726
14	0.456	0.097	0.012	0.026	17.690	3.765
15	0.483	0.139	0.014	0.029	16.645	4.781
16	0.994	0.205	0.092	0.357	2.786	0.573
17	0.946	0.221	0.163	0.247	3.824	0.892
18	1.155	0.187	0.106	0.129	8.954	1.447
19	0.870	0.187	0.310	0.173	5.026	1.081
20	0.930	0.194	0.071	0.177	5.244	1.095
21	3.091	0.732	0.082	0.135	22.911	5.425
22	2.712	0.234	0.066	0.161	16.843	1.456
23	3.055	0.340	0.051	0.106	28.880	3.218
24	2.435	0.220	0.037	0.140	17.408	1.575
25	2.020	0.356	0.050	0.146	13.859	2.443
26	2.444	0.659	0.017	0.899	2.717	0.732
27	2.251	0.263	0.033	0.771	2.918	0.341
28	3.274	0.474	0.036	0.790	4.146	0.600
29	3.093	0.446	0.032	0.827	3.742	0.539
30	2.579	0.575	0.044	0.675	3.822	0.852
31	5.314	0.434	0.227	0.452	11.760	0.960
32	4.513	0.291	0.162	0.657	6.869	0.443
33	8.485	0.568	0.131	0.934	9.088	0.608
34	4.877	0.471	0.124	0.637	7.653	0.739
35	3.776	0.323	0.117	0.513	7.361	0.631
Min	**0.456**	**0.097**	**0.012**	**0.023**	**2.717**	**0.341**
Max	**8.485**	**0.732**	**0.310**	**0.934**	**38.605**	**8.473**

4.8.2. Summary statistics of total C, N, P, S, C:S and N:S ratio before cultivation

4.8.2.1. Total carbon

The *Kari* soil reported significantly higher mean value (5.39 per cent) whereas *Onattukara* sandy soil (0.55 per cent) reported the lowest value which is on par with *Poonthalpadam* soil, black cotton soil as well as laterite soil.

4.8.2.2. Total nitrogen

The mean values extended between 0.154 to 0.483 per cent. The significantly highest value was observed for *Pokkali* soil which is on par with *Kari* soil and *Kole* land. The *Onattukara* sandy soil reported lowest value which is on par with black cotton soil, *Poonthalpadam* soil as well as laterite soils.

4.8.2.3. Total phosphorous

The mean values for total P ranged between 0.018 to 0.152 per cent. The *Kari* soils recorded significantly higher value which is on par with *Poonthalpadam* soils. The lowest value was obtained from *Onattukara* sandy soil which is on par with black cotton soil, *Pokkali* soils as well as *Kole* land.

4.8.2.4. Total sulphur

The significantly highest value was identified to be from *Pokkali* soil (0.792 per cent) whereas lowest value (0.025 per cent) was identified from *Onattukara* sandy soils which is on par with laterite soil and black cotton soil.

4.8.2.5. Total carbon: Total sulphur ratio (C:S ratio)

The laterite soils recorded significantly highest value for C:S ratio (32.532) while the lowest value (3.469) was reported from *Pokkali* soil which is on par with *Poonthalpadam* soil and *Kari* soils.

4.8.2.6. Total nitrogen : Total sulphur ratio (N:S ratio)

The mean values of N:S ratio was found to vary between 0.613 to 6.455. The significantly higher value was obtained in laterite soil which is on par with *Onattukara* sandy soil and the lowest value was reported from *Pokkali* soil which is on par with *Kari* soil, *Poonthalpadam* soils and black cotton soils.

Table 48. Summary statistics of total C, N, P, S, C:S and N :S ratio before cultivation

locations	TC %	TN %	TP %	TS %	C:S Ratio	N :S ratio
Black cotton soils of Chittoor	1.179[c]	0.192[b]	0.02[c]	0.109[cde]	11.976[c]	1.872[bc]
Low land brown hydromorphic laterite	1.183[c]	0.235[b]	0.081[b]	0.036[de]	32.532[a]	6.455[a]
Onattukara sandy soil	0.549[c]	0.154[b]	0.018[c]	0.025[e]	22.118[b]	6.236[a]
Poonthalppadam - Slushy paddy land soils	0.979[c]	0.199[b]	0.148[a]	0.217[c]	5.167[d]	1.018[c]
Kole lands	2.663[b]	0.376[a]	0.057b[c]	0.138[cd]	19.98[b]	2.823[b]
Pokkali	2.728[b]	0.483[a]	0.032[bc]	0.792[a]	3.469[d]	0.613[c]
Kari soils of Kuttanad	5.393[a]	0.417[a]	0.152[a]	0.639[b]	8.546[cd]	0.676[c]
CD	0.949	0.141	0.054	0.11	5.245	1.427

4.9.1. Relationship between total C, N, P, S and C:S, N:S ratio

The correlation coefficients are given in table 48.

The total C had a significant and positive correlation with total N (0.672**), total P (0.370*), total S (0.714**) and negative correlation with N:S ratio (-0.457**). The total N was found to have a significant and positive correlation with total S (0.676**). The total S recorded significant and negative correlation with C:S ratio (-0.668**), N:S ratio (-0.656**).

The C:S ratio significantly and positively correlated with N:S ratio (0.871**).

Table 49. Correlation between total C, N, P, S and C:S, N:S ratio

	TC %	TN	TS	C:S Ratio	N :S ratio
TN	0.672**	1			
TP	0.350*				
TS	0.714**	0.676**	1		
C:S Ratio			-0.668**	1	
N :S ratio	-0.457**		-0.656**	0.871**	1

4.9.2. Relationship between physico-chemical properties and total C, N, P, S, C:S, N:S ratio

The correlation coefficients of above relationship are given in table 50. The total C significantly and positively correlated with EC (0.571**), CEC (0.630**), organic carbon (0.992**) and temperature (0.493**). The total N was found to have a significant and positive correlation with EC (0.570**),CEC (481**) and organic carbon (0.614**). The total P had a significant and positive correlation with organic carbon (0.399*).

The total S reported significant and positive correlation with EC (0.909**), CEC (0.750**) and organic carbon (0.694**)

The C:S ratio had shown a significant and positive correlation with silt content (0.515**) and negative correlation with EC (-0.554**), CEC (-0.792**). The N:S ratio significantly and negatively correlated with EC (-0.522**), CEC (-0.867**), organic carbon (-0.447**).

Table 50. Correlation between physico-chemical properties and total C, N, P, S, C:S, N:S ratio

	pH	**EC**	**CEC**	**OC**
TC		0.571**	0.630**	0.992**
Total N		0.570**	0.481**	0.614**
Total P	-0.535**			0.399*
Total S		0.909**	0.750**	0.694**
C:S		-0.554**	-0.792**	
N:S		-0.522**	-0.867**	-0.447**

4.9.3. Relationship between total C, N, P, S, C:S, N:S ratio and Av. N, Av. P and Av. S

The correlation coefficients are given in table 51.

The total carbon was found to have a significant and positive correlation with Av. N (0.749**), Av. S (0.641**), and negative correlation with Av. P (-0.350*).

Table 51. Correlation between total C, N, P, S, C:S, N:S ratio and available N, P and S

	Av.N	Av.P	Av. S
TC	0.749**	-0.350*	0.641**
Total N	0.908**		0.708**
Total S	0.542**		0.960**
C:S			-0.560**
N:S			-0.533**

The total N had a significant and positive correlation with Av. N (0.908**) and Av. S (0.708**). The total sulphur recorded a significant and positive correlation with Av. N (0.542**) and Av. S (0.960**). The C:S ratio had a significant and negative correlation with Av. S (-0.560**).

The N:S ratio significantly and negatively correlated with Av. S (-0.533**).

4.9.5. Relationship between biological properties and C, N, P, S ,N:S, ratio

The correlation coefficients are given in table 52.

The microbial biomass carbon (MBC) had a significant and positive correlation with total C (0.894**), total N (0.689**), total S (0.652**) and negative correlation with N:S ratio (-0.433**). The dehydrogenase activity was found to have a significant and positive correlation with total P (0.479**).

The aryl sulphatase activity had significant and positive correlation with total C (0.856**), total N (0.420*), total P (0.454**), total S (0.510**) and negative correlation with N:S ratio (-0.412*).

Table 52. Correlation of biological properties and C, N, P, S and N:S ratio

	Total C	Total N	Total P	Total S	N:S
MBC	0.894^{**}	0.689^{**}		0.652^{**}	-0.433^{**}
Dehydrogenase			0.479^{**}		
Aryl sulphatase activity	0.856^{**}	0.420^{*}	0.454^{**}	0.510^{**}	-0.412^{*}

4.10. **Total C, N, P, S, C:S and N:S ratio at active tillering stage**

The total C, N, P, S, C:S ratio and N:S ratio status was estimated for soil samples and the data are given in table 53.

4.10.1. Total carbon

The total C content varied from 0.618 to 7247 per cent. The highest value was recorded for *Kari* soil (Sample No.21) and lowest for *Onattukara* sandy soil (Sample No.8).

4.10.2. Total nitrogen

The total N content extended between 0.061 to 0.251 per cent. The maximum value was identified to be from *Kari* soil (Sample No.21) and minimum from *Onattukara* sandy soil (Sample No.8).

4.10.3. Total phosphorous

The values for total P ranged from 0.021 to 0.567 per cent. The highest value was reported from *Kari* soil (Sample No.21) and lowest from *Onattukara* sandy soil (Sample No.8).

4.10.4. Total sulphur

The values for total S varied from 0.019 to 0.680 per cent. The *Kari* soil (Sample No.21) recorded the highest value for total S whereas *Onattukara* sandy soil (Sample No.8) recorded the lowest value.

4.10.5. Total carbon: Total sulphur ratio (C:S ratio)

The values for C:S ratio ranged from 5.045 to 47.900. The highest ratio was observed in laterite soil (Sample No.5) and the lowest ratio in *Pokkali* soil (Sample No.16).

Table 53. Total C, N, P, S, C:S and N :S ratio at active tillering stage

Sample No	**TC %**	**TN %**	**TP %**	**TS %**	**C:S Ratio**	**N:S ratio**
1	0.834	0.067	0.026	0.065	12.856	1.027
2	0.932	0.070	0.023	0.058	16.124	1.219
3	1.000	0.077	0.023	0.103	9.676	0.742
4	1.167	0.084	0.182	0.048	24.401	1.748
5	1.429	0.086	0.146	0.030	47.900	2.898
6	1.364	0.102	0.168	0.031	43.974	3.303
7	0.699	0.073	0.031	0.028	24.554	2.581
8	0.618	0.061	0.021	0.019	32.661	3.235
9	0.719	0.080	0.047	0.020	36.413	4.044
10	1.255	0.074	0.186	0.180	6.987	0.411
11	1.422	0.093	0.204	0.164	8.694	0.568
12	1.057	0.092	0.182	0.120	8.818	0.764
13	2.434	0.119	0.507	0.128	19.038	0.929
14	2.254	0.090	0.319	0.130	17.298	0.688
15	2.616	0.087	0.289	0.101	25.944	0.867
16	3.185	0.119	0.032	0.631	5.045	0.189
17	2.896	0.100	0.048	0.510	5.675	0.195
18	2.991	0.135	0.031	0.511	5.851	0.264
19	5.122	0.086	0.204	0.392	13.060	0.218
20	5.649	0.085	0.296	0.475	11.888	0.179
21	7.247	0.251	0.567	0.680	10.665	0.370
Min	0.618	0.061	0.021	0.019	5.045	0.179
Max	7.247	0.251	0.567	0.680	47.900	4.044

4.10.6. Total nitrogen: Total sulphur ratio (N:S ratio)

The total N:S ratio extended between 0.179 to 4.044. The *Onattukara* sandy soil (Sample No.9) reported the highest ratio whereas *Kari* soil (Sample No.20) reported the lowest ratio.

***4.11.* Summary statistics of total C, N, P, S, C:S and N:S ratio at active tillering stage**

The mean values for total C, N, P, S, C:S ratio, and N:S ratio was estimated for soil samples and the data are given in table 54.

4.11.1. Total carbon

The mean values for total C varied between 0.679 to 6.006 per cent. The significantly higher value was recorded from *Kari* soils while the lowest value was recorded from *Onattukara* sandy soil which was on par with black cotton soils, *Poonthalpadam* soil and laterite soils**.**

4.11.2. Total nitrogen

The mean values for total N ranged between 0.0712 to 0.141 per cent. The highest value was recorded for *Kari* soil while the lowest for black cotton soil. There were no significant differences among the soil types.

4.11.3. Total phosphorous

The significantly higher value was observed in *Kole* land (0.372 per cent) which is on par with *Kari* soil. The lowest value (0.024 per cent) was reported for black cotton soil which is on par with *Onattukara* sandy soil, *Pokkali* soil and laterite soils**.**

4.11.4. Total sulphur

The *Pokkali* soils were identified to have the significantly highest value (0.551 per cent) which is on par with *Kari* soils. The lowest value (0.022 per cent) was identified to be from *Onattukara* sandy soils which is on par with laterite soils, black cotton soils and *Kole* land

4.11.5. Total carbon: Total sulphur ratio (C:S ratio)

The mean values for C:S ratio extended between 5.524 to 38.758. The laterite soils reported significantly higher value which is on par with *Onattukara* sandy soils. The lowest value for C:S ratio was observed in *Pokkali* soils which is on par with *Poonthalpadam* soils, *Kari* soils and black cotton soils.

Table 54. Summary statistics of total C, N, P, S, C:S and N:S ratio at active tillering stage

locations	TC %	TN %	TP %	TS %	C:S Ratio	N :S ratio
black cotton soils of Chittoor	0.922[c]	0.071	0.024[c]	0.075[bc]	12.885[bc]	0.996[b]
Low land brown hydromorphic laterite	1.32[c]	0.091	0.165b[c]	0.036[c]	38.758[a]	2.65[a]
Onattukara sandy soil	0.679[c]	0.071	0.033[c]	0.022[c]	31.209[a]	3.287[a]
Poonthalppadam - Slushy paddy land soils	1.245[c]	0.086	0.191[b]	0.155[b]	8.166[c]	0.581[bc]
Kole lands	2.435[b]	0.099	0.372[a]	0.12b[c]	20.76[b]	0.828b[c]
Pokkali	3.024[b]	0.118	0.037[c]	0.551[a]	5.524[c]	0.216[c]
Kari soils of Kuttanad	6.006[a]	0.141	0.356[a]	0.516[a]	11.871b[c]	0.256[bc]
CD	0.766	N/A	0.148	0.112	10.02	0.756

4.11.6. Total nitrogen: Total sulphur ratio (N:S ratio)

The *Onattukara* sandy soils recorded significantly higher value (3.287) which is on par with laterite soils whereas *Pokkali* soils had the lowest value (0.216) which is on par with *Kari* soils, *Poonthalpadam* soils and *Kole* land.

4.11.7. Relationship between total C, N, P, S and C:S, N:S ratio at active tillering stage

The correlation coefficients between total C, N, P, S and C:S, N:S, ratio at active tillering stage are furnished in table 55

The total C had a significant and positive correlation with total N (0.713**), total P (0.610**), total S (0.831**) and negative correlation with N:S ratio (-0.549*). The total N was found to have a significant and positive correlation with total P (0.614**) and total S (0.675**). Total S had a significant and negative correlation with C:S ratio (-0.619**) and N:S ratio (-0.665**).

C:S ratio reported a significant and positive correlation with N:S ratio (0.892**).

Table 55. Correlation between total C, N, P, S and C:S, N:S ratio at active tillering stage

	TC	Total N	Total P	Total S	C:S
Total N	0.713**				
Total P	0.610**	0.614**			
Total S	0.831**	0.675**	0.248^{NS}		
C:S		-0.238^{NS}	-0.052^{NS}	-0.619**	
N:S	-0.549*	-0.310^{NS}	-0.298^{NS}	-0.665**	0.892**

4.11.8. Relationship between C, N, P, S, C:S, N:S ratio and organic carbon, Av .N, Av .P, Av. S at active tillering stage

The correlation coefficients among the above relationship are furnished in table 56.

The total C was found to have significant and positive correlation with organic carbon (0.996**), Av. N (0.780**), Av. S (0.640**), water soluble sulphur (0.600**), heat soluble S (0.690**), sulphate soluble after ignition (0.627**), total organic S (0.853**) and total S (0.831**). The total N recorded significant and positive correlation with organic carbon (0.733**), Av. N (0.929**) and Av. S (0.507*)

Table 56. Correlation co efficient of C, N, P, S, C:S, N:S ratio and organic carbon, available N, P, S at active tillering stage

	TC	Total N	Total P	Total S	C:S ratio	N:S ratio
OC	0.996**	0.733**	0.609**	0.838**		-0.546*
Av.N	0.780**	0.929**	0.708**	0.587**		
Av.P				-0.552**	0.466*	0.461*
Av. S	0.640**	0.507*		0.922**	-0.535*	-0.553**

The total P had shown a significant and positive correlation with organic carbon (0.609**) and Av. N (0.708**). The total S had a significant and positive correlation with organic carbon (0.838**), Av. N (0.587**), Av. S (0.922**).

The C:S ratio recorded significant and positive correlation with Av. P (0.466*) and negative correlation with Av. S (-0.535*).

The N:S ratio significantly and positively correlated with Av. P(0.461*) and negatively correlated with organic carbon (-0.546*), Av. S (-0.553**).

4.12. Total C, N, P, S, C:S ratio and N:S ratio at harvest stage

The total C, N, P, S, C:S ratio, N:S ratio and P:S ratio status was estimated for soil samples and the data are given in table 57.

4.12.1. Total carbon

The total C content varied from 0.553 to 6.069 per cent. The highest value was observed in *Kari* soil (Sample No.21) and lowest in *Onattukara* sandy soil (Sample No.8).

4.12.2. Total nitrogen

The total N extended between 0.051 to 0.131 per cent. The *Kole* land soil (Sample No.13) reported the maximum value for total N whereas *Onattukara* sandy soil (Sample No.8) reported the minimum value.

4.12.3. Total phosphorous

The total P ranged from 0.23 to 0.716 per cent. The highest value was reported from *Kari* soil (Sample No.21) and lowest from black cottonsoil (Sample No.3).

4.12.4. Total sulphur

The values for total S extended between 0.18 to 0.570 per cent. The *Kari* soil (Sample No.21) was found to have maximum value for total S whereas *Onattukara* sandy (Sample No.9) soils had the minimum value.

4.12.5. Total carbon :Total sulphur ratio (C:S ratio)

The total C:S ratio was found to extend between 3.793 to 50.887. The highest ratio was observed in laterite soil (Sample No.5) and lowest in *Pokkali* soil (Sample No.17).

Table 57. Total C, N, P, S, C:S ratio and N:S ratio at harvest stage

Sample No.	TC %	TN %	TP %	TS %	C:S Ratio	N :S ratio
1	0.857	0.057	0.029	0.065	13.166	0.877
2	1.213	0.066	0.027	0.063	19.295	1.050
3	1.113	0.076	0.023	0.062	17.876	1.213
4	1.203	0.108	0.170	0.036	33.088	2.958
5	1.291	0.106	0.143	0.025	50.887	4.164
6	1.138	0.113	0.166	0.028	40.880	4.049
7	0.637	0.071	0.048	0.025	25.094	2.799
8	0.553	0.051	0.026	0.021	26.521	2.448
9	0.577	0.072	0.060	0.018	31.425	3.927
10	1.175	0.082	0.183	0.115	10.259	0.712
11	1.004	0.084	0.222	0.128	7.853	0.656
12	0.722	0.079	0.174	0.134	5.407	0.590
13	4.267	0.131	0.527	0.169	25.227	0.772
14	2.717	0.126	0.348	0.153	17.714	0.823
15	3.129	0.116	0.353	0.102	30.721	1.141
16	1.966	0.068	0.036	0.362	5.432	0.189
17	1.914	0.079	0.049	0.505	3.793	0.157
18	3.428	0.075	0.042	0.285	12.013	0.263
19	5.302	0.074	0.278	0.417	12.712	0.177
20	4.076	0.085	0.296	0.415	9.826	0.205
21	6.069	0.076	0.716	0.570	10.651	0.134
Min	**0.553**	**0.051**	**0.023**	**0.018**	**3.793**	**0.134**
Max	**6.069**	**0.131**	**0.716**	**0.570**	**50.887**	**4.164**

4.12.6. Total nitrogen: Total sulphur (N:S ratio)

The total N:S ratio varied from 0.134 to 4.164. The laterite soil reported the highest ratio (Sample No.5) whereas *Kari* soil (Sample No.21) reported the lowest ratio.

4.13. Summary statistics of total C, N, P, S, C:S and N:S ratio at harvest stage

The mean values for total C, N, P, S, C:S ratio, and N:S ratio status was estimated for soil samples and the data are given in table 58.

4.13.1. Total carbon

The mean values for total C was found to vary between 0.589 to 5.149 per cent. The significantly higher value was observed for *Kari* soils whereas the lowest value was observed for *Onattukara* sandy soils which is on par with *Poonthalpadam* soils, black cotton soils and laterite soils.

4.13.2. Total nitrogen

The *Kole* land recorded significantly highest value (0.124 per cent) for mean total N while *Onattukara* sandy soils recorded the lowest value (0.065 per cent) which is on par with black cotton soils and *Pokkali* soils**.**

4.13.3. Total phosphorous

The mean values were found to vary between 0.026 to 0.43 per cent. The significantly higher value was observed in *Kari* soils which is on par with *Kole* lands whereas the minimal value was reported for black cotton soil which is on par with *Pokkali* soil, *Onattukara* sandy soils, laterite soils and *Poonthalpadam* soils.

4.13.4. Total sulphur

The significantly higher value (0.467 per cent) was identified to be from *Kari* soils which is on par with *Pokkali* soil and the lower value (0.021 per cent) was reported for *Onattukara* sandy soil which is on par with laterite soil as well as black cotton soils

Table 58. Summary statistics of total C, N, P, S, C:S ratio and N:S ratio at harvest stage

Locations	TC %	TN %	TP %	TS %	C:S Ratio	N :S ratio
Black cotton soils of Chittoor	1.061[c]	0.066d[e]	0.026[b]	0.063[bcd]	23.469	1.489
Low land brown hydromorphic laterite	1.211[c]	0.109[b]	0.16[b]	0.03[cd]	18.717	1.722
Onattukara sandy soil	0.589[c]	0.065[e]	0.045[b]	0.021[d]	10.643	0.694
Poonthalppadam - Slushy paddy land soils	0.967[c]	0.082[c]	0.193[b]	0.126[bc]	17.651	1.292
Kole lands	3.371[b]	0.124[a]	0.409[a]	0.141[b]	23.002	1.644
Pokkali	2.436[b]	0.074[cde]	0.042[b]	0.384[a]	25.311	1.675
Kari soils of Kuttanad	5.149[a]	0.078[cd]	0.43[a]	0.467[a]	17.82	1.252
CD	1.044	0.013	0.179	0.098	NA	NA

4.13.5. *Total carbon: Total sulphur ratio (C:S ratio)*

The mean values for total C:S ratio varied between 10.643 to 25.311. The *Pokkali* soils reported highest value soils and the lowest value was reported form *Onattukara* sandy soils.

4.13.6. *Total nitrogen: Total sulphur ratio (N:S ratio)*

The significantly higher value (1.675) was recorded for *Pokkali* soils whereas least value (0.694) was reported from *Onattukara* sandy soil **4.13.7. *Relationship between total C, N, P, S and C:S, N:S ratio***

The correlation coefficients of relationship between total C, N, P, S and C:S, N:S ratio are furnished in table 59

The total carbon had a significant and positive correlation with total P (0.771**), total S (0.757**) and negative correlation with N:S ratio (-0.535*). The total N was found to have significant and positive correlation with total P (0.521*) and C:S ratio (0.447*). A significant and positive correlation was observed between total P and total S (0.436*). The total S reported significant and negative correlation with C:S ratio (-0.630**) and N:S ratio (-0.696**).

Table 59. Correlation between total C, N, P, S and C:S, N:S ratio

	Total C	Total N	Total P	Total S	C:S ratio
Total N					
Total P	0.771**	0.521*			
Total S	0.757**		0.436*		
C:S ratio		0.447*		-0.630**	
N:S ratio	-0.535*			-0.696**	0.889**

The C:S ratio significantly and positively correlated with N:S ratio (0.889**).

4.13.8. *Relationship between C, N, P, S, C:S, N:S ratio and organic carbon, Av.N, Av.P, sulphur fractions at harvest stage*

The correlation coefficients are shown in table 60

The total carbon had significant and positive correlation with organic carbon (0.997**), Av. S (0.477*), water soluble S (0.459*), heat soluble S (0.532*), sulphate soluble after ignition (0.704**), total organic S (0.761**) , total S (0.757**) and negative correlation with Av. P(-0.438*). A significant and positive correlation was observed between total N and Av. N (0.886**). The total P reported a significant and positive correlation with organic carbon (0.776**) and Av. N (0.571**).

Table 60. Correlation co-efficient between C, N, P, S, C:S, N:S, P:S ratio and organic carbon, Available N, P, S at harvest stage

	Total C	Total N	Total P	Total S	C:S ratio	N:S ratio
OC	0.997**		0.776**	0.772**		-0.546*
Av.N		0.886**	0.517*		0.452*	
Av.P	-0.438*			-0.529*	0.480*	0.600**
Av. S	0.477*			0.792**	-0.542*	-0.580**

The C:S ratio was found to have significant and positive correlation with Av. N (0.452*), Av. P(0.480*) and negative correlation with Av. S (-0.542*).

The N:S ratio significantly and positively correlated with Av. P (0.600**) and negatively correlated with organic carbon (-0.546*) and Av. S (-0.580**).

4.13.9. Adsorption study of sulphur

Quantity - intensity relation

Quantity - intensity relationship of S in 12 samples having lowest and highest available S were studied at two temperatures viz. 25℃ and 40 ℃ as described in section 3.3. Q-I curves were plotted based on the data obtained with the amount of S adsorbed or desorbed on Y axis and equilibrium concentration on X axis. In that *Kari* soil and *Pokkali* soil exhibited desorption (table 60) whereas samples from laterite and *Onattukara* sandy soil had shown adsorption nature which was explained with the support of Langmuir and Freundlich adsorption isotherm (table 61)

Table 61. Parameter of Q-I curve for S (desorption)

Soil type	Temp	Linear equation	Buffer power (L kg-1)	Max. quantity desorbed (mg kg-1)	R2
Kari soil	25	y = -4.8922x + 286.4	-4.8922	1931.42	0.0121
	40	y = 60.866x - 26745	60.866	1996.87	0.8898
Pokkali soil 1	25	y = 33.101x - 15599	33.101	2111.941	0.1401
	40	y = -1.3635x - 1228.7	-1.3635	2122.815	0.0024
Pokkali soil 2	25	y = 77.842x - 33862	77.842	2042.362	0.7918
	40	y = 26.793x - 13018	26.793	2087.991	0.042
Pokkali soil 2	25	y = -30.964x + 11365	-30.964	2115.52	0.2028
	40	y = 59.165x - 27072	59.165	2111.941	0.61
Pokkali soil 4	25	y = -73.853x + 30232	-73.853	2179.524	0.2235
	40	y = 89.533x - 40160	89.533	2141.81	0.5992
Pokkali soil 5	25	y = -2.1976x - 782.55	-2.1976	2105.248	0.1526
	40	y = 79.524x - 36069	79.524	2141.81	0.7051

The maximum quantity desorbed was reported at 40°C (2141.81 mg kg^{-1}) in *Pokkali* soil and the minimum in *Kari* soil at 25°C (1931.42 mg kg^{-1}).

Table 62. Langmuir and Freundlich adsorption characteristics

Samples	Temperature	Langmuir			Freundlich		
		Q Max (mg kg^{-1})	K (l mg^{-1})	AIC	K	N	AIC
Laterite soil	25	10.083	-0.049	34.125	631.573	-1.193	35.919
	40	2.686	-0.035	45.081	30.461	-9.371	43.791
Laterite soil	25	13.929	-0.063	29.522	199.906	-1.847	25.911
	40	4.209	-0.033	44.309	30.461	-9.371	43.791
Laterite soil	25	21.371	-0.075	34.570	202.371	-2.173	31.122
	40	4.724	-0.095	38.474	284.8	-1.08	35.958
Laterite soil	25	7.262	-0.043	23.471	4494.187	-7201	30.006
	40	16.175	-0.195	46.364	74.636	-2.878	45.28
Onattukara sandy soils	25	1.045	-0.071	41.060	16390	-4.822	33.529
	40	9.207	-0.081	53.756	269.433	-1.399	52.931
Onattukara sandy soils	25	10.28	-0.117	35.467	103.585	-2.006	28.484
	40	19.972	0.215	46.585	2.937	3.139	46.711

In Langmuir adsorption isotherm, Q max denotes the adsorption maxima and k is the Langmuir constant which is related to the energy of adsorption or binding affinity. In Freundlich adsorption isotherm k represents the sorption capacity and n is the correction factor. The Langmuir and Freundlich model were compared for the best fit model for adsorption data in soil based on Akaike information criterion (AIC).

Out of four samples from laterite soil two samples each could be explained by Langmuir adsorption isotherm and Freundlich adsorption isotherm at 25°C. All the samples from laterite soil exhibits Freundlich adsorption isotherm at 40°C while *Onattukara* sandy soils exhibits Freundlich adsorption isotherm at 25 as well as 40°C.

Discussion

5. DISCUSSION

The results of various experiments of the study titled 'Sulphur dynamics in major rice-growing soils of Kerala' presented in chapter 4 are discussed herein the light of available literature, wherever possible.

5.1 INITIAL CHARACTERISATION

5.1.1 Physico-chemical properties

The data on physico- chemical properties of 35 soil samples were furnished in table 5 and the results obtained are discussed here under.

5.1.1.1 Soil pH

About three fourth of the soil samples analysed were found to be acidic in nature (Fig.1). The pH ranged from 3.35 to 8.26. In general the low pH of the soils under tropical humid climate were due to leaching of bases. Sixteen samples out of 35 samples belonged to the category of strongly acidic (<4.5) to moderately acidic (4.5 -5.5) whereas 10 samples were categorised as slightly acidic (5.5-6.5), which consisted of all soils except the black cotton soil. The *Kari*, *Kole* as well as *Pokkali* soils are potential acid sulphate and acid saline soils. The presence of sulphide minerals and their oxidation combined by high organic matter might have accumulated organic acids leading to acidic condition (Reshma2020). The increased loss of bases through leaching in *Onattukara* sandy soil has contributed to the acidic nature whereas accumulation of sesquioxides rendered an acidic condition in laterite soil (ISSS,2002). The presence of mixed layer lattice clays with dominance of vermiculite or montmorillonite in black cotton soil might have resulted in neutral pH of black cotton soil (Bhindhu, 2017).

5.1.1.2 Electrical conductivity

The electrical conductivity extended between 0.043 to 1.92 dS m^{-1} (Fig 2). The highest value was reported from *Pokkali* soil because of sea water intrusion. The EC of *Kari* and *Kole* land soils were relatively less than that of *Pokkali* soil as the sea water intrusion is controlled by barriers. Reshma (2020) also reported the same trend for EC in *Pokkali, Kole, and Kari* soils.

5.1.1.3. Cation exchange capacity (CEC)

It was observed that the CEC ranged from 1.09 to 13.84 (Fig 4). The highest CEC was reported from *Kari* soil and the lowest from *Onattukara* sandy soil. The highest CEC in *Kari* soil may be due to the higher organic matter content and least CEC in *Onattukara* sandy soil could be due to the sandy texture. Which is in conformity with the findings of Bhindhu, 2017 on the texture of *Onattukara* sandy plains (AEU 3).

5.1.1.4 Organic carbon

The organic carbon status of soil ranged from 0.037 to 7.80 per cent (Fig 3). Forty percent of collected soil sample recorded high organic carbon status, whereas 46 and 16 per cent respectively belonged to medium and low status in terms of organic carbon. The reduced decomposition rate of huge amount of organic matter under submerged condition has resulted in high organic carbon status of *Pokkali*, *Kole* land and *Kari* soils. Reshma (2020) also reported the same trend in high organic carbon status of *Pokkali* soil, *Kole* land and Kuttanad soils (2.57-6.74 %). A similar trend on organic carbon status of *Pokkali* soil, *Kole* land and *Kari* soils of Kuttanad was also reported by Reshma (2020). All the samples from *Onattukara* sandy soil were found to be low in organic carbon status, thus agreeing with the findings of Santhosh (2013) who investigated on the chemistry and transformation of boron in soils of Kerala.

5.1.1.5. Bulk density

The bulk density of soils extended from 1.23 to 1.59 gcm^{-3}. The lowest bulk density was observed in black cotton soils and highest in *Onattukara* sandy soil. The higher bulk density in *Onattukara* sandy soil could be due to high sand content.

5.1.1.6. Soil texture

A wide variety of texture was exhibited by the collected soils. Sand, silt and clay content of the collected soils are presented in table 5. The sand content ranged from 25.2 to 83 per cent, The silt fraction ranged from 3.6 to 39.8 per cent and the clay content extended from 6 to 45.3 per cent. The *Onnatukara* sandy soil contained the highest amount of sand (>76.8 %) by virtue of its origin whereas the highest sand content of low land soils such as *Kari* and *Pokkali* soils may be due to the influence of sea water. Study conducted by Reshma (2020) also related the relatively higher sand content to tidal influence

5.1.1.7. Soil temperature

The soil temperature ranged from 28 to 37°C. The lowest temperature was recorded from *Pokkali* soils (Sample No. 27 and 30) and highest from *Kari* soil (Sample No. 31 and 33). The lowest temperature in *Pokkali* soil is due to submerged condition and the combined effect of black colour as well as sand content resulted in highest soil temperature of *Kari* soil.

5.1.2. Soil biological properties

The soil biological properties (Microbial biomass carbon, Dehydrogenase activity, Aryl sulphatase activity) of the samples are presented in table 6 and the results obtained are discussed here under.

5.1.2.1. Microbial biomass carbon (MBC)

The Microbial biomass carbon a measure of the carbon (C) contained within the living component of soil organic matter ranged from 11.54 to 402.45 mg kg^{-1} among the samples collected. It was the lowest in *Onattukara* sandy soil due the high oxidation of organic matter and the highest in *Kari* soil because of the high organic matter content

5.1.2.2. Dehydrogenase activity

The dehydrogenase activity of soils varied from 0.08 to 8.63µg TPF g^{-1}soil 24 hr^{-1}. The lowest dehydrogenase activity was reported in *Onattukara sandy* soil and the highest in *Pokkali* soil. The anaerobic soil conditions prevailing in Pokkali soils would have favoured the activity of dehydrogenase enzyme (Weaver *et al.,* 2012).

5.1.2.3. Aryl sulphatase activity

The aryl sulphatase activity of soils ranged from 0.38 to 58.66mg p-nitrophenol released g^{-1}soil h^{-1}. The lowest activity was reported from *Onattukara* sandy soil and the highest from *Kari* soil. The enzyme activity was more than 10 mg p- nitrophenol released g^{-1}soil h^{-1} in *Kole* land, *Pokkali soils* and *Kari* soils. This is directly due to the high level of organic matter, contained in these soils, that acts as the nutrient and energy supply for microbial biomass. The Onattukara sandy soils with very low organic matter naturally registered the lowest activity for the enzyme aryl sulphatase. The *Onattukara* sandy contain low amount of organic matter that made the lowest aryl sulphatase activity.

5.1.2.4. Cysteine desulfhydrase

Cysteine, the semi essential proteinogenic amino acid to hydrogen sulphide. The samples of the present study were free of this enzyme which could be due to the absence of the co factor Pyridoxal phosphate in the samples. Similar observation was reported by Alharbi *et al*. (2012) from his study on L-cysteine desulfhydrase -an enzyme which can be assayed in soil but is unlikely to function in the environment.

5.1.3. Available nutrients

5.1.3.1 Available nitrogen

The lowest available nitrogen (122.89 kg ha^{-1}) (Fig 5) was observed from *Onattukara* sandy soil whereas highest value (773.31 kg ha^{-1}) was observed from *Kole* land soil. Six and twelve samples out of 35 were found to be high and medium in available nitrogen whereas seventeen samples were low in available nitrogen. The available nitrogen content of samples from *Kari* soil, *Kole* land and *Pokkali* soil ranged from 360 to 773.31 kg ha^{-1} falling under medium to high category of available nitrogen which could be due to the high organic content. All the samples from *Onattukara* sandy soil were deficient in available nitrogen. The low organic content added with sandy texture make them more prone to leaching losses as pointed out by Reshma (2020).

5.1.3.2 Available phosphorus

The available phosphorus ranged from 10.15 to 110.73 kg ha^{-1} (Fig 6)Of all the 35 samples analysed, 71.42 per cent of soils were high in available phosphorous (>24 kg ha^{-1}), Low available P was reported from *Kole* land which could be due to P fixation by Fe, Al and Mn under acidic condition. Bhindhu (2017) reported that the available P was found to be low in *Kuttanad* and *Kole* lands (1.97-5.48 kg ha^{-1}) which Was ascribed to the fixation of P by Al, Fe and Mn under acidic condition. The occlusion of P might occur during precipitation of hydrous oxides of iron and aluminium. The available P content of *Onattukara* sandy soil ranged from 21.56 to 59.43 kg ha ^{1}. The high available P content in this soil could be due to low fixation of phosphorous. Reshma (2020) concluded that the high status of available P in costal sandy soil may be due to its reduced chances for fixation.

5.1.3.3 Available potassium

The available potassium varied from 38.53 to 1980.16 kg ha^{-1} (Fig 7). The lowest available K was observed in *Onattukara* sandy soil and the highest in *Pokkali* soil. Categorising further it could be seen that 17.1 per cent analysed soil samples were low in available potassium (<108 kg ha^{-1}) whereas 51.42 per cent of soil samples contained potassium to rate them as high (>280kg ha $^{-1}$). All the samples from *Onattukara* sandy soil were found to be low in available K which could be due to low CEC and high leaching loss. Reshma (2020) reported that the low CEC and coarse texture of soils along with humid climate results in low retention of K in soil in turn resulting in lowest available potassium in the soils of northern coastal plain irrespective of adding potassic fertilisers.

5.1.3.4. Available calcium

The available calcium content of samples varied from 108.85 to 2121.27 mg kg^{-1} (Fig 8). Among the samples analysed, 37.14 per cent were deficient in available calcium. All samples from *Onattukara* sandy soil were found to be deficient in available Ca which might be due to low CEC and high leaching loss. Reshma (2020) observed that the coastal sandy soils are deficient in available Ca because of the low CEC and A conducive leaching environment.

A comparison on available calcium content between *Pokkali* soils and black cotton soil revealed that it was the highest in the former and was closely followed by the latter which could be due to the presence of 2:1 clay minerals in black cotton soil S and the intrusion of sea water in *Pokkali* soil.

5.1.3.5. Available magnesium

The available magnesium ranged from 13.94 to 591.09 mg kg^{-1} (Fig 9). The trend was almost similar to that of calcium with nearly 37 per cent of collected soil samples are reporting deficient (<120 mg kg^{-1}) in available magnesium. All the samples from *Onattukara* sandy soil were deficient in available magnesium, which could be due to coarse texture and high level of leaching loss. The highest available magnesium was reported in *Pokkali* soil, An after effect of sea water intrusion.

Samples from black cotton soils and *Poonthalpadam* soils recorded sufficient amount of available magnesium, which was the direct impact of high CEC and the presence of 2:1 clay minerals. Reshma (2020) Also observed the predominance of 2:1 minerals and high CEC as the reasons for the high content of available magnesium in soils of Palakkad eastern plain.

5.1.3.6. Available sulphur

The available sulphur extended between 6.07 and 2255.26 mg kg^{-1} (Fig 10). None of the analysed soil samples were deficient in available sulphur (<5 mg kg^{-1}). The lowest sulphur status was associated with *Onattukara* sandy soils (Sample No. 11-6.07 mg kg^{-1}) wherein the *Pokkali* soil sample (Sample No. 29-2255.26 mg kg^{-1}) recorded the highest value of available sulphur. Sea water effect may cause the high available sulphur content in *Pokkali*, *Kari* and *Kole* soils. Comparatively less sulphur content was reported in *Onattukara* sandy soil, it may be due to continues leaching and sandy structure.

5.1.3.7. Available iron

The available iron content of soil varied from 23.98 to 921 mg kg^{-1} (Fig 11). The highest value of iron was observed to be from *Kari* soils (Sample No.32). The *Kari* soils, *Kole* lands and *Pokkali* soils had relatively higher iron content which may be due to reduced condition. The Laterite soil contained higher amount of iron oxides which in turn contributes to its higher iron content. Reshma (2020) reported the higher iron content in samples of *Pokkali*, Kuttanad and *Kole* which was again due to the dominance of reduced form. Bhindu (2017) also reported the same. The lowest available Fe content of *Onattukara* sandy soils (Sample No. 15) could be due to its sandy texture and low CEC.

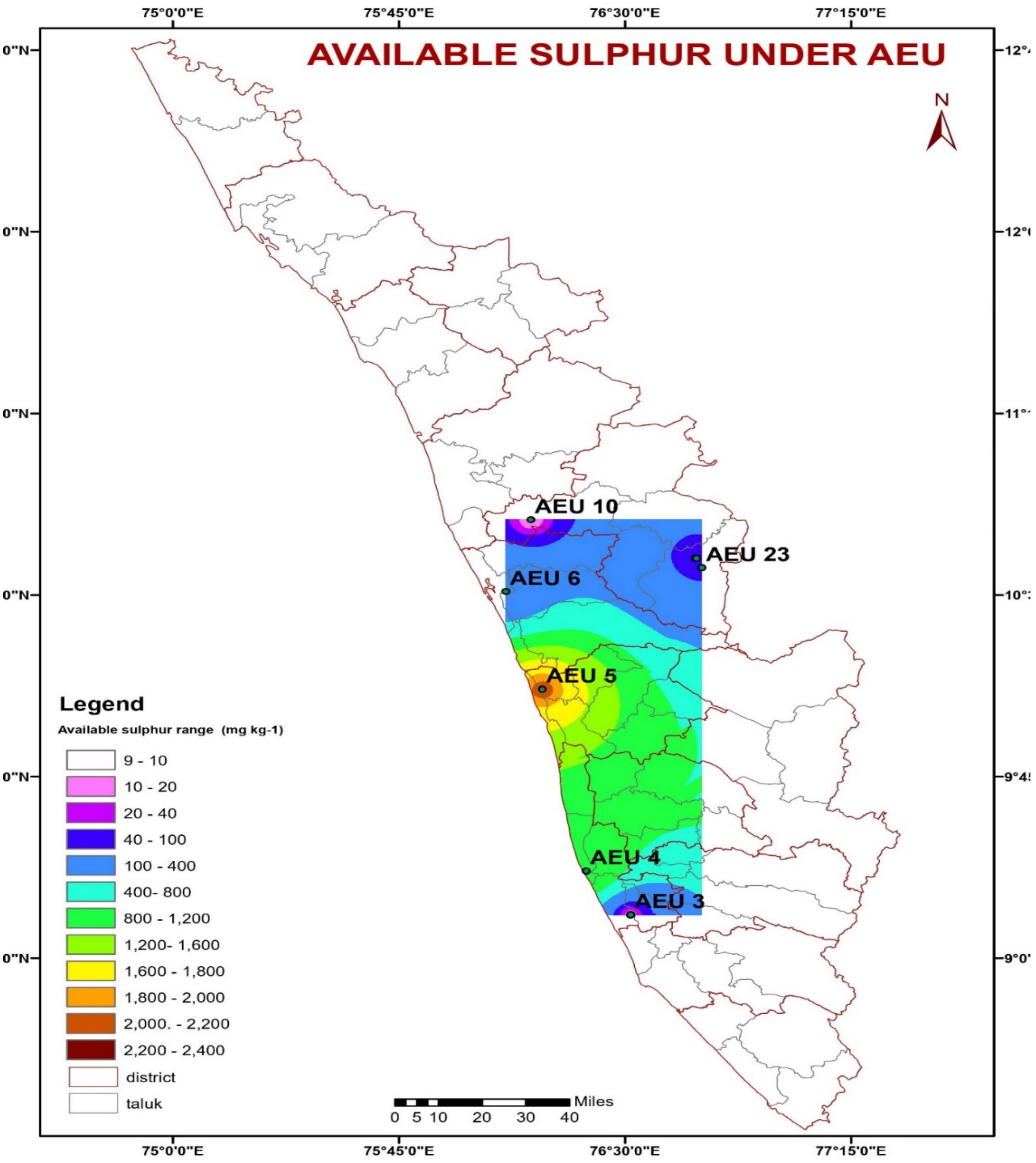
5.1.3.8 Available manganese

The available manganese differed between 8.27 to 97.09 mg kg^{-1} (Fig 12). The supremacy of reduced forms of Mn in low land condition has made the *Kole* lands high in its value. The minimal value was from *Onattukara* sandy soils for available Mn.

5.1.3.9 Available zinc

The available zinc in analysed soil samples ranged between 2.64 to 14.3 mg kg^{-1}(Fig 13). The highest value was observed in *Pokkali* soils and lowest value was obtained in Laterite soils. The available zinc was not deficient in any of the samples.

Plate 5. Available sulphure status of soil



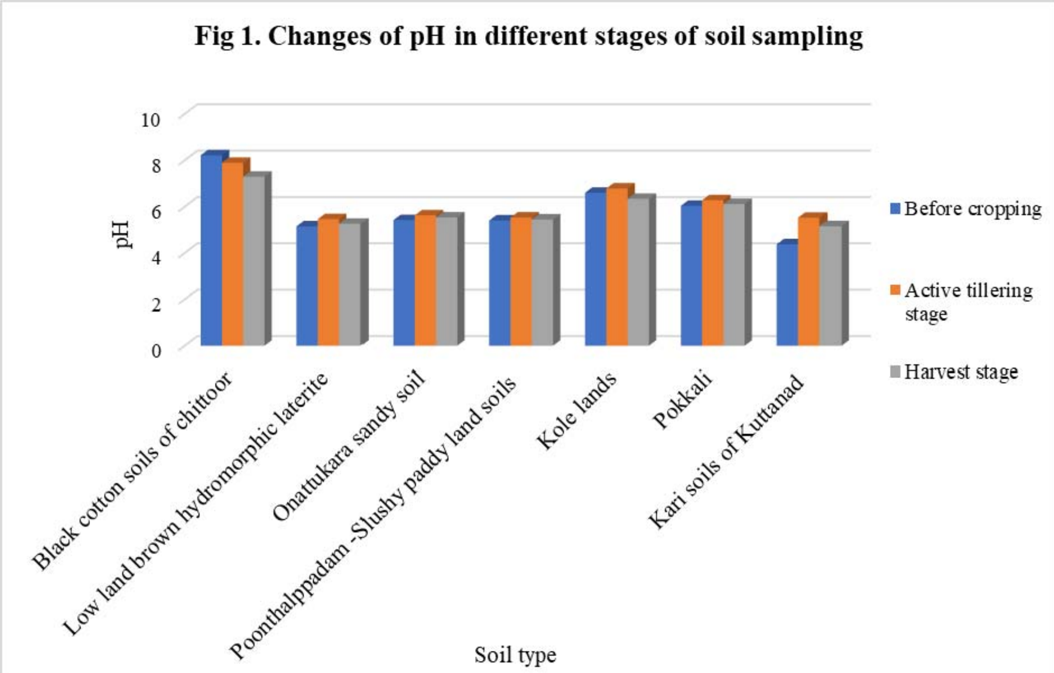


Fig 1. Changes of pH in different stages of soil sampling
10
8
6
4
2
0
pH
Before cropping
Active tillering stage
Harvest stage
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

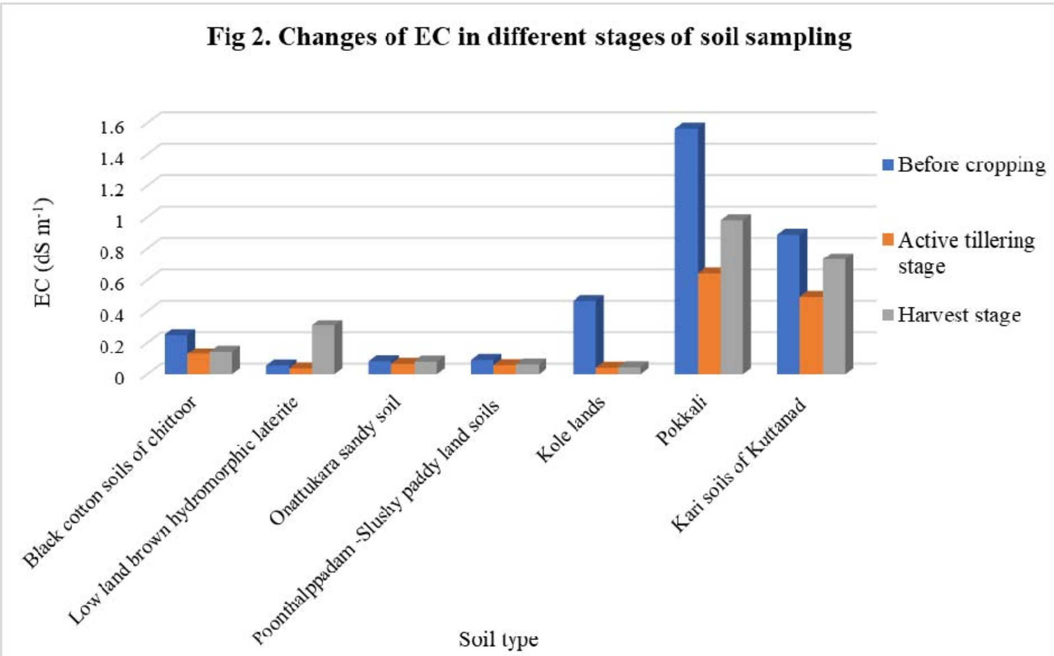


Fig 2. Changes of EC in different stages of soil sampling
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
EC (dS m-1)
Before cropping
Active tillering stage
Harvest stage
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

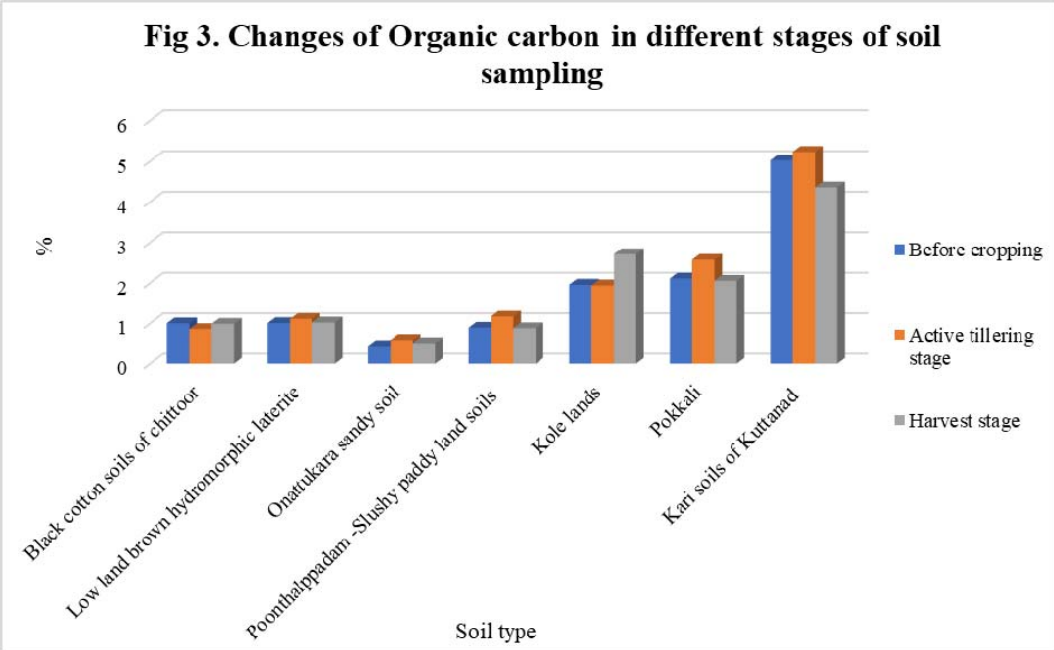


Fig 3. Changes of Organic carbon in different stages of soil sampling
%
6
5
4
3
2
1
0
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onatukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type
Before cropping
Active tillering stage
Harvest stage

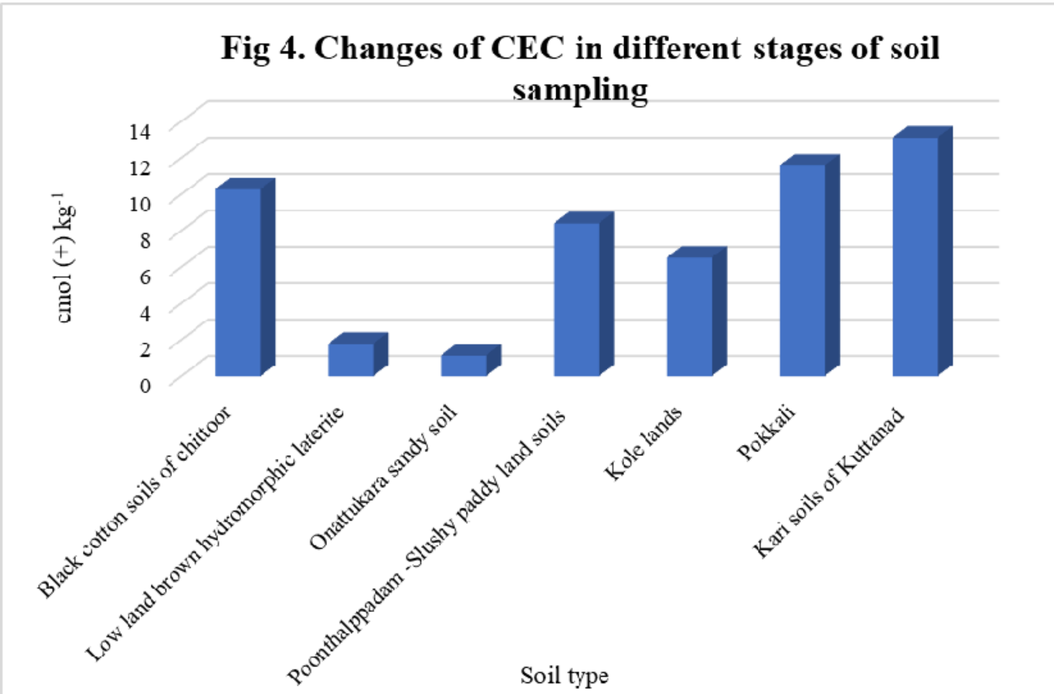


Fig 4. Changes of CEC in different stages of soil sampling
cmol (+) kg-1
14
12
10
8
6
4
2
0
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

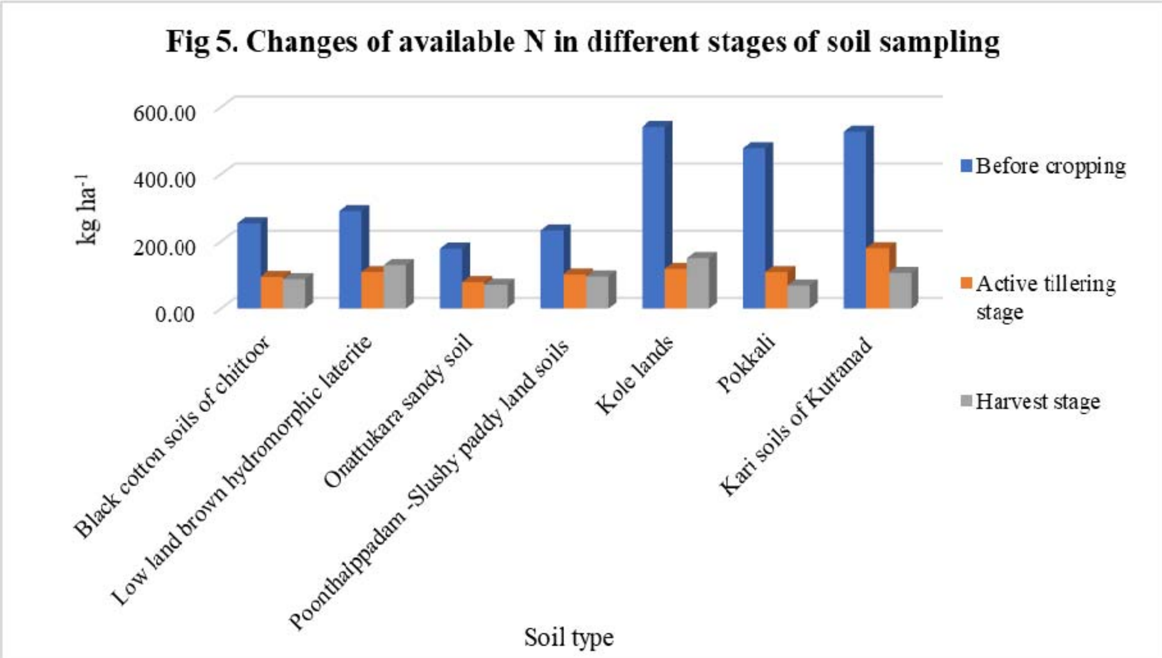


Fig 5. Changes of available N in different stages of soil sampling
600.00
400.00
200.00
0.00
kg ha-1
Before cropping
Active tillering stage
Harvest stage
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

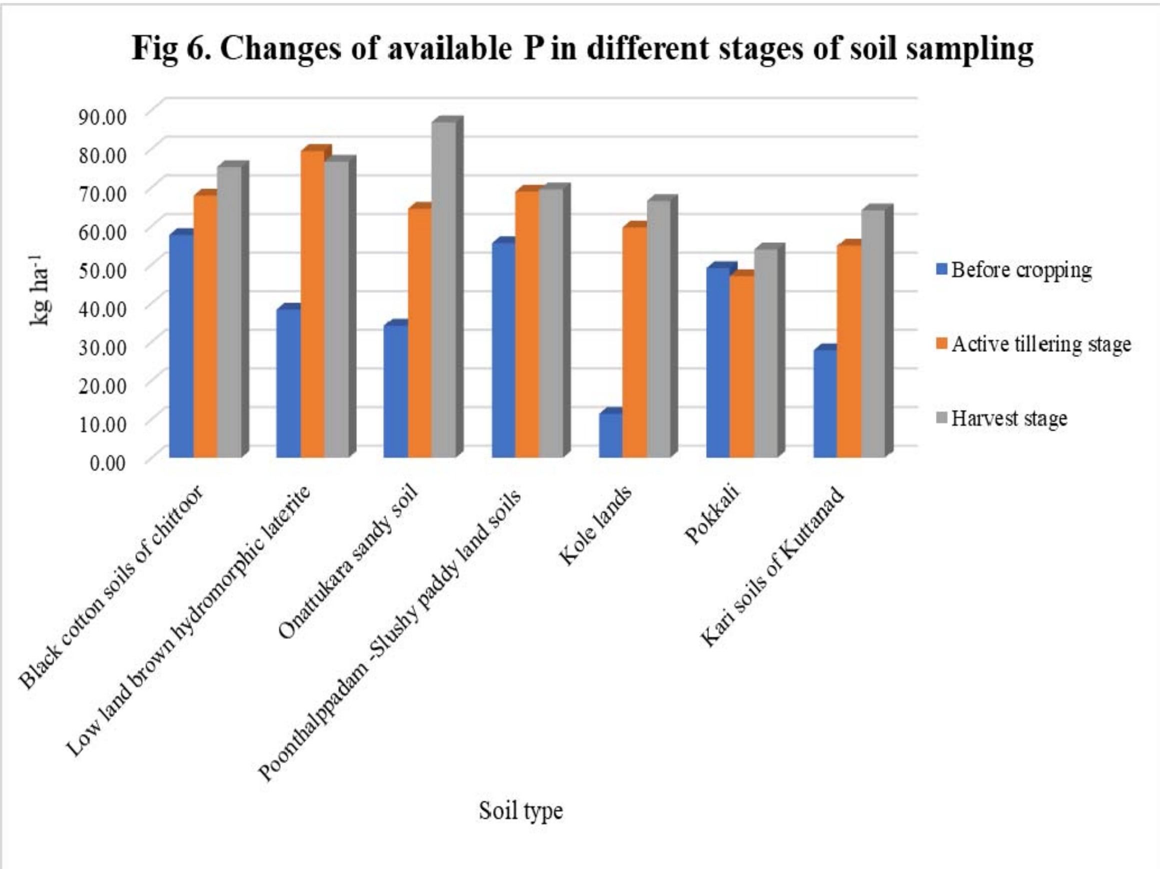


Fig 6. Changes of available P in different stages of soil sampling
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
kg ha-1
Before cropping
Active tillering stage
Harvest stage
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

Fig 7. Changes of available K in different stages of soil sampling

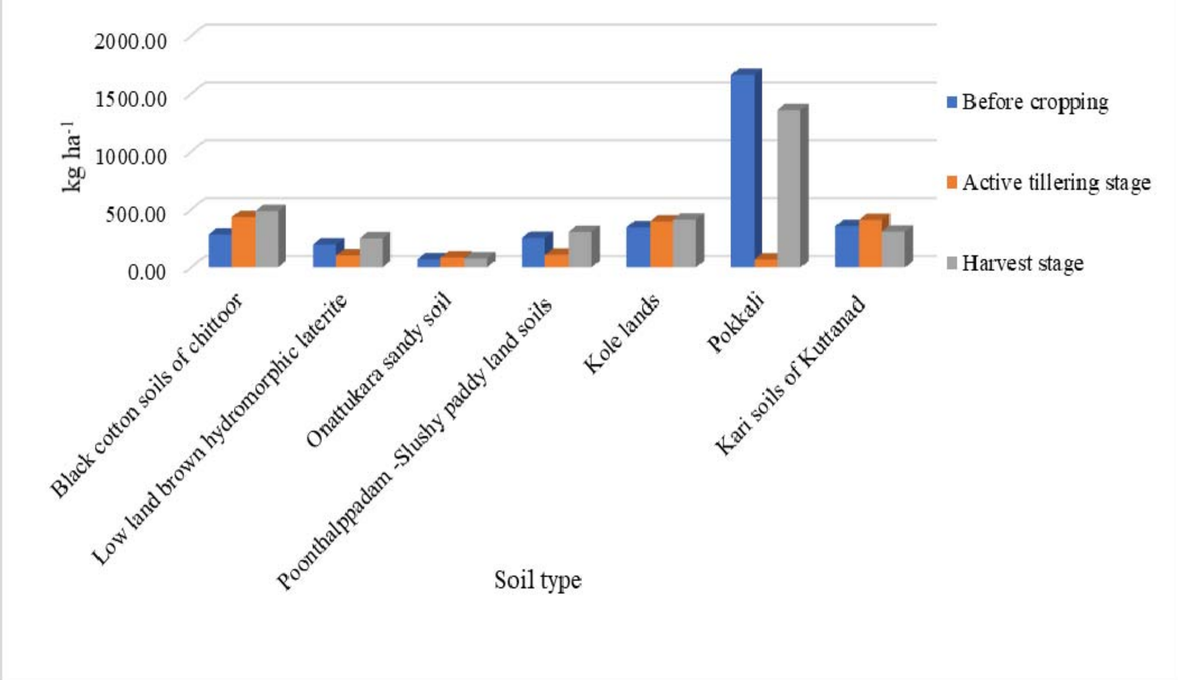
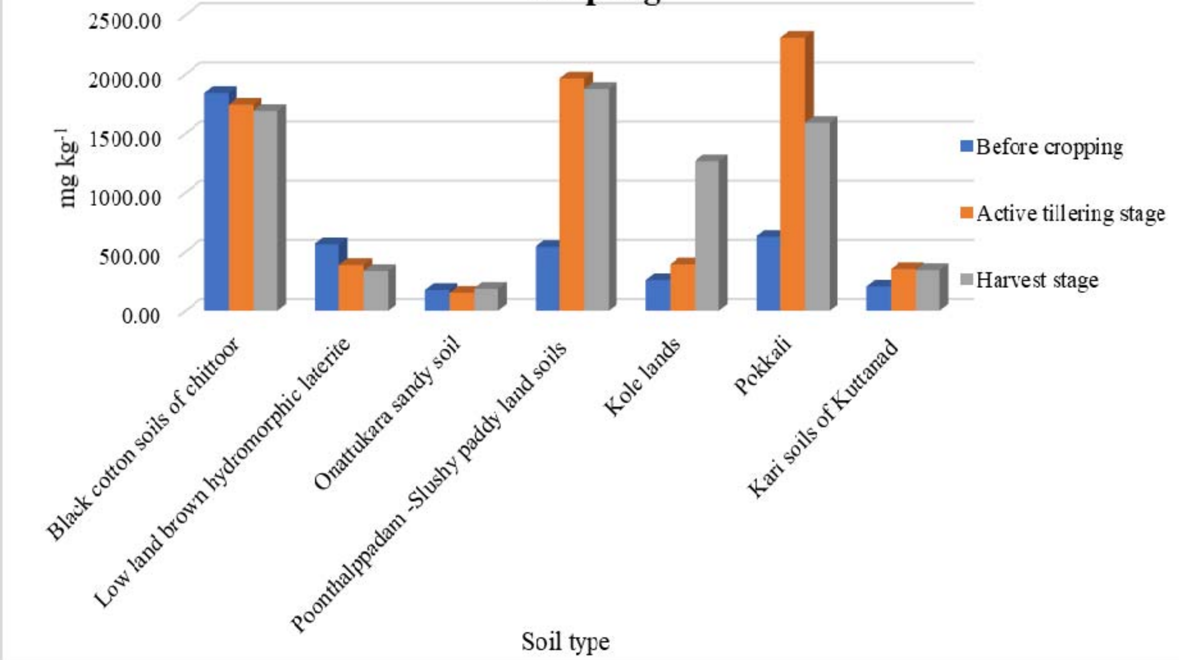


Fig 8. Changes of available Ca in different stages of soil sampling



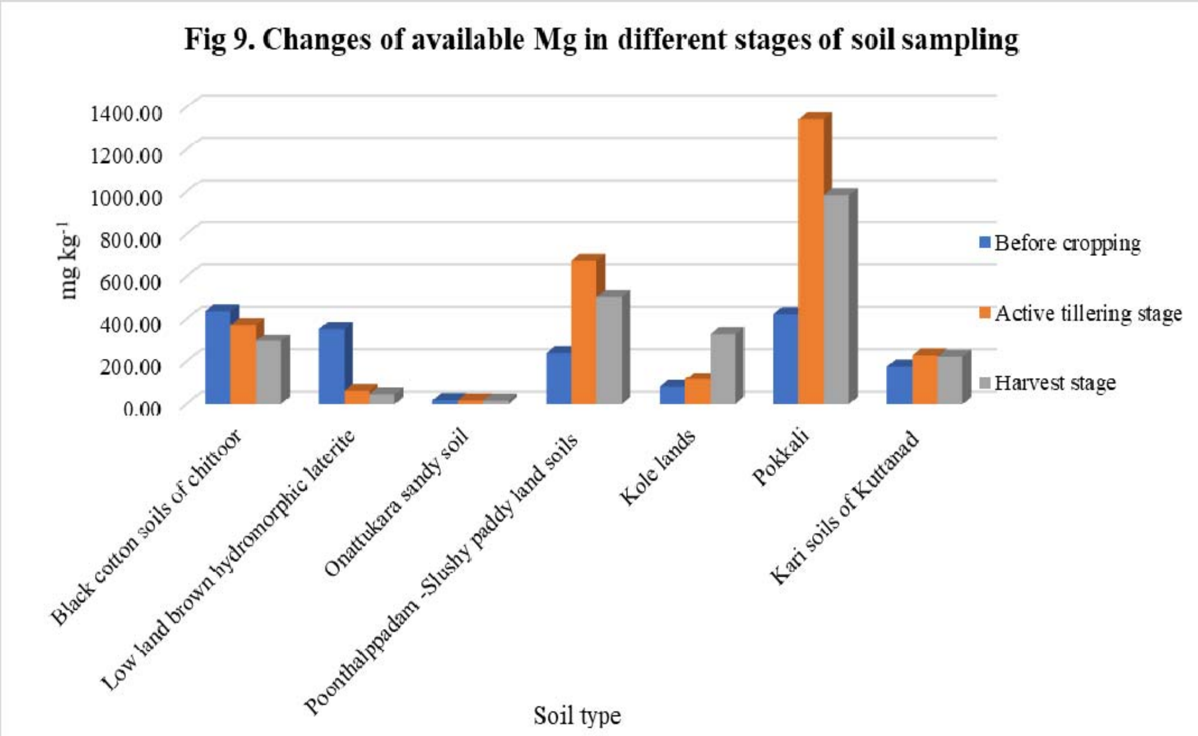


Fig 9. Changes of available Mg in different stages of soil sampling
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
mg kg-1
Before cropping
Active tillering stage
Harvest stage
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

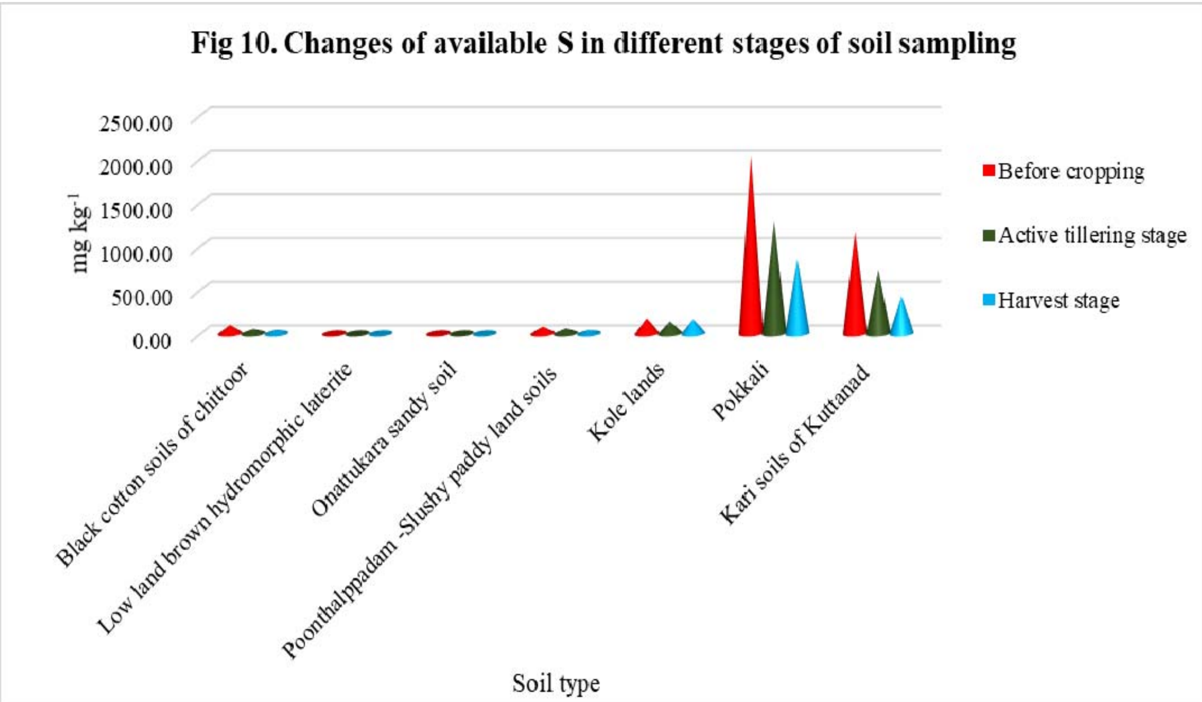


Fig 10. Changes of available S in different stages of soil sampling
2500.00
2000.00
1500.00
1000.00
500.00
0.00
mg kg-1
Before cropping
Active tillering stage
Harvest stage
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

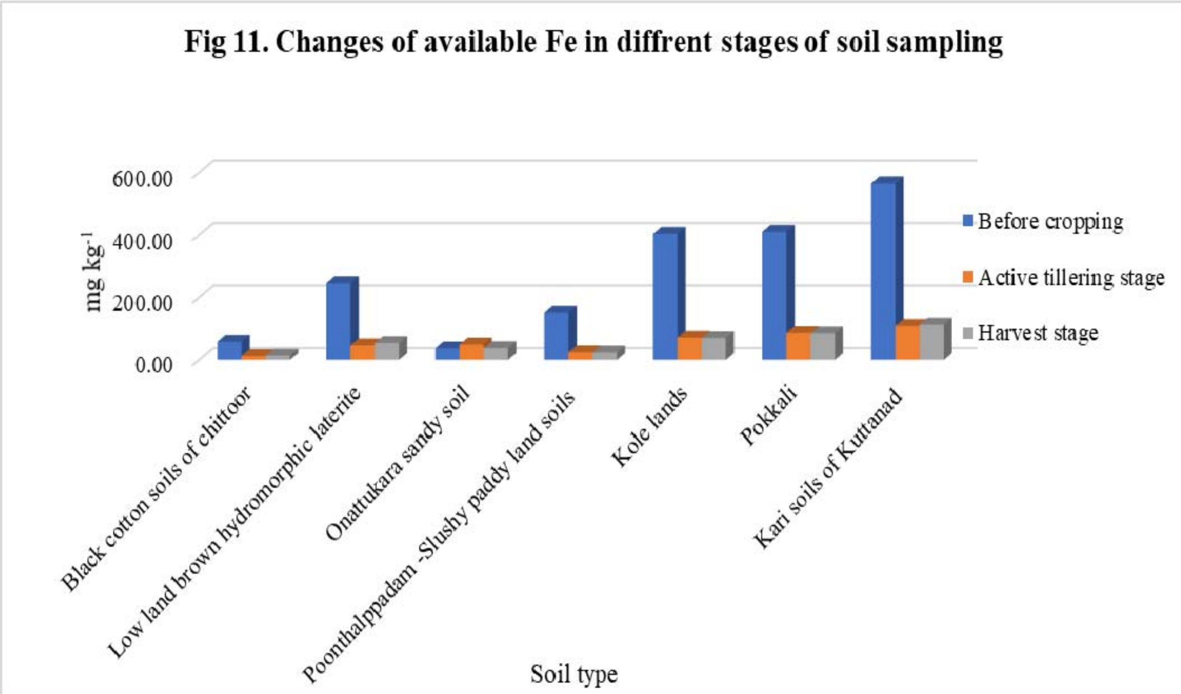


Fig 11. Changes of available Fe in diffrent stages of soil sampling
600.00
400.00
200.00
0.00
mg kg-1
Before cropping
Active tillering stage
Harvest stage
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

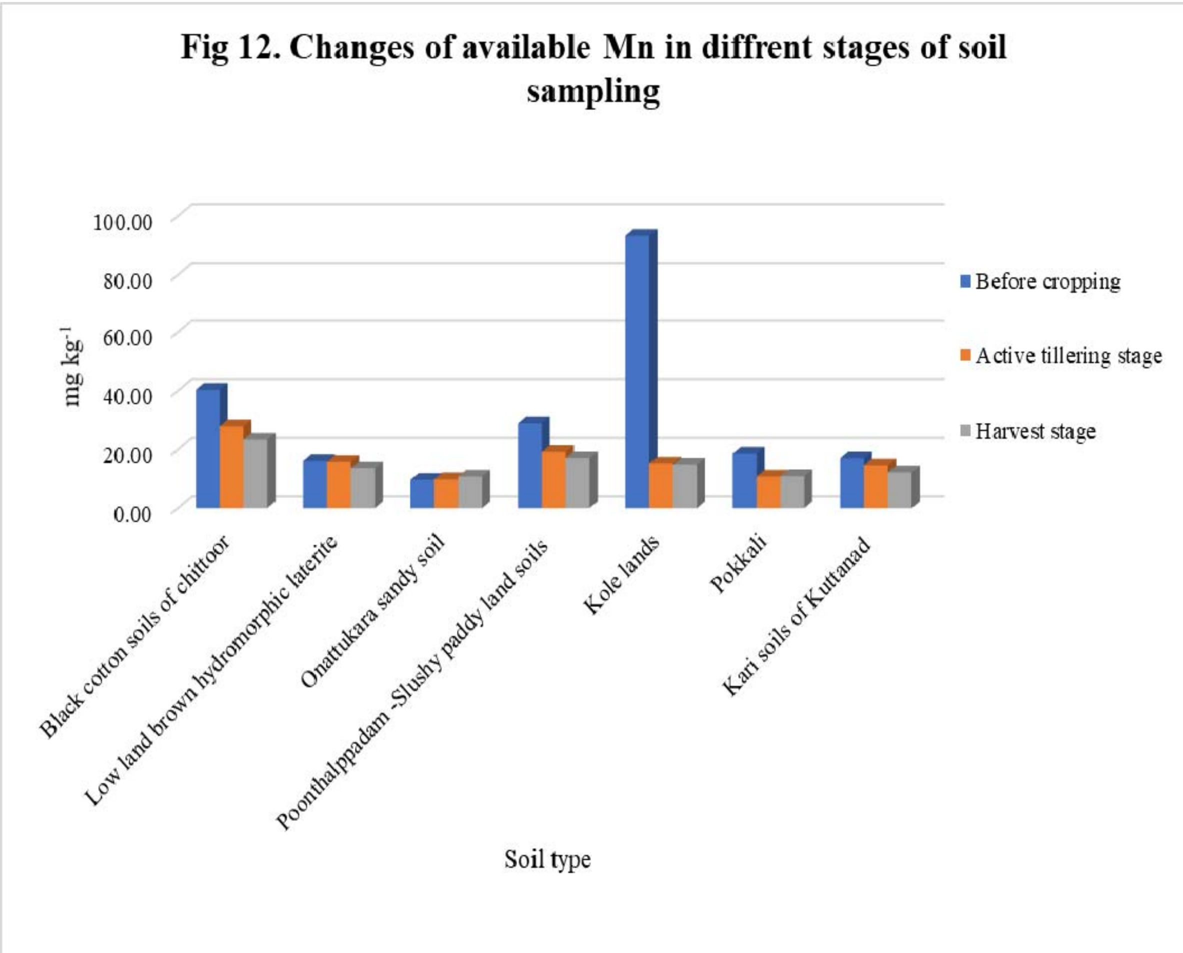


Fig 12. Changes of available Mn in diffrent stages of soil sampling
100.00
80.00
60.00
40.00
20.00
0.00
mg kg-1
Before cropping
Active tillering stage
Harvest stage
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

Fig 13. Changes of available Zn in diffrent stages of soil sampling

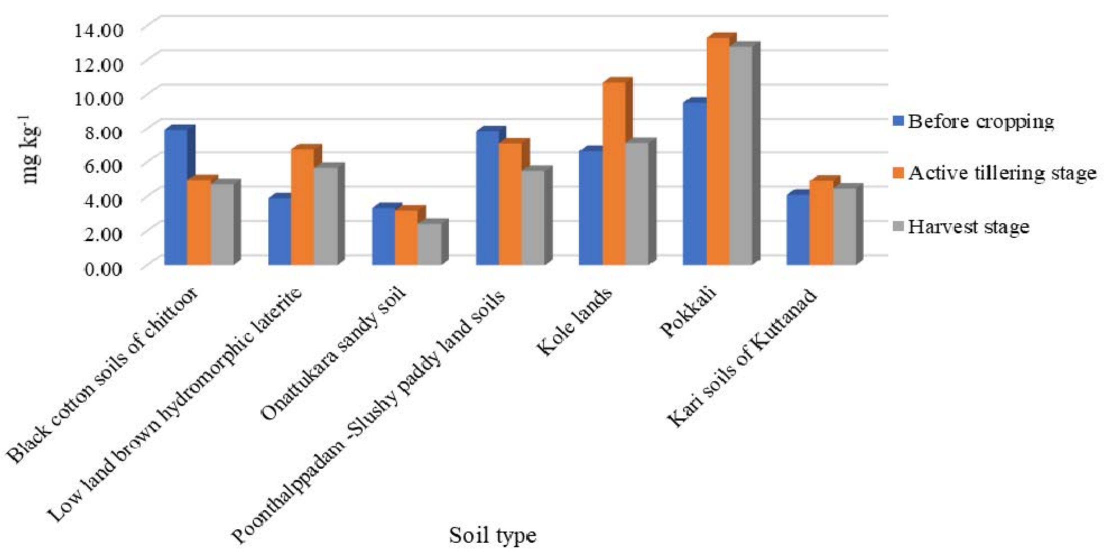
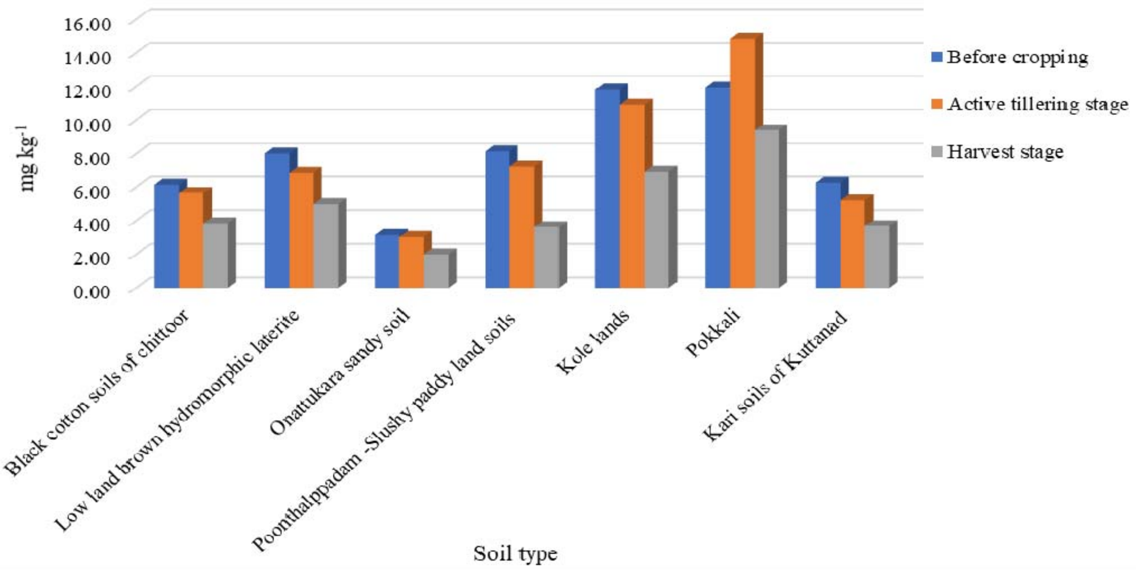


Fig 14. Changes of available Cu in diffrent stages of soil sampling



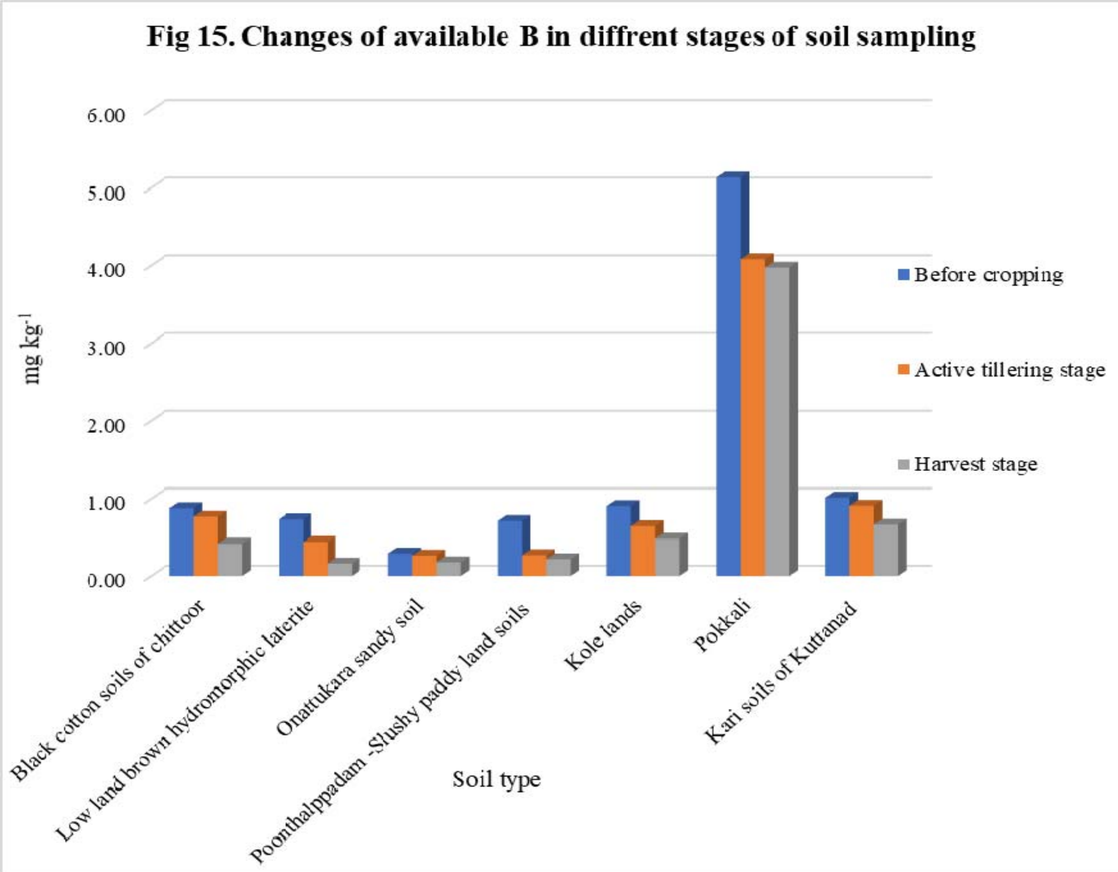


Fig 15. Changes of available B in diffrent stages of soil sampling
6.00
5.00
4.00
3.00
2.00
1.00
0.00
mg kg-1
Before cropping
Active tillering stage
Harvest stage
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

5.1.3.10 Available copper

The available copper status ranged between 2.63 to 20.65 mg kg $^{-1}$(Fig 14). The available copper was recorded low in *Onattukara* sandy soils and the high in *Pokkali* soils.

5.1.3.11 Available boron

The hot water extractable boron was found to vary between 0.24 to 7.37 mg kg^{-1} (Fig 6). The soil samples analysed from *Onattukara* region reported a deficiency in available B (<0.5 mg kg^{-1}) due to excessive leaching loss while the *Pokkali* soils were relatively higher with respect to available boron content which might be due to marine influence and higher organic content.

5.1.4Mean values of initial characterization

5.1.4.1 Electrochemical properties

The soil pH was found to vary between 4.37 to 8.21 for black cotton soil and *Kari* soils. It gets reflected from the values that *Kari* soils are strongly acidic (pH< 4.5), Laterite soils, *Onattukara* sandy soils as well as *Poonthalpadam* soils are moderately acidic (pH 4.5-5.5), *Pokkali* soils are slightly acidic (pH 5.5-6.5), *Kole* lands are observed as nearly neutral and black cotton soils of Chittoor are alkaline in nature.

It is evident from the analysed values that *Pokkali* soils had significantly higher value for EC while Laterite soil had the lowest electrical conductivity. The electrical conductivity of Laterite soil is on par with *Onattukara* sandy soil and *Poonthalpadam* soils.

The values of cation exchange capacity reveals that the *Kari* soils had significantly higher CEC which might be due to increased organic matter content. The minimal value was obtained in *Onattukara* sandy soil which is on par with Laterite soil. The *Onattukara* sandy soils have relatively lesser clay content and Laterite soils contain 1:1 clay mineral which could have resulted in reduced CEC.

The significantly higher value of organic carbon was recorded in *Kari* soils of Kuttanad and lowest value in *Onattukara* sandy soils which is on par with *Poonthalpadam* soil, black cotton soil as well as Laterite soil.

The *Kari* soil was found to have significantly higher soil temperature whereas *Pokkali* soils had the lowest which is on par with *Onattukara* sandy soil and *Kole* land**.**

The bulk density was reported significantly higher in *Onattukara* sandy soil while the black cotton soils reported the lowest bulk density**.**

It gets revealed from the analysed values that the *Onattukara* sandy soil recorded significantly higher sand fractions which is on par with *Kari* soil whereas the lowest value was from *Kole* land which is on par with Laterite soil.

On the other hand, the *Kole* land recorded significantly highest value for silt fraction while *Pokkali* soil recorded the lowest value.

The significantly highest value for clay fraction was identified to be from Laterite soil which is on par with *Pokkali* soil as well as black cotton soil and lowest value was observed in sandy soils of *Onattukara* which is on par with *Kari* soil.

The Laterite soil and *Kole* land have clay loam texture, *Poonthalpadam* soils belong to sandy clay loam textural class, black cotton soil as well as *Pokkali* soil are sandy clay in texture and finally *Onattukara* sandy soils as well as *Kari* soils belong to loamy sand class of soil texture.

5.1.4.2. Biological properties

The *Kari* soil reported significantly higher value for Microbial Biomass Carbon whereas lowest value was reported from *Onattukara* sandy soil which is on par with black cotton and *Poonthalpadam* soil.

The dehydrogenase activity was significantly higher in Laterite soil which is on par with *Poonthalpadam* soil and *Pokkali* soil. The *Kole* land reported the lowest value which is on par with black cotton as well as *Onattukara* sandy soil.

The aryl sulphatase activity was estimated as significantly higher in *Kari* soil and lower in Laterite soil which is on par with *Onattukara* sandy soil, black cotton soil and *Poonthalpadam* soil.

5.1.4.3. Available nutrient status

The *Kole* land recorded significantly higher value for Av. N which is on par with *Kari* soils and *Pokkali* soil whereas *Onattukara* sandy soils recorded the lowest value which is on par with *Poonthalpadam* soil, black cotton soil and Laterite soil respectively. Organic matter content is the major source of available nitrogen in soils which has resulted in the increased Av. N status in *Kari* soil, *Kole* land and *Pokkali* soil.

The significantly highest value for Av. P was identified to be from *black cotton* soils which is on par with *Poonthalpadam* soil and the lowest value was observed in *Kole*land which is on par with *Kari* soil.

It is evident from the analysed values that the *Pokkali* soil had significantly higher value for Av. K whereas *Onattukara* sandy soil had the lowest value which is on par with Laterite soil and *Poonthalpadam* soil.

The significantly highest value for Av. Ca was estimated from black cotton soil and lowest value from *Onattukara* sandy soil which is on par with *Kari* soil as well as *Kole* land.

The analysed data on available magnesium reveals that black cotton soil had significantly highest value which is on par with *Pokkali* soil while lowest value was observed in *Onattukara* sandy soil which is on par with *Kole* land.

It gets reflected from the analysed values of Av. S that the significantly higher value was reported from *Pokkali* soil whereas lowest sulphur status was associated with *Laterite* soils which is on par with *Onattukara* sandy soil, *Poonthalpadam* soil, black cotton and *Kole* land.

The significantly higher value for Av. Cu was obtained from *Kari* soil and lowest from *Onattukara sandy* soils which is on par with black cotton soil as well as *Poonthalpadam* soil.

The *Kole* land had significantly highest value for Av. Mn while *Onattukara* sandy soil had the lowest value which is on par with Laterite soil and *Kari* soil.

The available zinc was estimated to be significantly high in *Pokkali* soils which is on par with black cotton soil, *Poonthalpadam* soil as well as *Kole* land. The lowest value was obtained from *Onattukara* sandy soil which is on par with Laterite soil, *Kari* soil and *Kole* land.

The *Pokkali* soil reported significantly higher value for Av. Cu which is on par with *Kole* land, *Poonthalpadam* soil as well as Laterite soil. The lowest value was reported from *Onattukara* sandy soils which is on par with black cotton soil and *Kari* soil.

It gets reflected from the analysed samples that the significantly highest value for Av. B was observed to be from *Pokkali* soil whereas all other soils do not exhibit any significant differences among them.

5.1.5. Correlation study

5.1.5.1. Relationship between physico-chemical properties and available nutrients before cultivation

The pH correlated significantly and positively with Av. Ca, and negatively with available Fe. An increase in pH will in turn result in an increased Ca and decreased Fe availability in soils. Electrical conductivity (EC) was significantly and positively correlated with OC, Av. K, Av. S, Av. Mg, Av. Fe, which could be due to sea water intrusion and organic salts. Cation exchange capacity (CEC) had given a significant positive correlation with OC, Av. N, Av. K, Av. Mg, Av. Fe, Av. Zn. The organic matter content is directly proportional to CEC and an increase in CEC will result in subsequent increase of Av. N, Av. K, Av. Mg, Av. Fe as well as Av. Zn.

Organic carbon had shown significant and positive correlation with temperature, Av. N , Av. S , Av. Fe. The organic matter content combined by chemical and biological reactions associated with organic matter will contribute to raised soil temperature. The available nutrients provided by organic matter on mineralization reveals the significant and positive correlation with Av. N, Av. S, Av. Fe. A significant as well as positive correlation between organic matter and most of the available nutrients was reported by Reshma (2020).

5.1.5.2. Relationship between biological properties and physico – chemical properties

The correlation coefficient study worked out between biological properties and physico – chemical properties given in table 9 are discusses here under. Microbial biomass carbon (MBC) had significant positive correlation with aryl sulphatase activity EC, CEC, OC, temperature. Dehydrogenase activity had shown a negative correlation with pH. Aryl sulphatase activity seemed to be significantly and positively correlated with CEC, OC, temperature and negatively correlated with pH. Zomic *et al.,* (2016) reported that the organic carbon have positive influence on aryl sulphatase activity in soil since they reflect the amount of organic matter. In general, the organic carbon and temperature will enhance the biological activities of soil which in turn result in raised CEC values. The alkaline pH of soil may suppress its biological activities.

5.1.5.3. Relationship between biological properties, available status of N, P and S

The Microbial biomass carbon and Aryl sulphatase activity significantly and positively correlated with Av. N, Av. S and negatively correlated with Av. P. The microbial biomass carbon and aryl sulphatase contributes to nitrogen as well as sulphur availability whereas the reduced phosphorous availability in soil could be due to an increased microbial activity (Phosphorous is the energy source of all microbes).

5.2. ACTIVE TILLERING STAGE

The mean values of electro chemical properties and available nutrient status at active tillering stage furnished in table17 & 18. are discussed here under.

5.2.1. Electrochemical properties

The significantly highest value for soil pH was reported from black cotton soil and lowest from Laterite soil which is on par with *Kari* soil, *Poonthalpadam* as well as *Onattukara* sandy soil. The soil pH showed slightly elevated values in active tillering stage (it could be due to flooded condition) when compared to initial sampling except black cotton soils. According to Ponnamperuma (1972) consumption of H^+ ions for reduction in anaerobic soil environment has resulted in the increased soil pH.

The analysed data on electrical conductivity reveals that the significantly higher value was reported from *Pokkali* soil whereas Laterite soil reported the lowest value which is on par with *Kole* land, *Poonthalpadam*, *Onattukara* sandy soil and black cotton soil. The EC values at active tillering stage has shown a decreasing trend when compared to the initial sampling which could be due to the impact of dilution from flooded water on salinity.

It is evident from the obtained values on organic carbon that the *Kari* soil had significantly high value whereas *Onattukara* sandy soil had the lowest value which is on par with black cotton soil, Laterite soil as well as *Poonthalpadam* soil. It is evident from the analysed data that the organic carbon content got increased at active tillering stage when compared with initial content except for black cotton soils and *Kole* lands.

5.2.2. Available nutrient status

The significantly highest value for Av. N was obtained from *Kari* soils and lowest from *Onnatukara* sandy soils. The available nitrogen status has shown a declining trend at active tillering stage from the initial values which could be due to plant uptake and leaching loss.

The significantly highest value for Av. P gets revealed from samples of Laterite soils which is on par with *Poonthalpadam* soil, black cotton soil as well as *Onattukara* sandy soil and the lowest value is found to be associated with *Pokkali* soil which is on par with *Kari* soil, *Onattukara* sandy soil as well as *Kole* land. Other than *Pokkali* soils all other soil types reported an increased Av. P at active tillering stage from initial values. The high P availability in tillering stage is due to increased pH (towards neutral) availability of P maximum at near neutral pH. Von *et al* 2018 reported that the pH 6 to 6.8 got maximum P availability.

It was found that black cotton soil had significantly highest value of Av. K which is on par with *Kari* soil and *Kole* land and the lowest value was identified to be from *Pokkali* soils which is on par with *Onattukara* sandy soil, Laterite soil as well as *Poonthalpadam* soil. The K content in active tillering was low while comparing with before cropping in *Pokkali soil, Poonthalpadam* soil and Laterite soil it is due to dilution effect and plant up take.

Pokkali soil recorded significantly higher value for Av. Ca which is on par with *Poonthalpadam* soil whereas *Onattukara* sandy soil recorded the lowest which is on par with *Kari* soil, Laterite soil as well as *Kole* land. The Av. Ca content was relatively low at active tillering stage when compared to initial stage in black cotton soil, *Onattukara* sandy soil and Laterite soil due to dilution effect, i.e., the soils were dry at the time of initial soil sample collection compared to the flooded condition during active tillering stage.

It is clear from the analysed data that the significantly highest value for Av. Mg was identified to be from *Pokkali* soil while *Onnatukara* sandy soil had the lowest value which is on par with Laterite soil and *Kole* land . As like Av. Ca same trend was noticed in in Av. Mg also at active tillering stage.

The significantly highest value for Av. S was identified to be from *Pokkali* soil and lowest from Laterite soil which is on par with *Onattukara* sandy soil, black cotton soil , *Kole* land as well as *Poonthalpadam* soil. At active tillering stage all the soil types recorded a reduced Av. S content when compared with the initial values which may be due to plant uptake and complex formation with cations which were earlier associated with phosphorous.

It gets reflected from the analysed values that the significantly highest value for Av. Fe was found to be from *Kari* soil which is on par with *Pokkali* soil as well as *Kole* land while the lowest value was associated with *black cotton* soils which is on par with *Poonthalpadam* soil, Laterite soil as well as *Onattukara* sandy soil. The Av. Fe content has reduced at active tillering stage for all the soil types other than *Onattukara* sandy soils when compared with the initial values.

The black cotton soil recorded significantly higher value for Av. Mn which is on par with *Poonthalpadam* soil whereas *Onattukara* sandy soil recorded the lowest value which is on par with *Pokkali* soil, *Kari* soil, *Kole* land as well as Laterite soil. The Av. Mn content has shown a declining trend at active tillering stage for all the soil types other than *Onattukara* sandy soils from the initial values.

The *Pokkali* soils accounts for significantly high mean value for Av. Zn which is on par with *Kole* land whereas the lowest value was reported from *Onnatukara sandy* soils which is on par with *Kari* soil as well as black cotton soil.

The significantly highest value for Av. Cu was reported from *Pokkali* soils and lowest from *Onnatukara* sandy soils which is on par with *Kari* soil as well as black cotton soil. The Cu content has decreased at active tillering stage from the initial values in all the soils except *Pokkali* soils.

The *Pokkali* soils recorded the significantly highest value for Av. B whereas all other soils do not exhibit any significant differences among them. At active tillering stage the Av. B got reduced in all the soil types when compared to the initial values.

5.2.3. Total plant nutrient content at active tillering stage

The rice crop raised in black cotton soils reported significantly highest total N content which is on par with *Kole* land whereas the *Poonthalpadam*soil reported the lowest value which is on par with Laterite soil, *Onattukara* sandy soil, *Pokkali* soil as well as *Kari* soil.

It gets reflected from the analysed data on mean total P that the significantly highest value was reported from Laterite soils which is on par with *Onattukara* sandy soil, *Kole* land, black cotton soil, *Poonthalpadam* soil as well as *Pokkali* soil. The lowest value was observed in *Kari* soil which is on par with *Pokkali* soil and *Poonthalpadam* soil. The highest mean available phosphorous at active tillering stage was also reported in Laterite soils.

The *Laterite* soils accounts for significantly highest total plant K content value which is on par with *Onattukara* sandy soil, black cotton soil and *Poonthalpadam* soil. The *Pokkali* soil recorded the lowest value for total plant K content which is on par with *Kole* land, *Kari* soils, *Poonthalpadam* soil as well as black cotton soil. The *Poonthalpadam* soil contain 2:1 clay mineral which can fix potassium.

The total calcium content was significantly highest in black cotton soils which is on par with *Poonthalpadam* soil and lowest in *Laterite* soil which is on par with *Kari* soil, *Onattukara* sandy soil, *Pokkali* soil as well as *Kole* land. The black cotton soil have highest pH and exchangeable Ca content which leads to maximum up take. Irene (2014) also reported similar result.

It is evident from the analysed values that the *Pokkali* soils had significantly higher mean total Mg and the *Onnatukara* sandy soils recorded the lowest value. The *Pokkali* soils as well as *Onattukara* sandy soil accounts for the highest and lowest mean available Mg content at active tillering stage.

The significantly highest total S content was estimated to be from *Pokkali* soils and the lowest from *Onnatukara sandy* soil. The highest available S content was in *Pokkali* and lest was in *Onnatukara sandy* soil.

The significantly highest value for mean total Fe was concluded to be from *Kole* land which is on par with Laterite soil, *Onattukara* sandy soils, *Pokkali* soil as well as *Kari* soil. The lowest value was recorded from black cotton soil which is on par with *Poonthalpadam* soil. The lowest av. Fe was recorded from black cotton soil.

The significantly highest total plant Mn value was reported from *Poonthalpadam* soils which is on par with *Kole* land, Laterite soil as well as black cotton soil. The minimal value was obtained from *Kari* soils which is on par with *Pokkali* soils and *Onattukara* sandy soils.

The analysed data revealed the significantly highest value for mean total Zn to be from *Kole* land which is on par with *Kari* soil and lowest value from *Poonthalpadam* soil.

The *Poonthalpadam* soil was found to have significantly higher value for total Cu content which is on par with *Kari* soil. The minimal value was obtained black cotton soils which is on par with Laterite soil.

The *Kari* soils accounts for significantly higher mean total B content which is on par with *Kole* land, *Onattukara* sandy soil, *Pokkali* soil as well as Laterite soil wherein the *Poonthalpadam* soils recorded the lowest value which is on par with black cotton soil, Laterite soil and *Pokkali* soil.

5.2.4. Relationship between electrochemical parameters and available nutrients at active tillering stage

The data on correlation between electro chemical properties and available nutrient content of soil at active tillering stage is discussed here under.

The electrical conductivity had shown a significant and positive correlation with OC, Av. N, Av. Mg, Av. S, Av. Fe, Av. Cu, Av. B which could be due to the increased ion concentration, salts or organic salts. The similar conclusion was also reported by Irene (2014).

The significant and positive correlation of OC with Av. N , Av. S and Av. Fe could be due to the available nutrients from organic matter on mineralization. It points to the importance of organic matter on soil fertility.

5.2.5 Relationship between electrochemical properties and total plant nutrient content at active tillering stage

The soil pH had a significant and positive correlation with total N, total Ca and negative correlation with total Cu i.e. an increase in pH will enhance the uptake of total N and Ca but will adversely affect the total Cu intake. The higher electrical conductivity will in turn reduce the uptake of total P, total K and total Mn. Organic carbon was found to have a significant and positive correlation with total Zn, total Cu, total B. Organic matter may be a source of these micronutrients. The significantly negative correlation of OC with total plant P could be due to the competition from microorganisms in soil for phosphorous.

5.3. HARVEST STAGE

5.3.1. Electrochemical properties

The analysed data on mean soil pH states that as like before cropping the significantly highest value was recorded in black cotton soil and lowest in *Kari* soil which is on par with *Poonthalpadam* soil, Laterite soil as well as *Onattukara* sandy soil. The pH for all soils were reduced from active tillering stage. It is due to continues flooded effect and release of organic acids

The significantly highest mean value for electrical conductivity was concluded to be from *Pokkali* soil while *Kole* land soil reported the lowest value which is on par with *Poonthalpadam* soil and *Onattukara* sandy soil. EC was increased in the harvest stage while comparing with active initial stage, because at active tillering stage the ponded water was high and in the harvest stage it became less.

It gets revealed from the analysis on mean organic carbon that the *Kari* soil accounts for significantly higher value whereas the *Onattukara* sandy soil had the lowest OC which is on par with *Poonthalpadam* soil, black cotton as well as

Laterite soil. This is the same trend noticed from the before cropping and active tillering stage.

5.3.2Available nutrient status

The *Kole land*s were identified to possess significantly highest value for mean Av. N whereas *Pokkali* soils exhibited the lowest value which is on par with *Onattukara* sandy soil and black cotton soil.

It is evident from the analysed data that the significantly highest values for mean Av. P were reported from *Onnatukara* sandy soils which is on par with Laterite soil, black cotton soil as well as *Poonthalpadam* soil whereas the lowest value was from *Pokkali* soils which is on par with *Kari* soil, *Kole* land and *Poonthalpadam* soil.

The estimated significantly highest mean value of Av. K was from *Pokkali* soils wherein the lowest was from *Onattukara* sandy soil which is on par with Laterite soil, *Poonthalpadam* soil and *Kari* soil.

It is clear from the analysis that the mean Av. Ca was significantly higher in *Poonthalpadam* soils which is on par with black cotton soil, *Pokkali* soil as well as *Kole* land. The lowest value was observed in *Onnatukara sandy* soil which is on par with Laterite soil and *Kari* soil.

The *Pokkali* soils accounts for significantly higher mean Av. Mg as estimated whereas the minimal value was reported in *Onnatukara* sandy soils which is on par with Laterite soil as well as *Kari* soils.

The *Pokkali* soil type revealed the significantly higher mean value for Av. S while *Laterite* soils reported the lowest value which is on par with *Onattukara* sandy soil, *Poonthalpadam* soil and black cotton soils.

The *Kari* soil was reported to be the soil type with significantly higher mean value for Av. Fe which is on par with *Pokkali* soil as well as *Kole* land. The lowest value was reported in *black cotton* soils which is on par with *Poonthalpadam* soil, *Onattukara* sandy soils as well as Laterite soils.

The analysed data on mean Av. Mn concludes the significantly highest value to be from black cotton soil which is on par with *Poonthalpadam* soils and

Onnatukara sandy soils reported the lowest value which is on par with all other soil types except black cotton soils.

The significantly highest value for Av. Zn was reported in *Pokkali* soils and the lowest in *Onattukara* sandy soil which is on par with *Kari* soil, black cotton soil as well as *Poonthlapadam* soil.

The *Pokkali* soils accounts for significantly highest value for mean Av. Cu which is on par with *Kole* land. The *Onnatukara sandy* soils reported the lowest value which is on par with *Poonthalpadam* soil, *Kari* soils, black cotton soil as well as Laterite soil.

The significantly highest value for Av. B was reported from *Pokkali* soils and the lowest value Laterite soils which is on par with all other soil types except *Pokkali* soils.

5.3.3. Total plant nutrient status at harvest stage

It is concluded from the data on mean total N that the black cotton soils had significantly higher mean total N which is on par with *Kari* soil wherein *Pokkali* soils had the lowest N content which is on par with *Kole* land, Laterite soil, *Poonthalpadam* soils as well as *Onattukara* sandy soils.

The *Kole* land accounts for significantly higher value of total P which is on par with *Onattukara* sandy soil, Laterite soil, black cotton soil as well as *Poonthalpadam* soil. The lowest value was observed in *Kari* soils which is on par with *Pokkali* soil and *Poonthalpadam* soils.

The significantly highest value for total K was observed in Laterite soils and lowest in *Pokkali* soils.

The analysed data on mean total Ca reports the significantly highest value to be of black cotton soil and lowest was observed in *Kari* soils which is on par with Laterite soil, *Kole* land, *Onattukara* sandy soil as well as *Pokkali* soils.

The mean total Mg content for all the soil types were observed to be the same as far as the variations among the highest as well as lowest values of total magnesium is considered negligible.

The black cotton soil was found to have the significantly highest mean value for total S where in *Poonthalpaadam* soils had the minimal value.

The *Kole* land soils reported significantly higher mean value for total Fe which is on par with *Onattukara* sandy soils and Laterite soil. The lowest value was recorded in black cotton soils which is on par with *Poonthalpadam* soil.

The analysed data on mean total Mn shows the significantly highest value for mean total Mn to be from *Kole* land which is on par with *Poonthalpadam* soils and black cotton soils. The *Kari* soils had the lowest value which is on par with *Pokkali* soil, *Onattukara* sandy soil as well as Laterite soils.

It is evident from the data that mean total Zn was significantly high in *Kole* land and minimum in *black cotton* soils.

The significantly highest value for total Cu was identified to be from *Poonthalpaadam* soils which is on par with *Kari* soil. The lowest value was recorded in black cotton soils which is on par with Laterite soil, *Pokkali* soil and *Kole* lands.

It gets revealed from the analysis on total B that the *Poonthalpaadam* soils reported the highest total B content whereas Laterite soils reported the lowest.

5.3.4. Total nutrient content in grain

The analysed data on mean total N states that the black cotton soil reported significantly higher value which is on par with *Kari* soils, *Onattukara* sandy soils and *Poonthalpadam* soils. The lowest value was reported in *Kole* land which is on par with *Pokkali* soil.

The significantly highest mean total P was observed to be from black cotton soil and lowest from *Pokkali* as well as *Kari* soils.

It is evident from the analysis on mean total K that the significantly highest value was identified to be from *Poonthalpadam* soil which is on par with *Kole* land, black cotton soil and *Onattukara* sandy soils. The minimal value was obtained from *Kari* soils which is on par with Laterite soils.

The significantly higher total Ca value was concluded to be to be from black cotton soils which is on par with *Poonthalpadam* soil wherein the lowest value was obtained from *Kole* land which is on par with *Kari* soil, *Pokkali* soil, Laterite soil as well as *Onattukara* sandy soils.

The significantly higher mean for total Mg was reported from *Kole* land soils and minimal from *Onattukara* sandy soils.

The highest mean value for total S was recorded from *Kari* soils and the lowest from *Poonthalpadam* soils.

From the analysed data it can be concluded that the significantly higher value for total iron was reported in *Kole* land which is on par with *Onattukara* sandy soil and Laterite soil while the lowest was observed to be from black cotton soil which is on par with *Poonthalpadam* soil.

The study on mean total Mn shows the significantly higher value to be from *Kole* land which is on par with black cotton soil and *Poonthalpadam* soils. The lowest value was obtained from *Kari* soil which is on par with *Pokkali* soil, *Onattukara* sandy soil and Laterite soils.

As per analysis the mean total grain Zn content was significantly high in *Onattukara* sandy soil whereas low in black cotton soil.

The *Poonthalpadam* soils reported significantly higher mean total Cu which is on par with *Kari* soil. The lowest value was recorded in black cotton soil which is on par with Laterite soil.

Based on the estimated mean total B the *Poonthalpadam* soils reported the highest value whereas Laterite soils reported the lowest value.

5.3.5. Relationship between electrochemical parameters and available nutrients at harvest stage

It can be concluded from the correlation study conducted that an increase in soil pH will result in increased availability of calcium. An increased ion concentration, salts or organic salts would be the reason behind significant and positive correlation between electrical conductivity and OC, Av. K, Av. Mg , Av. S , Av. Fe, Av. Zn , Av. Cu , Av. B. The unavailability of Av. P due to complex formation with several cations has resulted in negative correlation of EC with Av. P .

Organic carbon reported significant and positive correlation with Av. S and Av. Fe .

5.3.6. Relationship between electrochemical properties and total plant nutrient content at harvest stage

It gets revealed from the data on correlation that an increase in soil pH will enhance the total Ca uptake and limit the uptake of Cu. An increased electrical conductivity and organic carbon will adversely affect the phosphorous uptake.

5.3.7. Antagonism of S with nutrients

The available sulphur shown a negative relation uptake of P, K and Mn at active tillering and harvest stage (table 32). Islam *et al.,* 2006 observed an antagonistic relationship between P and S in moong and wheat.

5.4. SULPHUR FRACTIONS

5.4.1. Sulphur fractions before cultivation

The *Pokkali* soil type accounts for the highest sulphur fractions (Fig 16) i.e., sulphate sulphur, water soluble sulphur, heat soluble sulphur, sulphate soluble after ignition, total organic sulphur and total sulphur. The intrusion of sea water in *Pokkali* soils might be the reason behind the elevated trend of sulphur fractions. The occurrence of 2.36 g/kg of sulphate content in the sea water of Atlantic provinces was reported by Young et al. (1959). The sea water inundation again accountsfor the elevated S fractions of Kuttanad as well as *Kole* land but the relatively lesser values for Kuttanad soil and *Kole* land could be due to the management of sea water entry. Shilpa 2020 reported an average S content of 298.77 mg/L in the water samples of *Pokkali* where paddy shrimp land use pattern is being followed.

It can inferred from the study on S fractions in various soil types that the *Onattukara* sandy soil had reported the least values which may be due to the heavy leaching nature of sandy soils. The decreased capacity of light textured soils to absorb sulphate was reported by Ensminger (1954). The availability of various S fractions in all soils except *Pokkali* soil and *Kari* soil can be arranged as total organic S > sulphate soluble after ignition > heat soluble S > total water soluble S > sulphate S. Reshma (2020) also concluded the occurrence of same dominant trend in S fractions. The superiority of organic S fraction in surface soil was reported by Srinivasarao *et al.* (2004) and Reshma (2020). Bhatnagar *et al.*

(2003) stated that organic sulphur fraction accounts for 84 per cent of total sulphur.

Williams and Steinbergs (1962) reported that the amount of soluble sulphate, as indicated by calcium chloride extraction, was low in the surface horizon of most well-drained soils, whether of acid or alkaline reaction, and generally comprised only a small fraction of total S. More organic S is released by gentle hydrolysis. This fraction is also coming under heat-soluble S. Williams and Steinbergs (1959) reported that heat is the main factor leading to the release of additional sulphur in soil. The content of sulphate soluble after ignition was found next to these fractions since much more organic S might have solubilized in this fraction.

The presence of high organic matter content in *Pokkali*, *Kole* and Kuttanad soils are also the reason for high content of all S fractions in these soils, whereas the soils from *Onattukara* sandy plain and northern coastal plain with very low organic matter were reported with less content of all S fractions. Bhatnagar *et al.* (2003) reported that total S exhibits positive correlation with organic matter. Similar conclusion was reported by Aggarwal and Nayyar (1998).

5.4.2. S fractions at active tillering stage

The significantly highest mean value for sulphate S was recorded from *Pokkali* soil and lowest from Laterite soil which is on par with black cotton soil, *Onattukara* sandy soils, *Poonthalpadam* soils and *Kole* lands (Fig 17). All the soils reported relatively low sulphate sulphur fraction at active tillering stage when compared to initial stage.

The data obtained from the study on S fractions in soil it can be concluded that the *Pokkali* soils reported significantly highest mean value for total water soluble S whereas Laterite soils reported the lowest value which is on par with black cotton soil, *Onattukara* sandy soils, *Poonthalpadam* soils and *Kole* lands. Water soluble S was comparatively low at active tillering state than before cropping.

The significantly higher mean value for heat soluble S was identified to be from *Pokkali* soil and lowest from *Laterite* soil which is on par with black cotton soil, *Onattukara* sandy soils, *Poonthalpadam* soils and *Kole* lands. Heat soluble S was found to be low at active tillering stage in comparison to initial stage.

It is evident from analysis on S fractions that the *Pokkali* soil reported significantly highest value for sulphate soluble after ignition while the *Onattukara* sandy soils had the lowest value which is on par with black cotton soil, Laterite soils and *Poonthalpadam* soils. In comparison with analysed soil sample before cropping, sulphate soluble after ignition was recorded low at active tillering stage.

The *Kari* soils showed significantly higher value for total organic sulphur which is on par with *Pokkali* soils whereas the *Onattukara* sandy soils had the lowest value which is on par with Laterite soils, black cotton soils and *Kole* lands. All the soils reported relatively low total organic sulphur fraction at active tillering stage when compared to initial stage.

Based on the study on S fractions it can be stated the significantly highest value for total S was recorded in *Pokkali* soils which is on par with *Kari* soils while the *Onattukara* sandy soils recorded the lowest value which is on par with Laterite soils, black cotton soils and *Kole* lands. The total S exhibited same trend as shown by the above S fractions at active tillering stage.

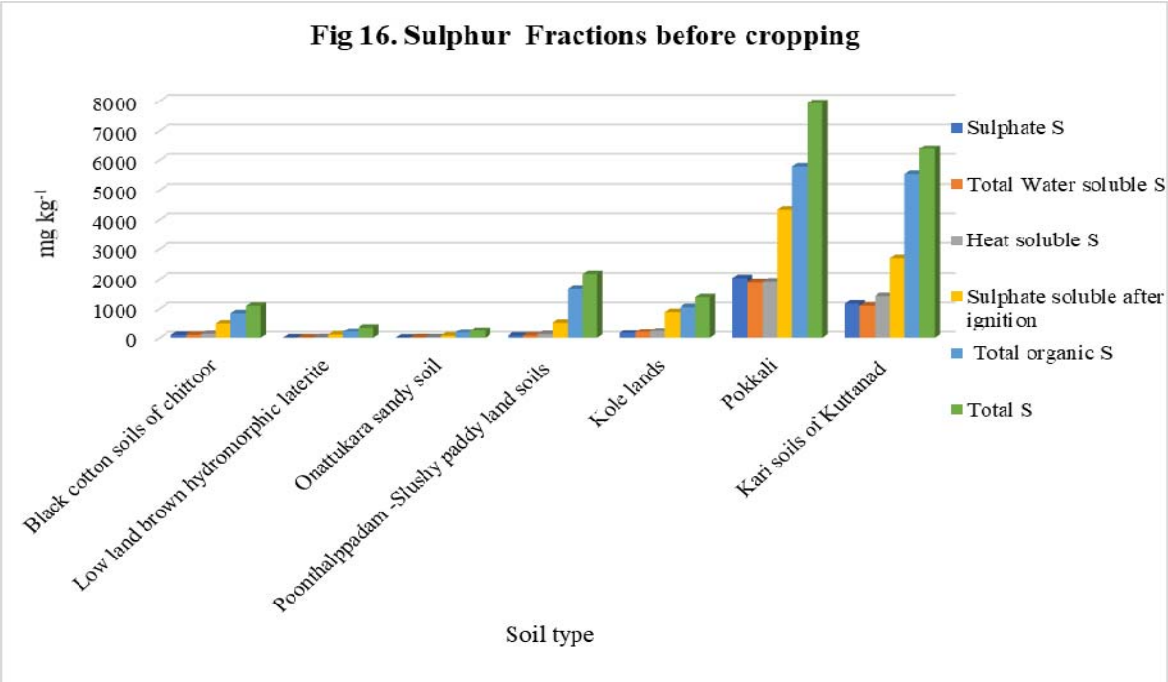


Fig 16. Sulphur Fractions before cropping
8000
7000
6000
5000
4000
3000
2000
1000
0
mg kg-1
Sulphate S
Total Water soluble S
Heat soluble S
Sulphate soluble after ignition
Total organic S
Total S
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

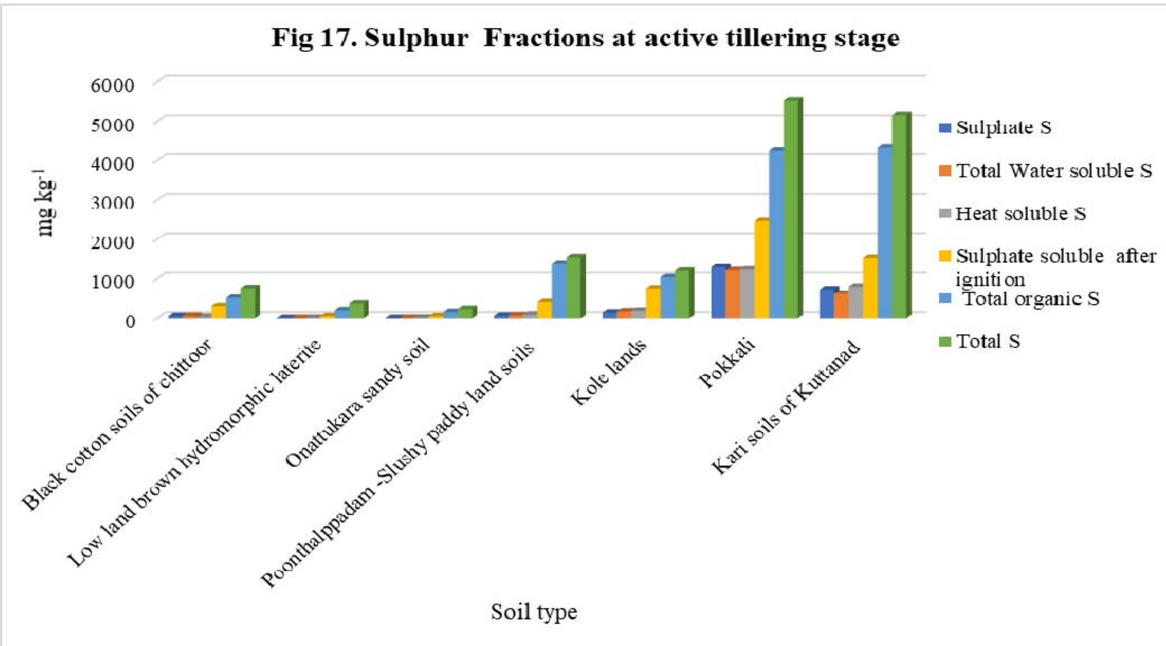
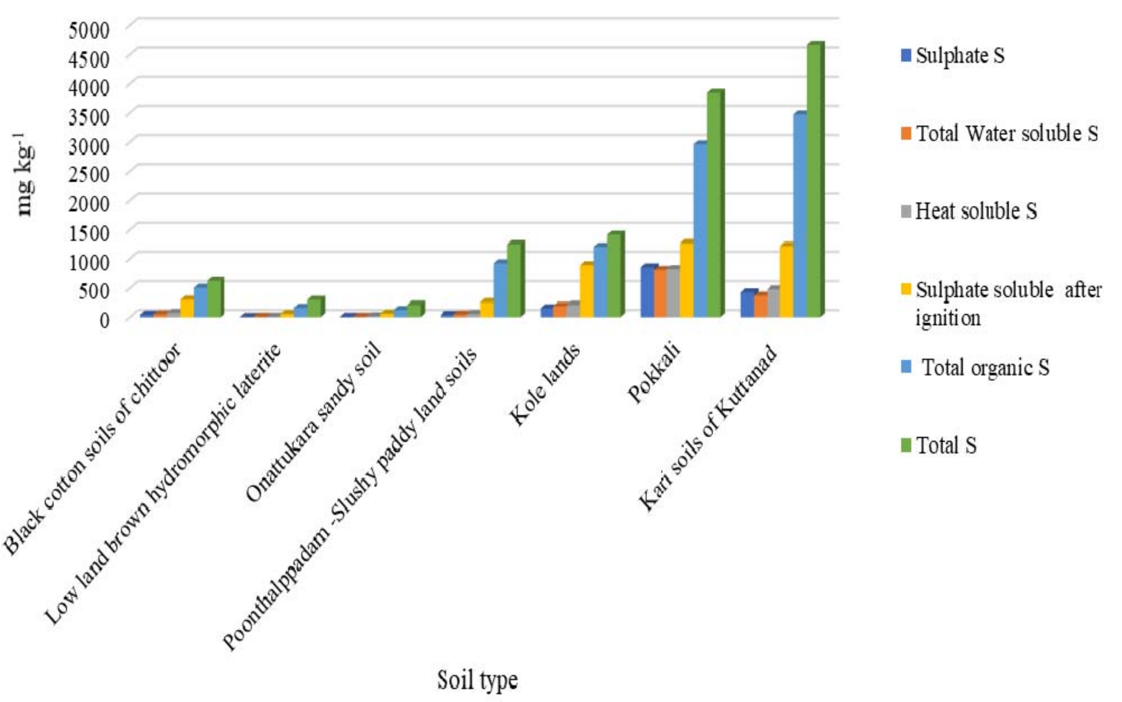


Fig 17. Sulphur Fractions at active tillering stage
6000
5000
4000
3000
2000
1000
0
mg kg-1
Sulphate S
Total Water soluble S
Heat soluble S
Sulphate soluble after ignition
Total organic S
Total S
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

Fig 18. Sulphur fractions at harvest stage



5.4.3. Sulphur fractions at harvest stage

The significantly highest mean sulphate S was estimated to be from *Pokkali* soil wherein the lowest value was observed in *Laterite* soil which is on par with black cotton soils, *Onattukara* sandy soils as well as *Poonthalpadam* soils (Fig 18).

The *Pokkali* soil reported significantly higher value for total water soluble S whereas Laterite soils reported the lowest value which is on par with black cotton soils, *Onattukara* sandy soils as well as *Poonthalpadam* soils.

It gets revealed from the data on S fractions that the *Pokkali* soils had significantly highest mean heat soluble sulphur while the Laterite soils recorded the lowest value which is on par with black cotton soils, *Onattukara* sandy soils and *Poonthalpadam* soils.

The significantly highest mean sulphate soluble after ignition was identified to be for *Pokkali* soils which is on par with *Kari* soils and *Kole* lands. The lowest value was reported from Laterite soil which is on par with black cotton soils, *Onattukara* sandy soils as well as *Poonthalpadam* soils.

Based on the study conducted on S fractions it can be reported that the significantly highest mean total organic sulphur was recorded in *Kari* soil which is on par with *Pokkali* soils whereas *Onattukara* sandy soil reported the lowest value which is on par with Laterite soils and black cotton soi

The significantly highest value for total S was observed in *Kari* soil which is on par with *Pokkali* soils and lowest in *Onattukara* sandy soils which is on par with Laterite soils as well as black cotton soils.

5.4.4. Contribution of different sulphur fractions to the available pool

The direct effect of all sulphur fractions to the available pool was concluded positive. The indirect effect of all the sulphur fractions to the available pool through organic S fraction was considered negative. The dissolution of organic matter will release organic S and it becomes available through other fractions. Hence the net effect of organic S on available pool would be positive.

Bloem in 1998 reported that the 98% of total S is present as organic S compounds. The negative indirect effect of all the sulphur fractions to the available pool through organic S fraction could be due to the temporary adsorption of other sulphur fractions on organic compounds. Studies reveal that the microbial biomass S generally accounts for 1.5-5% of total organic S (Srinivasarao *et al.*,1993).

5.4.5. Effect of electrochemical parameters on sulphur fractions

Soil pH had direct positive effect on heat soluble S and organic S and a negative effect on sulphate S, water soluble S. An increase in pH resulted in decreased sulphate S i.e. the sulphate S would have migrated to organic S and sulphate soluble after ignition. Similarly the water soluble S got converted to sulphate soluble after ignition.

The sulphate S and total water soluble S are available forms of sulphur. As pH increased the above fractions of S migrated to relatively unavailable fractions (sulphate soluble after ignition and organic S) (fig 19). Sharma and Gangwar (1997) reported negative relationship between pH and total S. Similar relationship was also stated by Jat and Yadav (2006).

Electrical conductivity exhibited positive effect on heat soluble S and negative impact on sulphate soluble after ignition. The positive effect of EC on heat soluble S as shown in fig 20, it could be due to the conversion of sulphate S to heat soluble S on an escalation in EC (indirect effect). The migration of sulphate soluble after ignition to water soluble S had resulted in the negative effect of sulphate soluble after ignition on EC.

Organic carbon had negative direct effect on water soluble S (fig 21), sulphate soluble after ignition. The decreased water soluble Son an increase in organic carbon could be due to the migration of the former to organic sulphur fraction. Suthera *et al.,* (2016) reported that water soluble S, sulphate S, heat soluble S, organic S and total S exhibited positive relation with EC as well as organic carbon.

Fig 19. Effect of pH on sulphur fractions

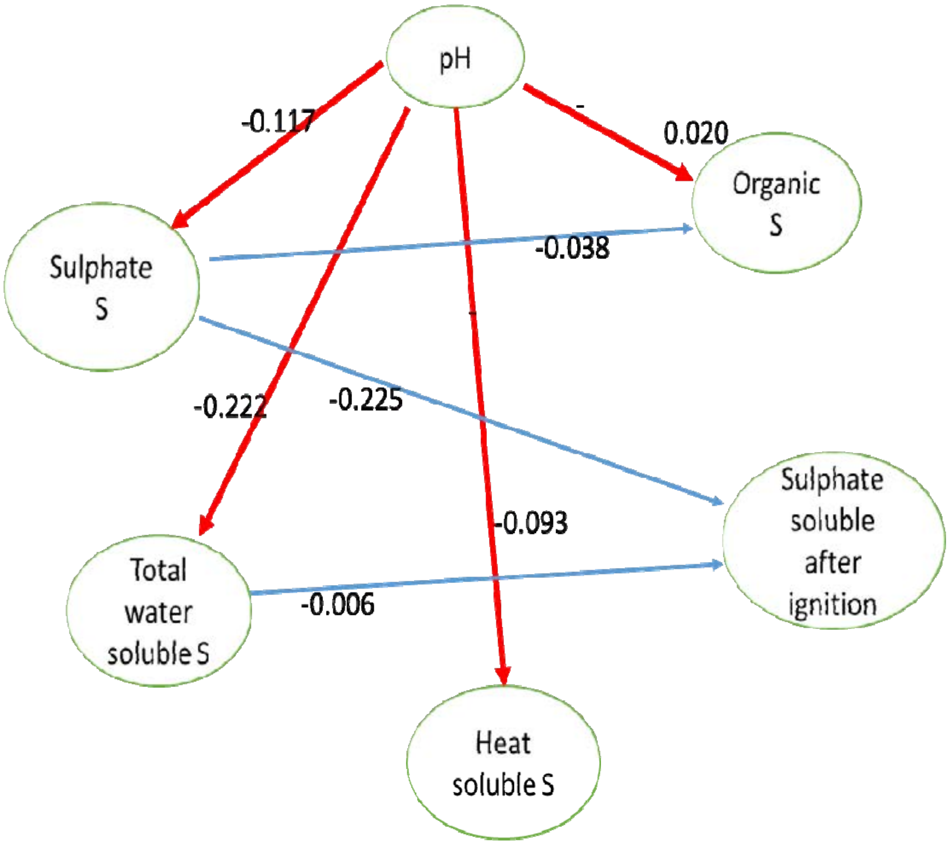


Fig 20. Effect of EC on sulphur fractions

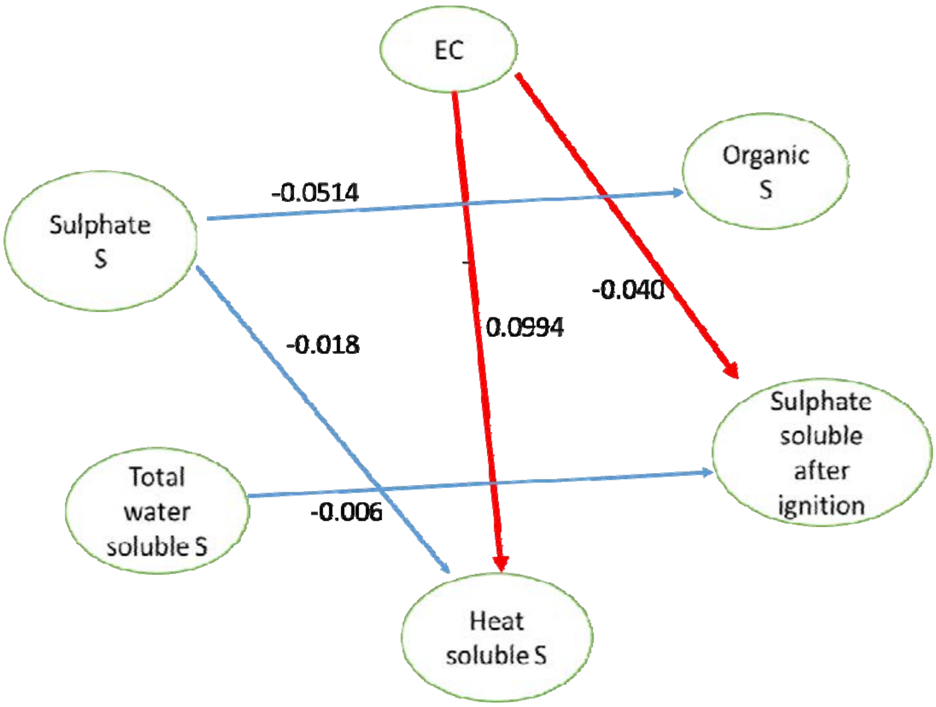
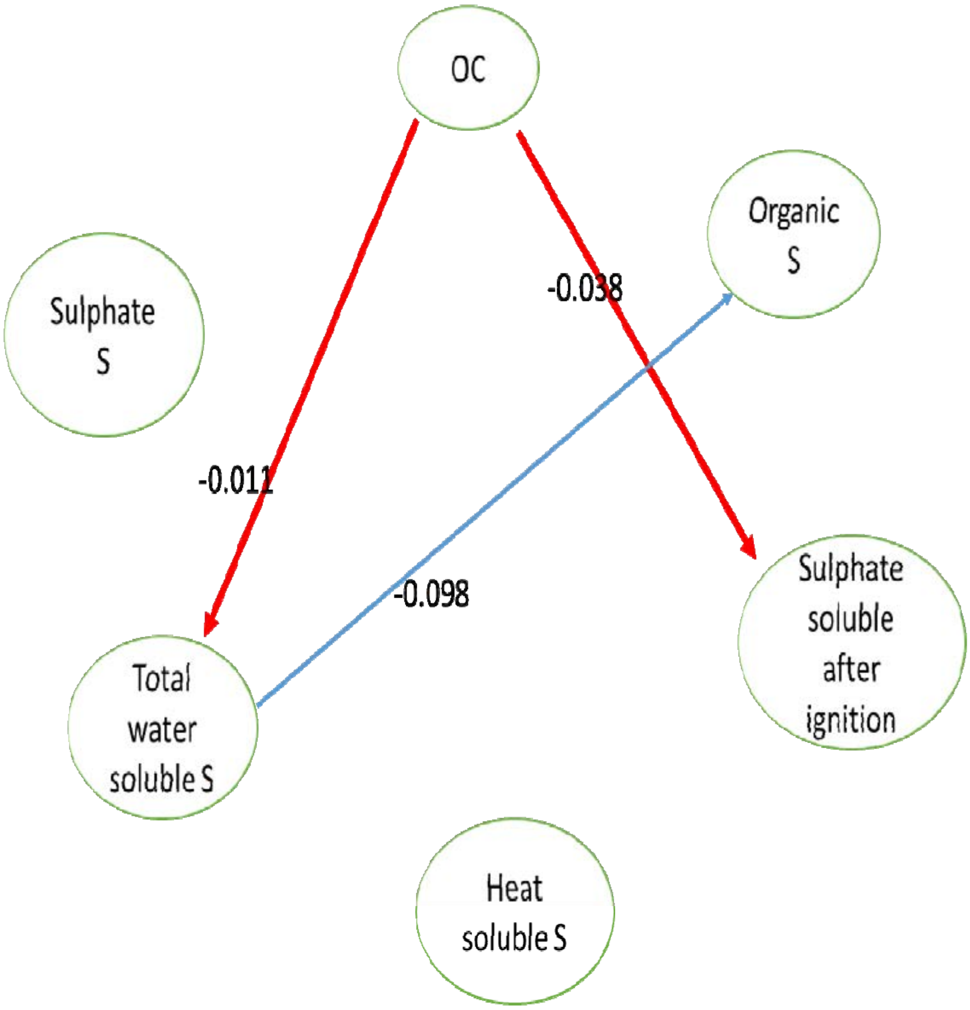


Fig 21. Effect of organic carbon on sulphur fractions


OC
Organic S
Sulphate S
-0.038
-0.011
-0.098
Sulphate soluble after ignition
Total water soluble S
Heat soluble S

5.4.6. Relationship between sulphur fractions and physico chemical as well as biological properties of soil

All the fractions of S had significant and positive correlation with EC, CEC, organic carbon. The significantly positive correlation of S fractions with EC, OC and CEC was also discussed by Reshma (2020). The results of Sharma *et al.* (2014) is in concordance with the very high correlation between S fractions and organic carbon. The positive relation between organic S and organic carbon was reported by Bhatnagar et. al. (2003). Chaudhary and Shukla (2002) concluded that, there is a positive relationship between Sulphate S, EC and organic carbon. Singh *et al.,* in 2006 suggested that water soluble S had positive relation with EC and organic carbon.

The Microbial biomass carbon and aryl sulphatase activity exhibited a significantly positive correlation with all the sulphur fractions.

The available N showed significant positive correlation with total organic S and total S. The organic matter serving as a common source for available N and organic form of S would have resulted in a positive correlation between the nutrient elements N and S.

5.5. TOTAL C, N, P, S, C:S AND N:S RATIO

5.5.1. Before cultivation

The *Kari* soil reported significantly higher mean total C as against *Onattukara* sandy soil which is on par with *Poonthalpadam* soil, black cotton soil as well as Laterite soil. Similarly organic C was relatively higher in *Kari* soil and low in *Onattukara* sandy soil.

It gets revealed from the data that the significantly highest mean total N was observed in *Pokkali* soil which was on par with *Kari* soil and *Kole* land. The *Onattukara* sandy soil reported lowest value remaining on par with black cotton soil, *Poonthalpadam* soil as well as Laterite soils.

As regards total P, *Kari* soils recorded significantly higher value that was on par with *Poonthalpadam* soils. However the lowest value was obtained from *Onattukara* sandy soil which is on par with black cotton soil, *Pokkali* and *Kole* land (fig 22)

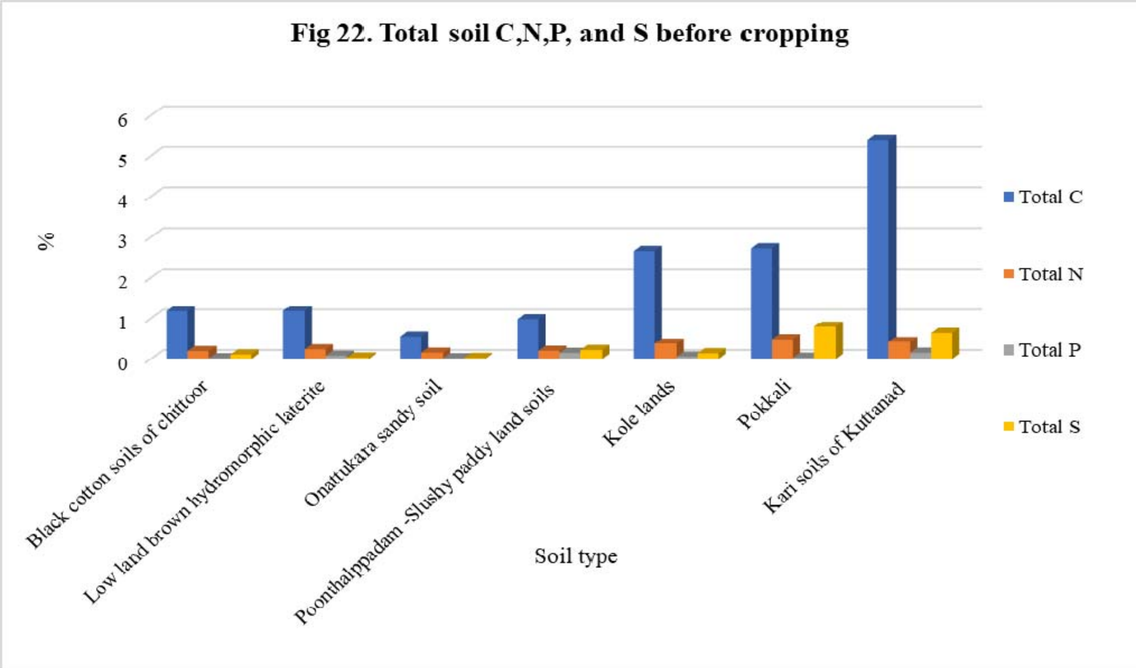


Fig 22. Total soil C,N,P, and S before cropping
6
5
4
3
2
1
0
%
Total C
Total N
Total P
Total S
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type

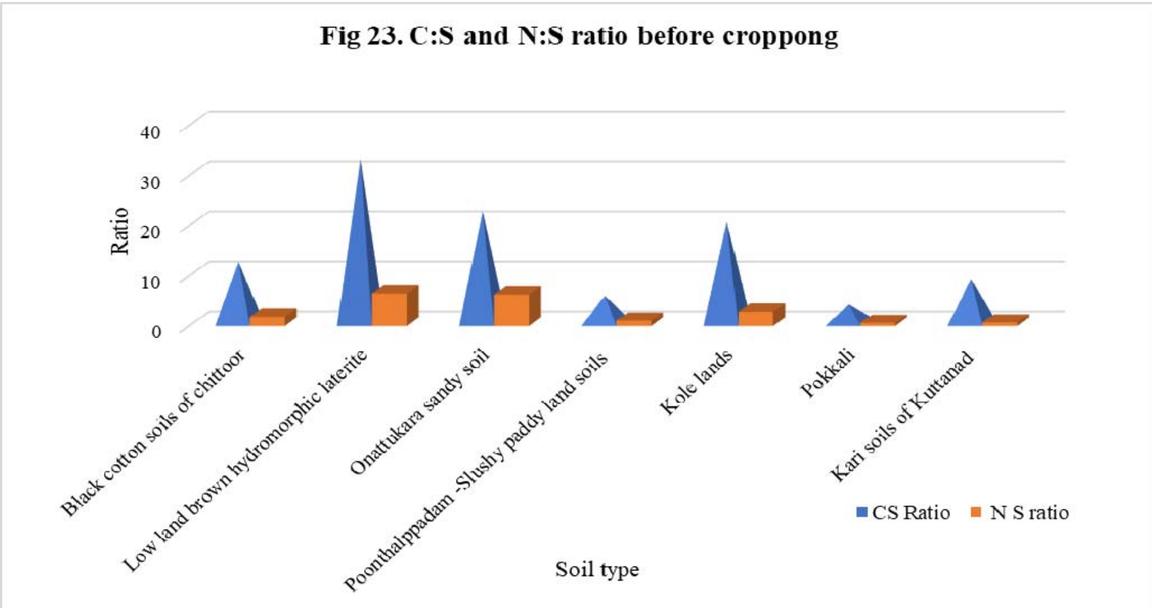


Fig 23. C:S and N:S ratio before croppong
40
30
20
10
0
Ratio
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
CS Ratio
N S ratio
Soil type

The significantly highest mean total S was identified to be from *Pokkali* soil whereas lowest value was identified from *Onattukara* sandy soils which on par with Laterite soil and black cotton soil. (fig. 23)

The Analytical results clearly indicated that the laterite soils recorded the highest mean C:S ratio and *Pokkali* soils the lowest, which was on par with *Poonthalpadam* soil and *Kari* soils

C:S ratio less than 200:1 denotes S mineralisation i.e. the S present in the soil is available for plant uptake while C:S ratios ranging between 200:1 to 400:1 indicated S mineralisation as well as immobilisation. Above 400:1 sulphur becomes immobile and thus unavailable for plants.

The narrowed C:S ratio resulted in better S supplying capacity in soils (Joshi,1984).

The significantly higher mean N:S ratio was obtained in Laterite soil which was on par with *Onattukara* sandy soil and the lowest value was reported from *Pokkali* soil that remained on par with *Kari* soil, *Poonthalpadam* soils and black cotton soils**.** Donald and Williams (1954) stated that generally the N :S ratio of a neutral soil will be 7 to 8 :1.

5.5.2. Active tillering stage

Based on the study, it could be concluded that the highest mean total C was recorded in *Kari* soil and the lowest in *Onattukara* sandy soil.

The significantly highest mean total N was identified to be from *Kari* soil and minimum from *Onattukara* sandy soil.

The highest mean value for total P was reported from *Kari* soil and the lowest from *Onattukara* sandy soil.

It could be arrived from the study conducted that the significantly highest mean total S was associated with the *Kari* soil and the lowest with *Onattukara* sandy soil.

The significantly highest mean C:S ratio was obtained laterite soil and the lowest in *Pokkali* soil.

Fig 24. Total soil C,N,P, and S at active tillering stage

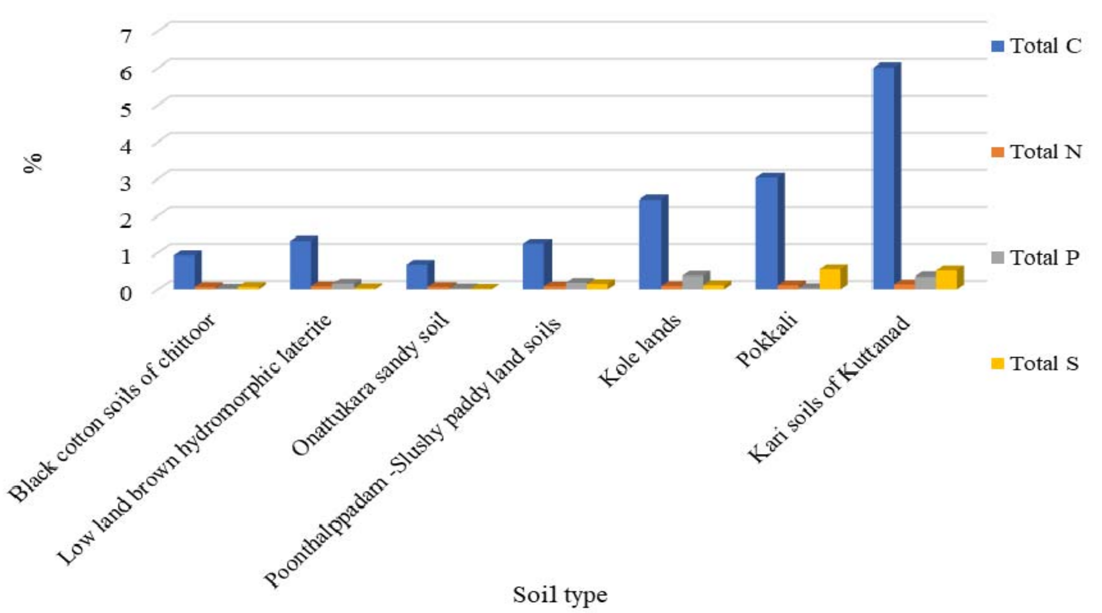
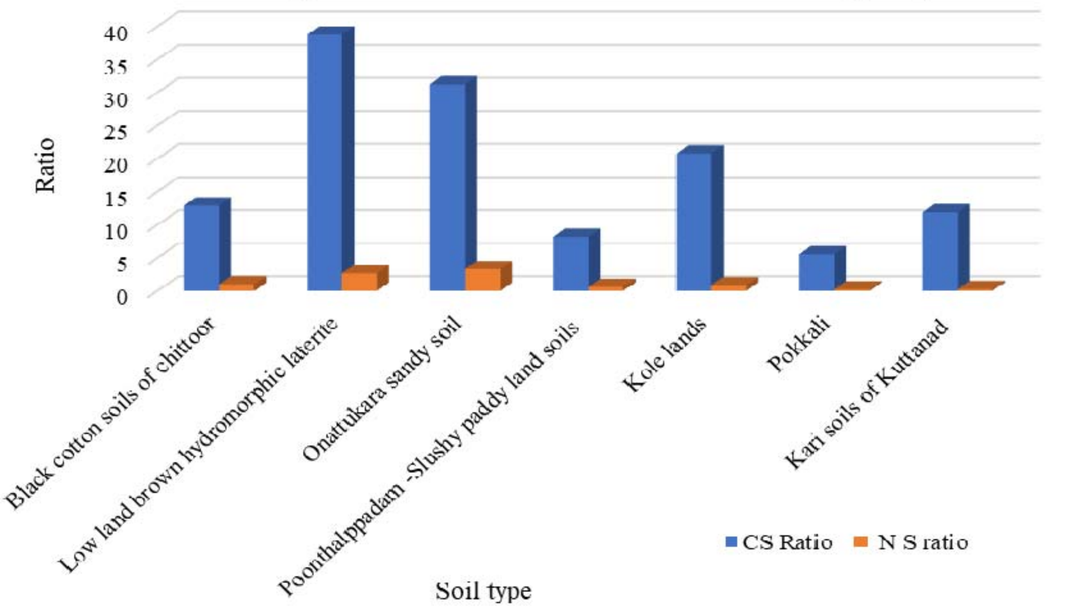


Fig 25. C:S and N:S ratio at active tillering stage



It could be concluded from the analysis on N:S ratio that the *Onattukara* sandy soil reported the significantly highest ratio whereas *Kari* soil the lowest ratio.

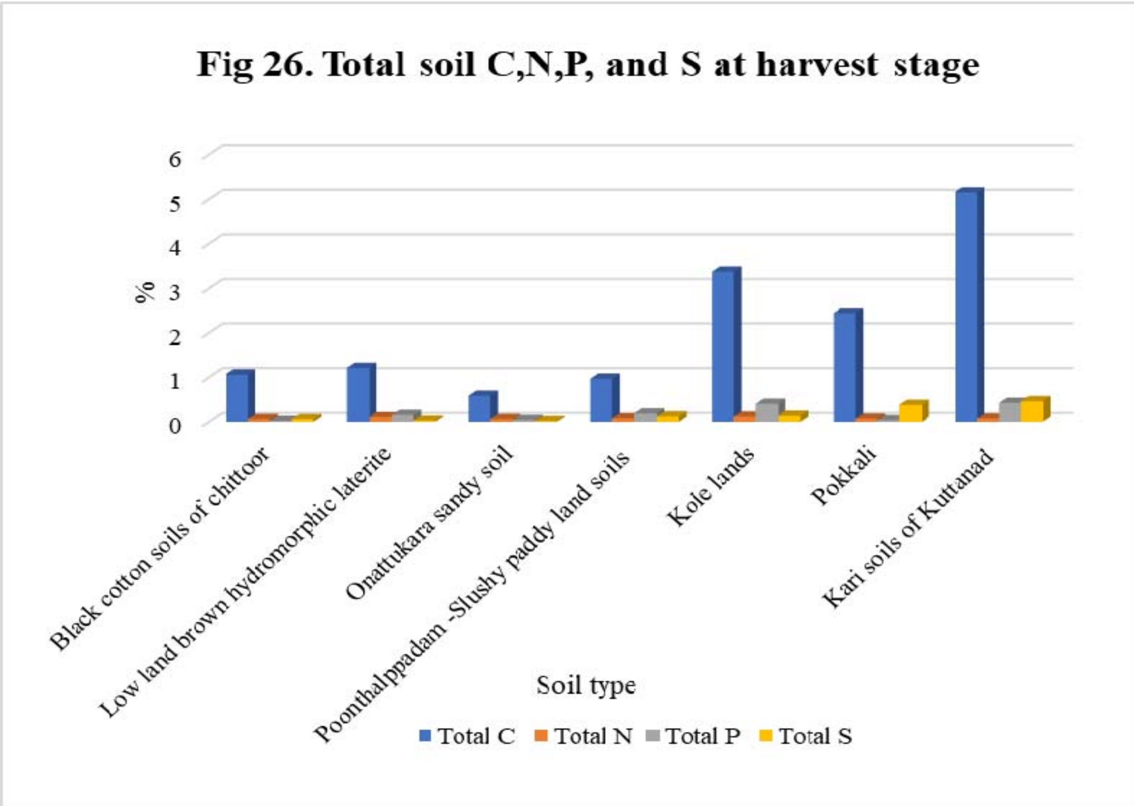


Fig 26. Total soil C,N,P, and S at harvest stage
6
5
4
3
2
1
0
%
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type
Total C
Total N
Total P
Total S

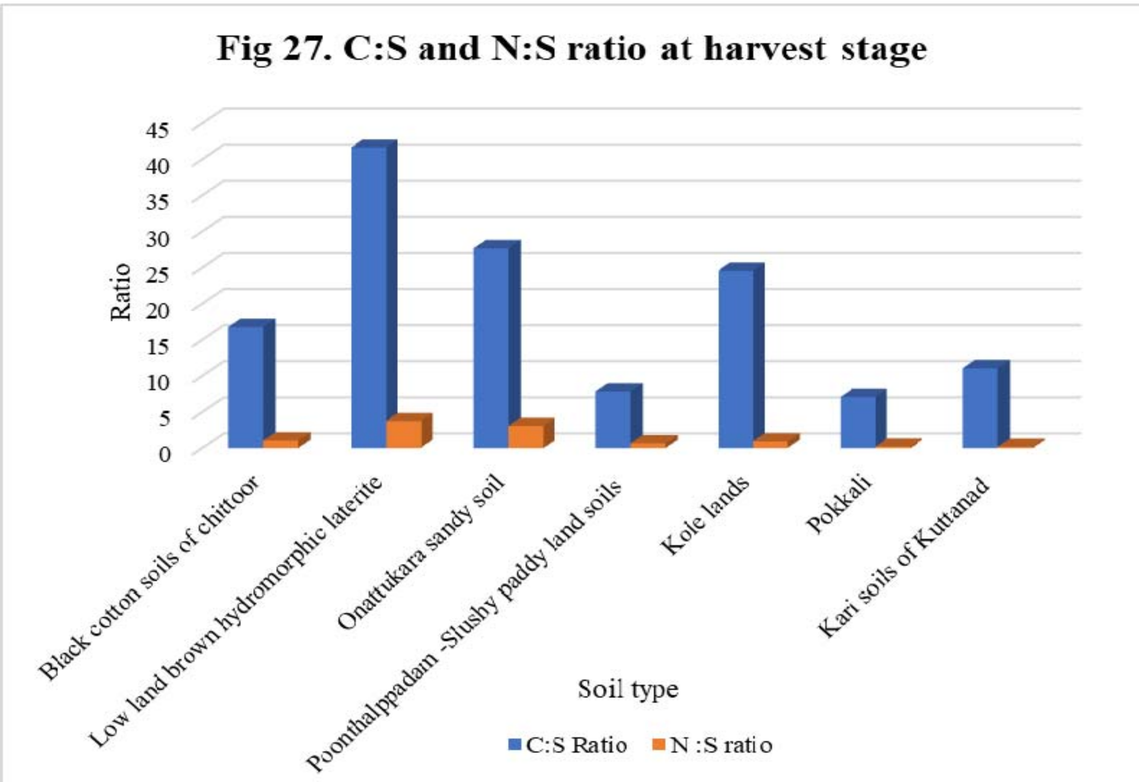


Fig 27. C:S and N:S ratio at harvest stage
45
40
35
30
25
20
15
10
5
0
Ratio
Black cotton soils of chittoor
Low land brown hydromorphic laterite
Onattukara sandy soil
Poonthalppadam -Slushy paddy land soils
Kole lands
Pokkali
Kari soils of Kuttanad
Soil type
C:S Ratio
N :S ratio

5.5.3. Harvest stage

The significantly highest mean total C was observed in *Kari* soil and lowest in *Onattukara* sandy soil.

The *Kole* land soil recorded significantly higher mean total N whereas *Onattukara* sandy soil reported the minimum value.

Based on the analysis on total C, N, P, S, C:S ratio and N:S ratio it could be inferred that the significantly highest mean total P was reported from *Kari* soil and lowest from black cotton soil.

The *Kari* soil was found to have significantly higher mean total S whereas *Onattukara* sandy soils had the minimum value. (fig 26)

It was evident from analysed values that the significantly highest C:S ratio was observed in Laterite soil and the lowest in *Pokkali* soil.

The significantly highest mean N:S ratio was identified to be from Laterite soil wherein the *Kari* soils had the minimal value (fig 27)

5.5.4. Relationship between physico-chemical properties and total C, N, P, S, C:S and N:S ratio

The total C showed a significant and positive correlation. In all the samples analysed, the content of total C and organic C were almost the same thus bringing about a positive correlation with EC, CEC and temperature. The total N was found to have a significant and positive correlation with EC, CEC and organic carbon. Hence, the main source for total N would have been organic matter.

The total S reported significant and positive correlation with EC, CEC, organic carbon. It could be deduced from the correlation study that soil salinity will get increased by the sulphur salts and also that the total organic sulphur in soil is a direct reflection of organic matter contained in it.

An increase in EC had an inverse effect on C:S ratio. Soil sulphur fractions got reduced with an increase in C:S and N:S ratios. Another finding was the narrowing down of C:S ratio with an increase in microbial biomass carbon and aryl sulphatase enzyme activity.

5.6. ADSORPTION STUDY OF SULPHUR

The mechanism by which charged ions are adsorbed by oppositely charged parts of the soil is called adsorption while the release of adsorbed ions is called desorption. The nutrients adsorbed in it become readily available to the plants.

Williams (1975) postulated that adsorbed sulphates, which are reversibly adsorbed by soil, can be replaced by ions such as hydroxyl or phosphate, but are not removed from water, making it generally the major source of sulphur for plants. Adsorbed sulphur has been shown to correlate well with the uptake of sulphur by plants (Westemann, 1947)

The data obtained from the present study could be best fit with Langmuir and Freundlich adsorption isotherms. The Langmuir adsorption isotherm equation (Langmuir, 1918) was developed to describe gas adsorption onto clean solids. It is precisely obeyed only for uniform adsorbent surfaces without lateral interactions, implying a constant free energy of adsorption (Brunauer et al., 1967). The amount of nutrients in the form of a single layer on the soil surface is measured using Langmuir isotherm, suggesting that this method is suitable for single layer surface adsorption reaction for adsorption sites that are fixed.

In the Freundlich adsorption isotherm equation, the affinity terms are distributed approximately log normally implying heterogeneity of adsorbing sites. Freundlich isotherm is an empirical relationship describing adsorption of nutrients to adsorbent surface. It assumes that there are different sites or heterogeneous adsorbent surface with several adsorption energies

In the present study the adsorption of sulphur revealed that both *Kari* and *Pokkali* soil exhibited desorption at 25 °C and 40 °C (fig 28). The inherent richness in available sulphur consequent to sea water intrusion made sulphur adsorption practically impossible at both temperatures in these soils corroborating the explanations arrived at by Reshma (2020) from her investigations on *Pokkali* soil of Kerala.

Among the isotherms worked out, best fit was obtained with Langmuir and Freundlich adsorption isotherm for explaining the adsorption of sulphur in laterite and *Onattukara* sandy soil fig 29, 30, 31 and 32)

Though with a difference in temperatures tried. In case of laterite soils the Freundlich adsorption isotherm could be obtained at 40 ℃ in contrast to the *Onattukara* sandy soil that exhibited Freundlich adsorption isotherm both at 25 ℃ and 40 ℃ reflecting multilayer adsorption of S in soil colloids. Adsorption of anions in soil could be best explained by using Freundlich adsorption isotherm which implies that the bonding energy of the adsorbate anion on the soil surface decreases with the fractional coverage of the adsorbent surface. This is closer to reality for a heterogenous surface like soil.

Two samples from Laterite soil exhibited Langmuir adsorption isotherm at 25℃ which point out the single layer adsorption of S in soil colloids.

Fig.28. Quantity-Intensity curves for sulphur at 25 °C and 40 °C in *Pokkali* and *Kari* soil

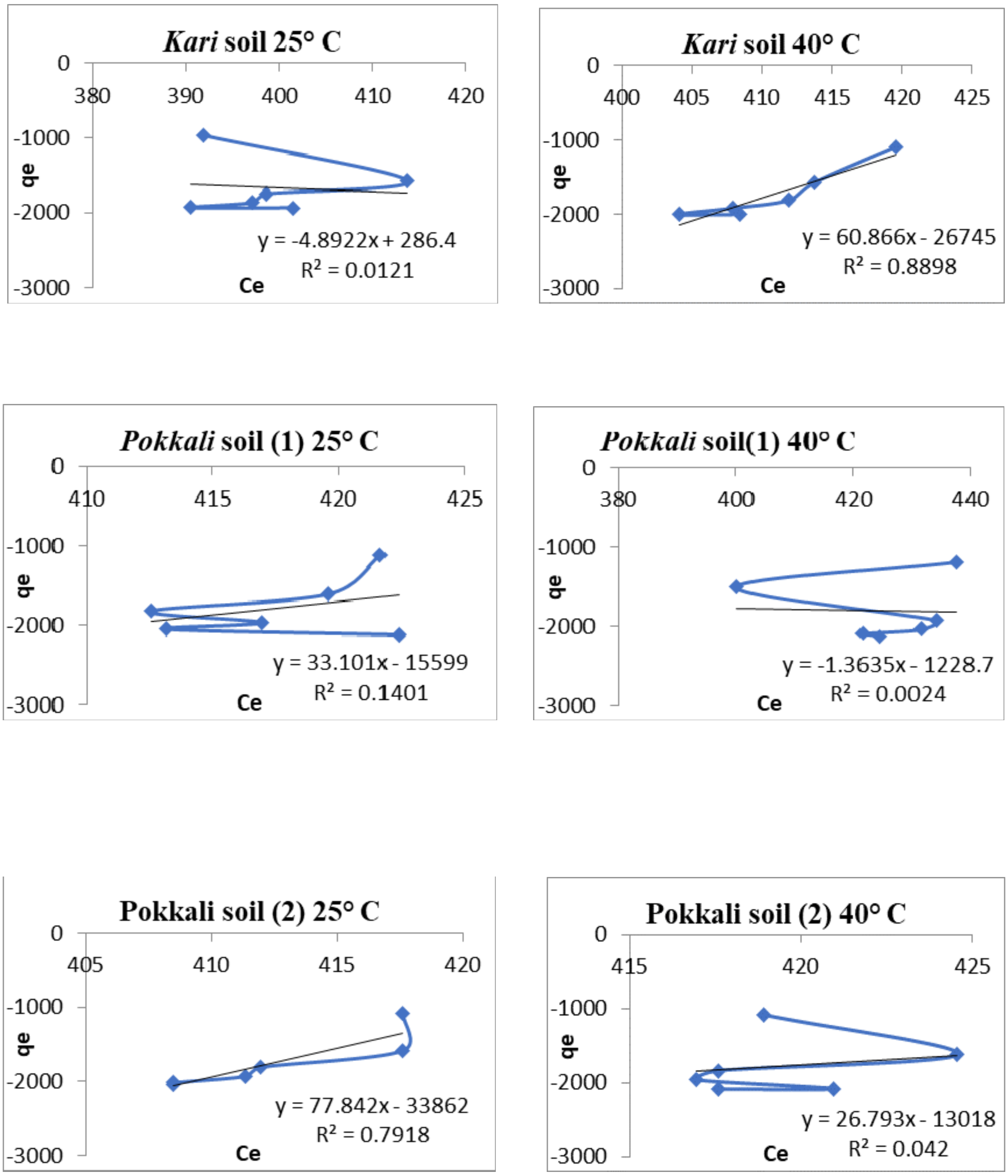
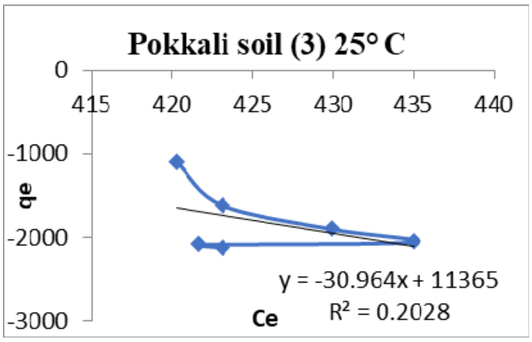
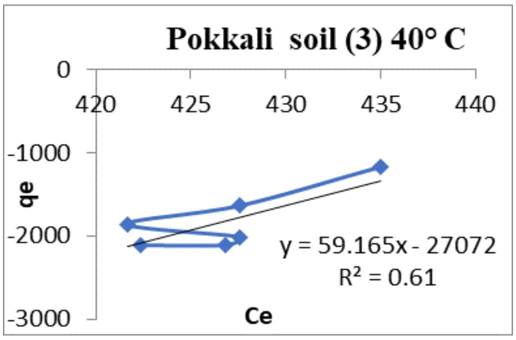
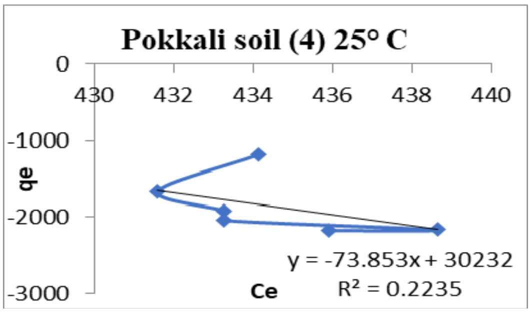
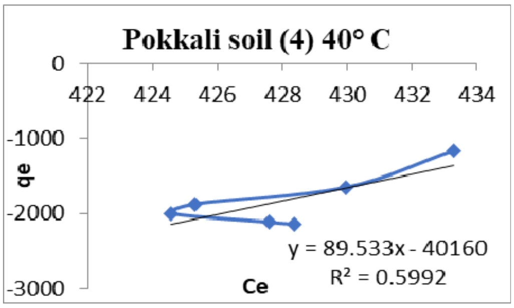


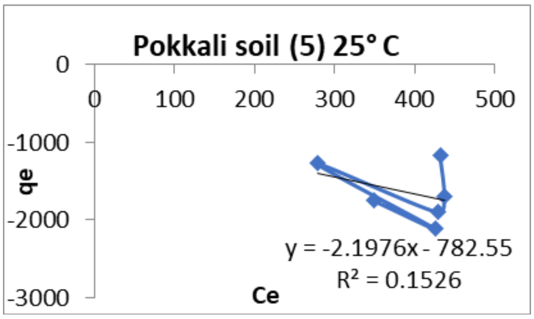
Fig.28 Continued











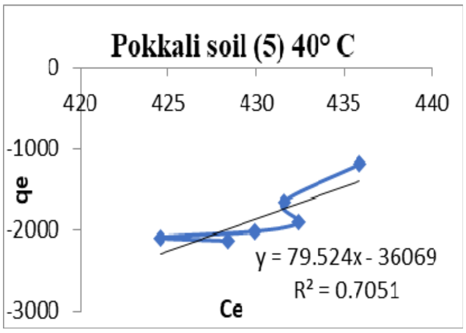
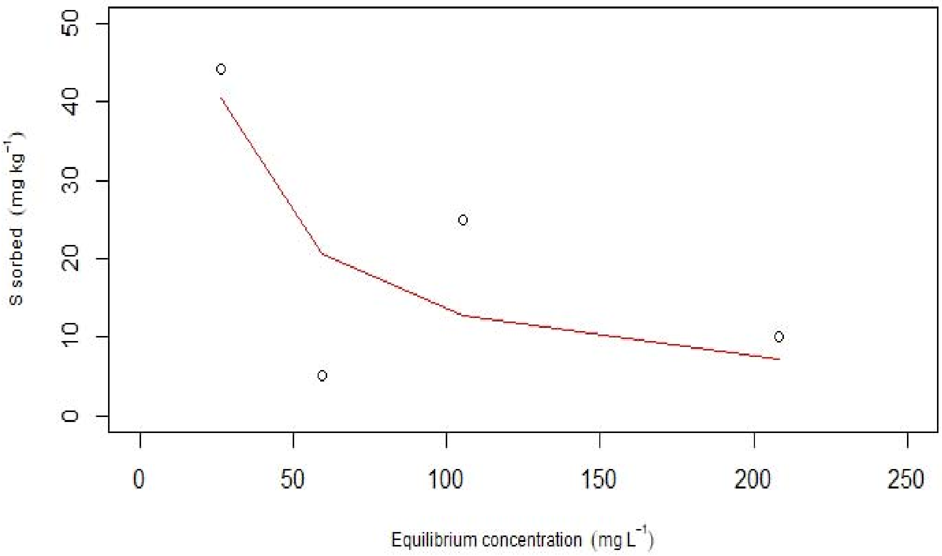


Fig 29. Freundlich adsorption isotherm 25 °C

Laterite soil 1



Laterite soil 2

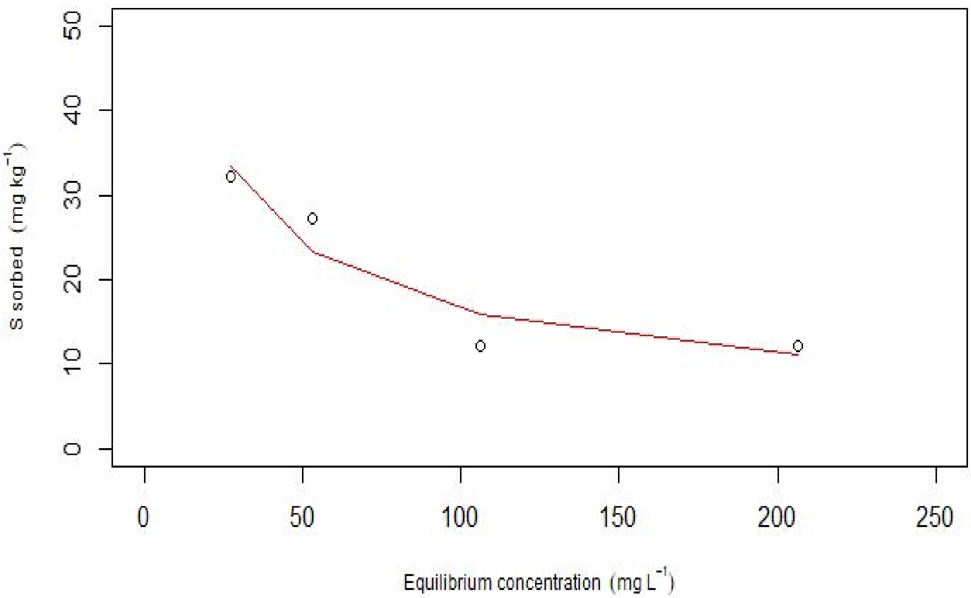
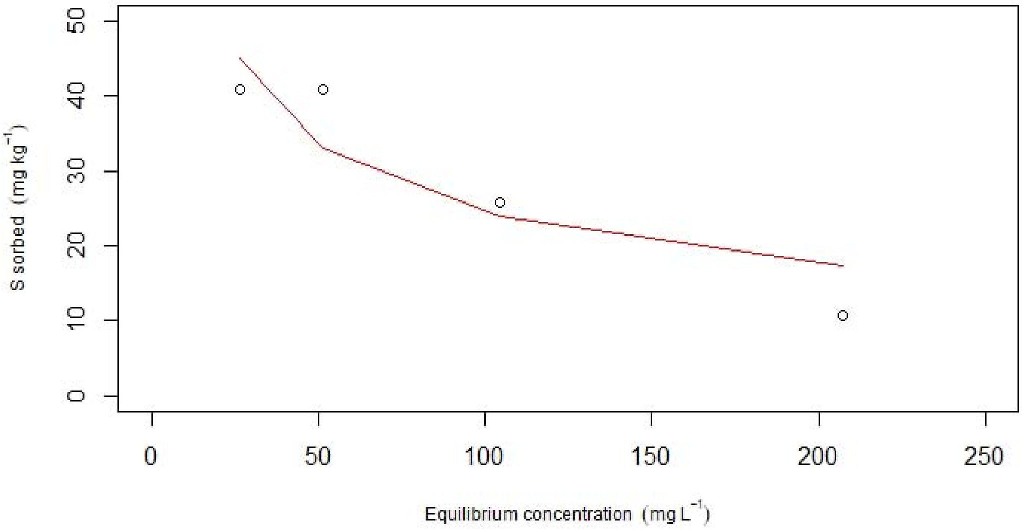


Fig 29. Continued

Laterite soil 3



Laterite soil 4

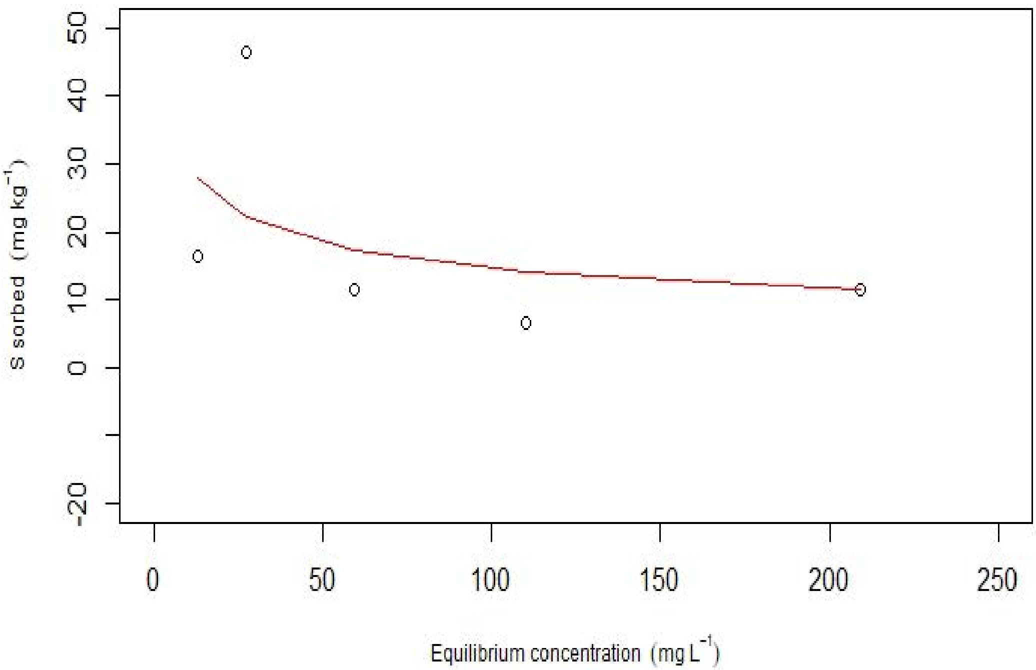
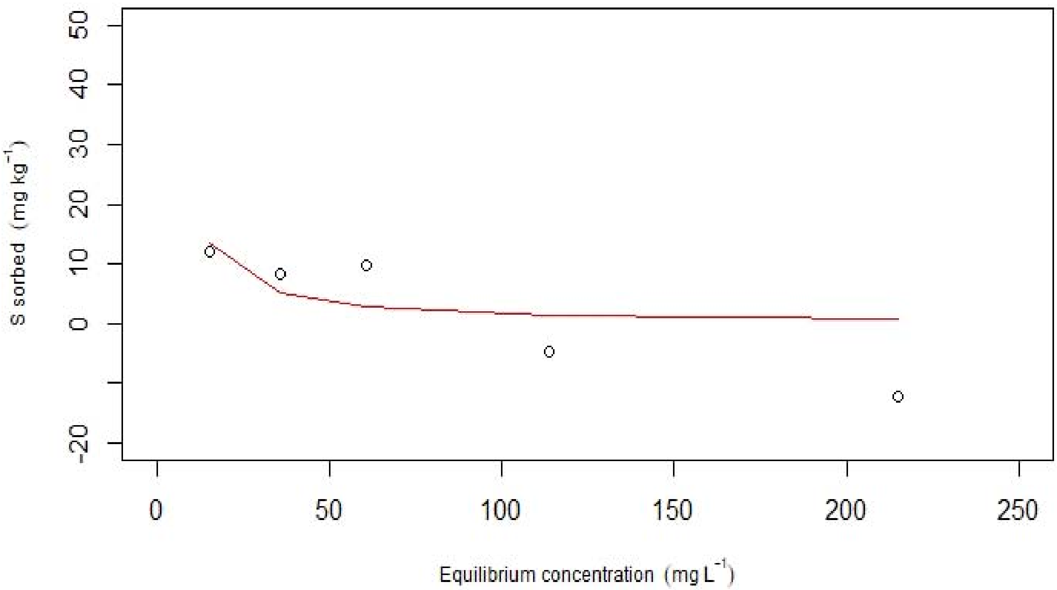


Fig 29. Continued

Onattukara sandy soil 1



Onattukara sandy soil 2

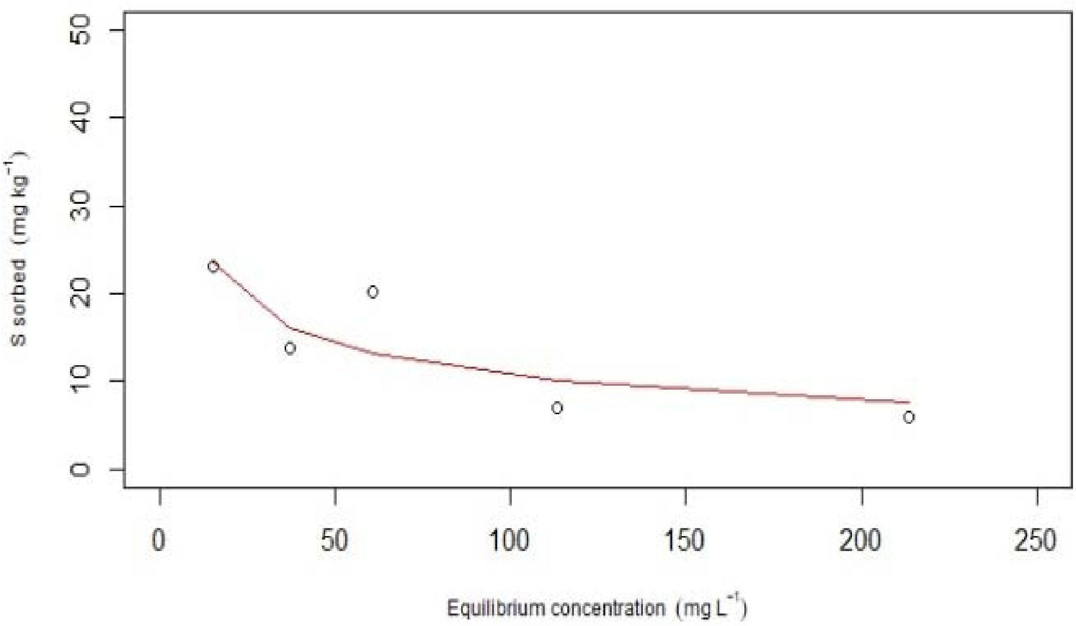
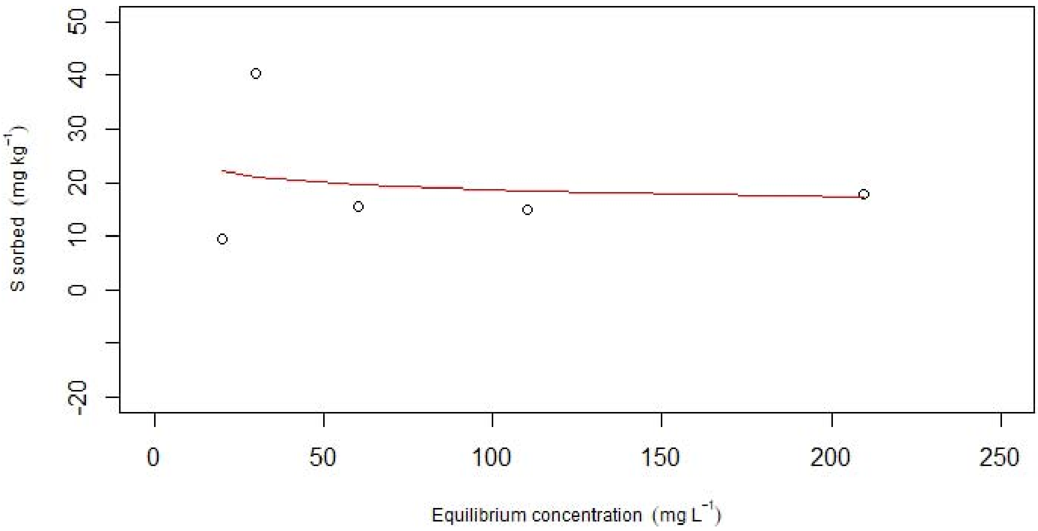


Fig 30. Freundlich adsorption isotherm at 40 °C

Laterite soil 1



Laterite soil 2

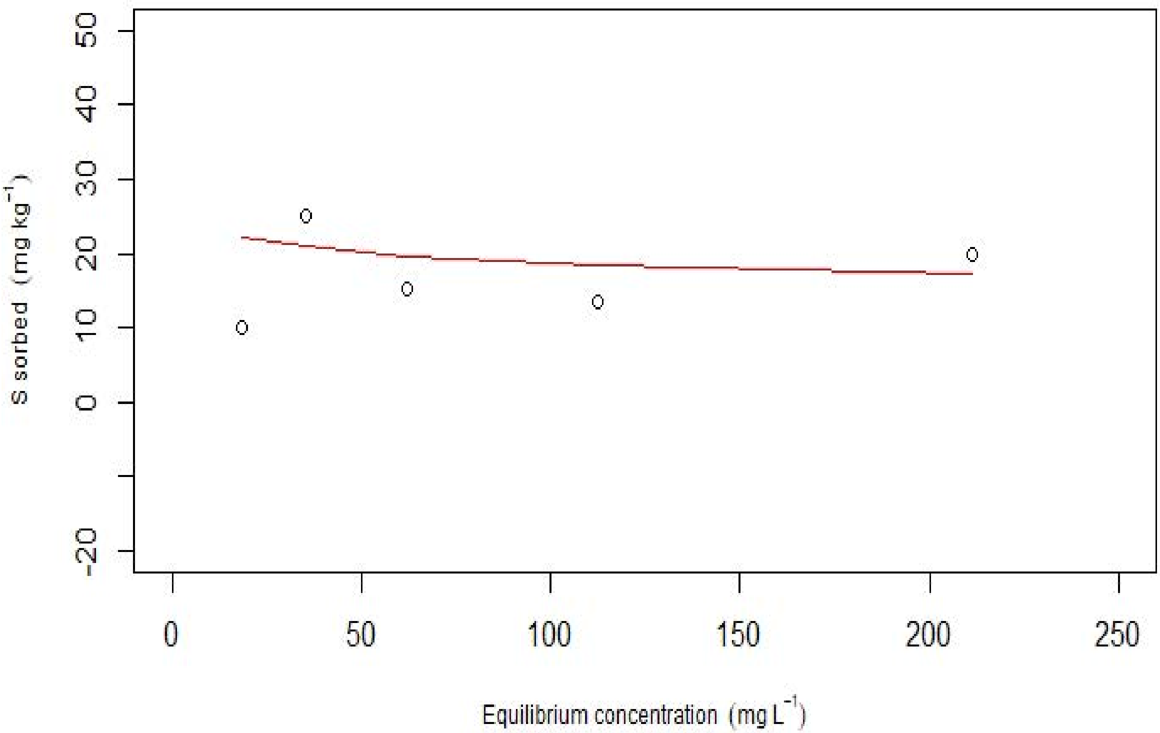
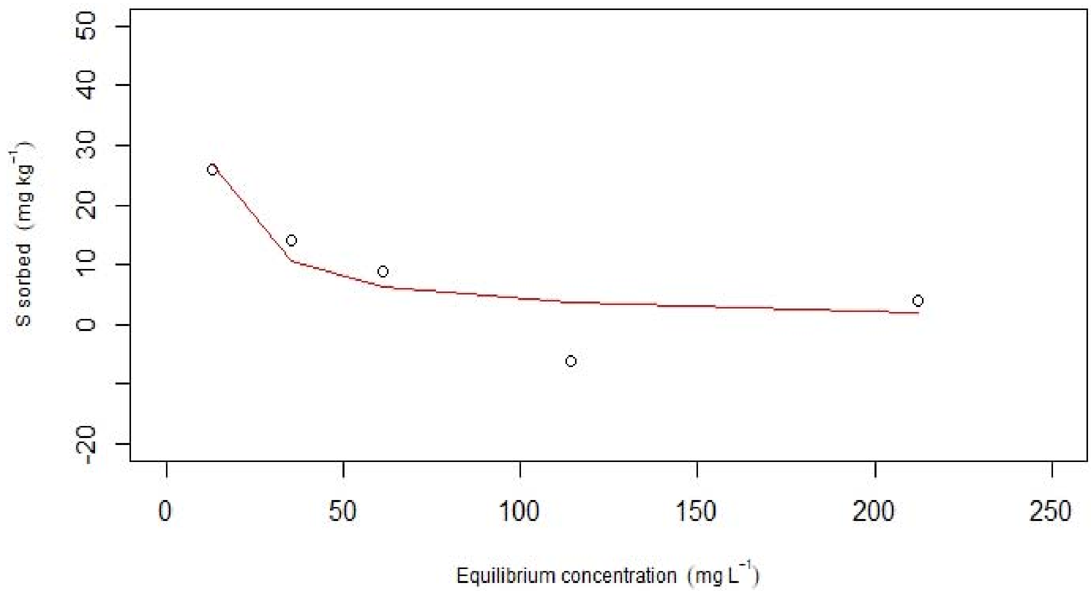


Fig 30. Continued

Laterite soil 3



Laterite soil 4

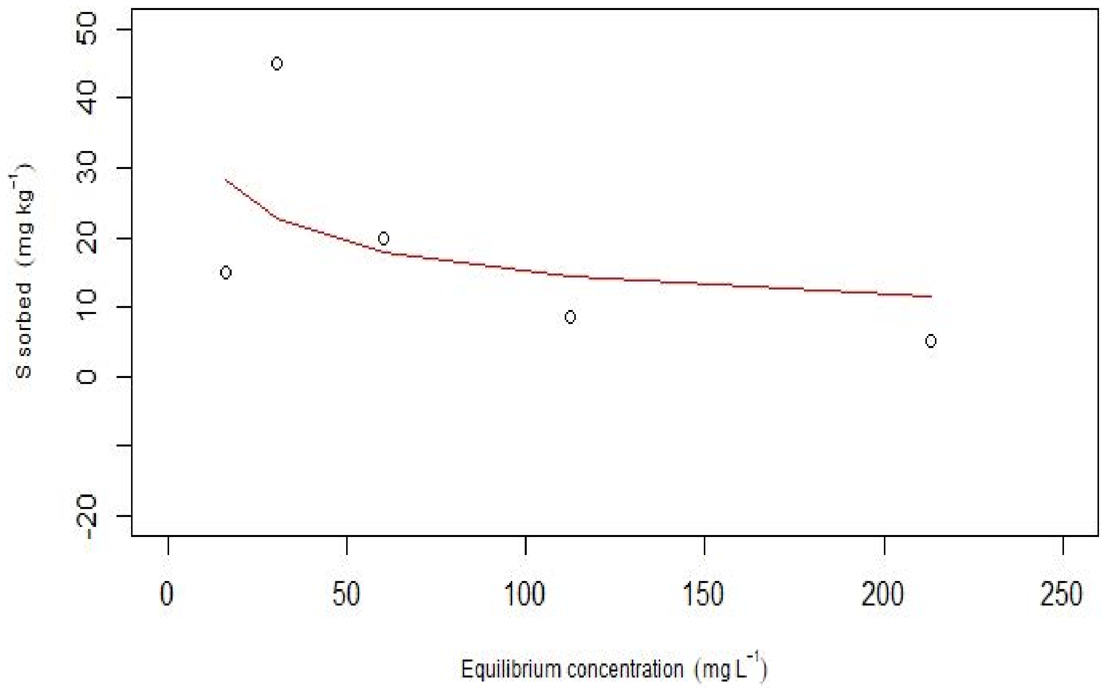
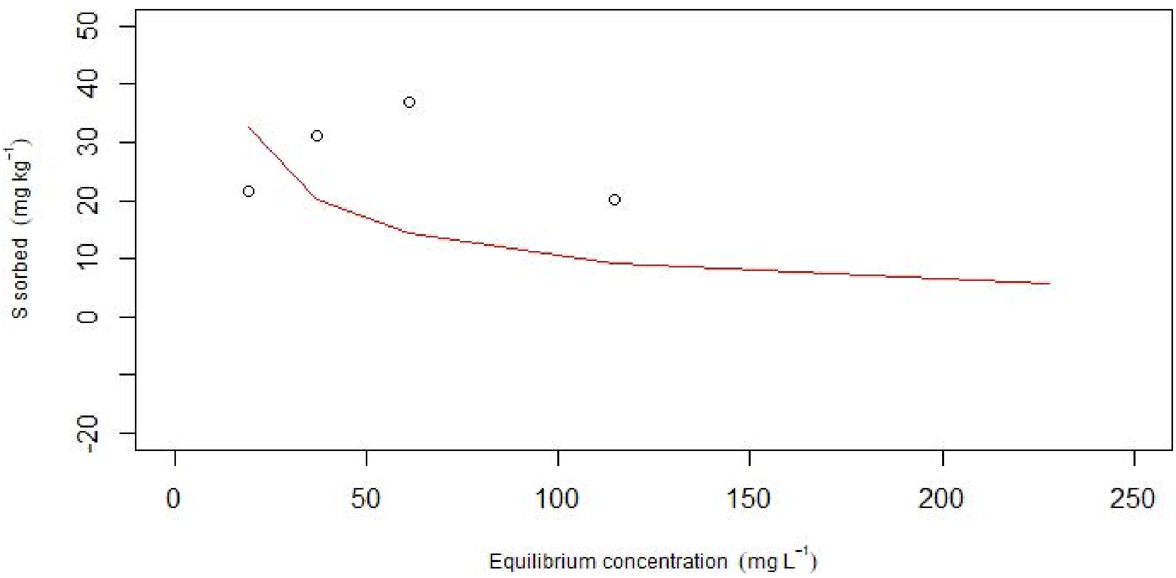


Fig 30. Continued



***Onattukara* sandy 2**

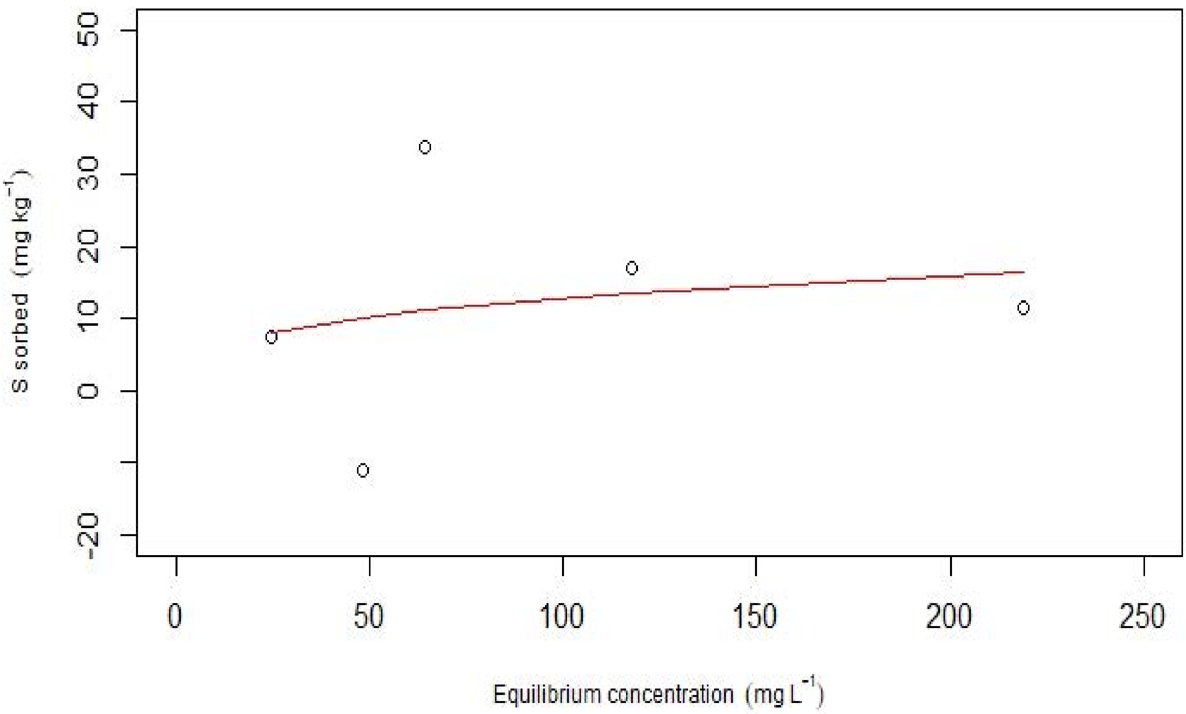
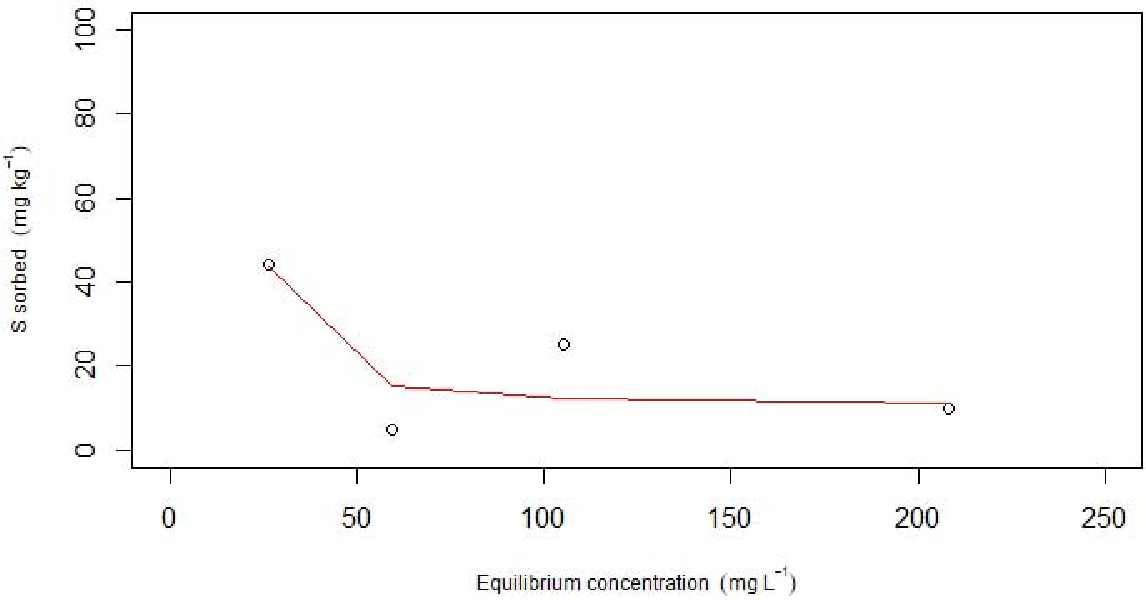
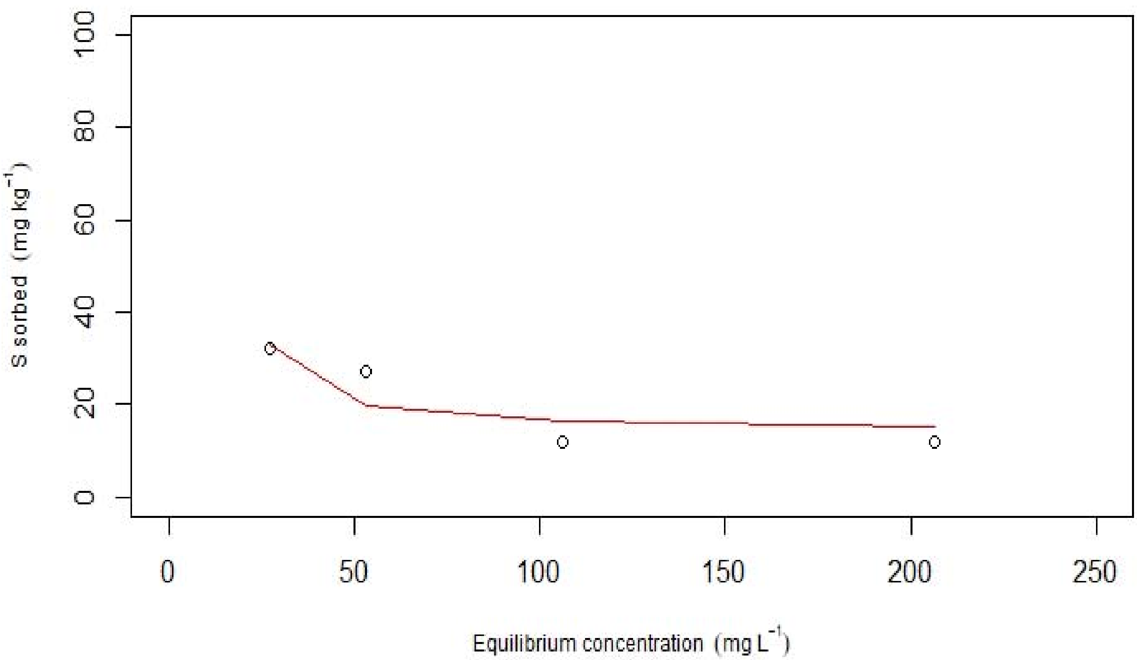


Fig 31. Langmuir adsorption isotherm 25 °C

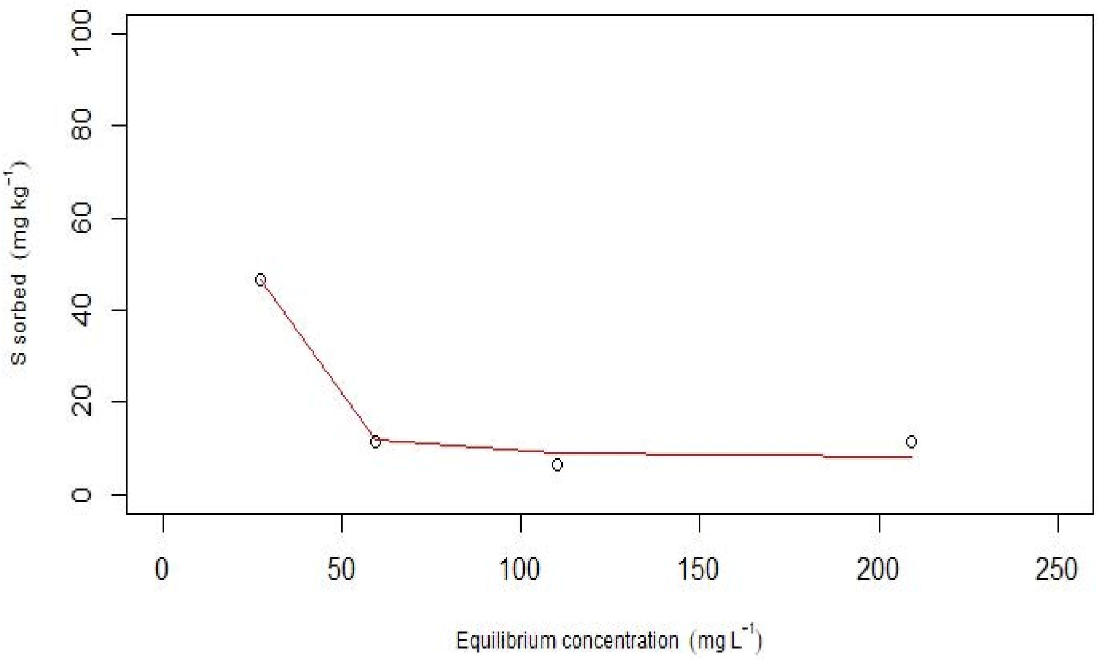
laterite soil 1



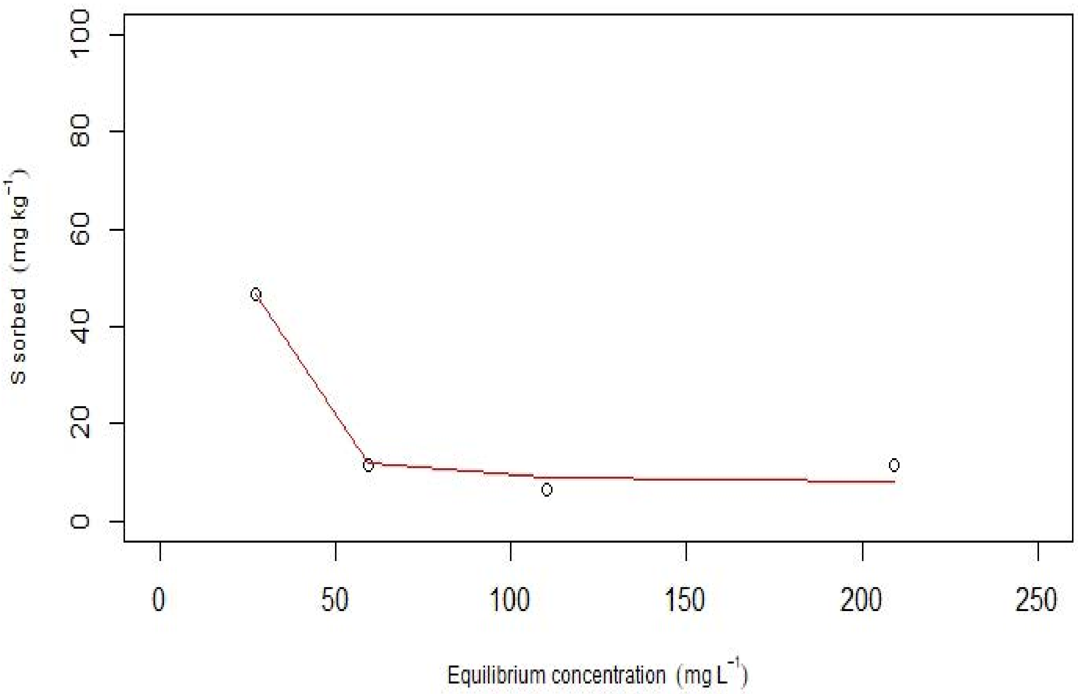
laterite soil 2



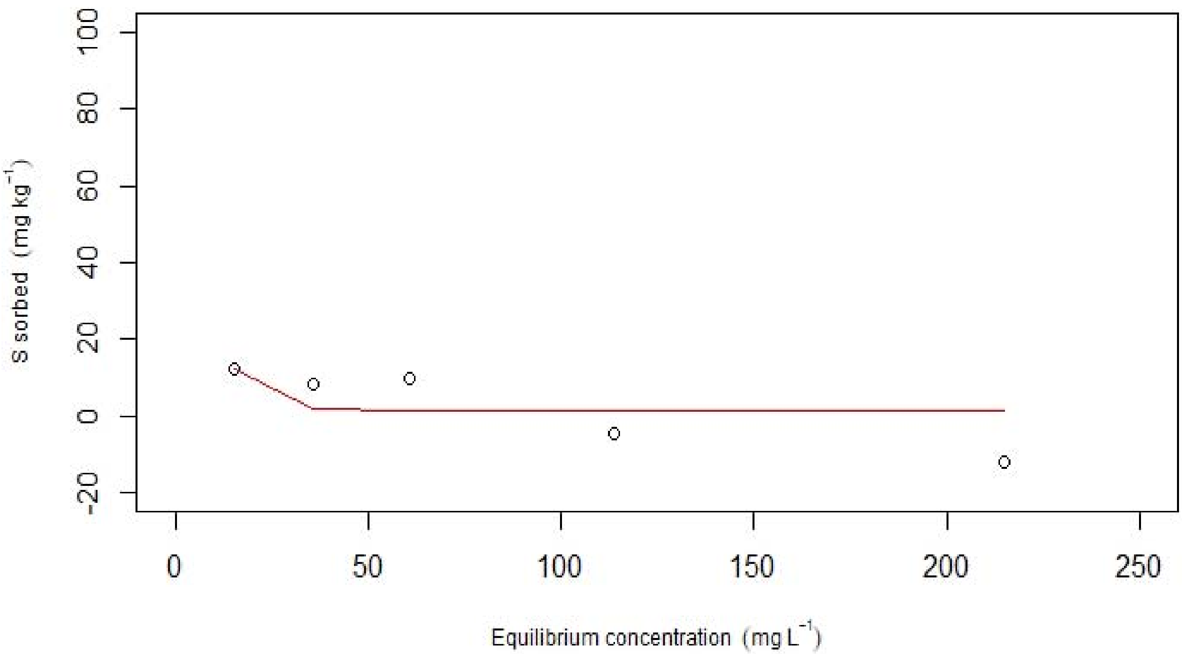
Laterite soil 3



Laterite soil 4



***Onattukara* sandy soil 1**



***Onattukara* sandy soil 2**

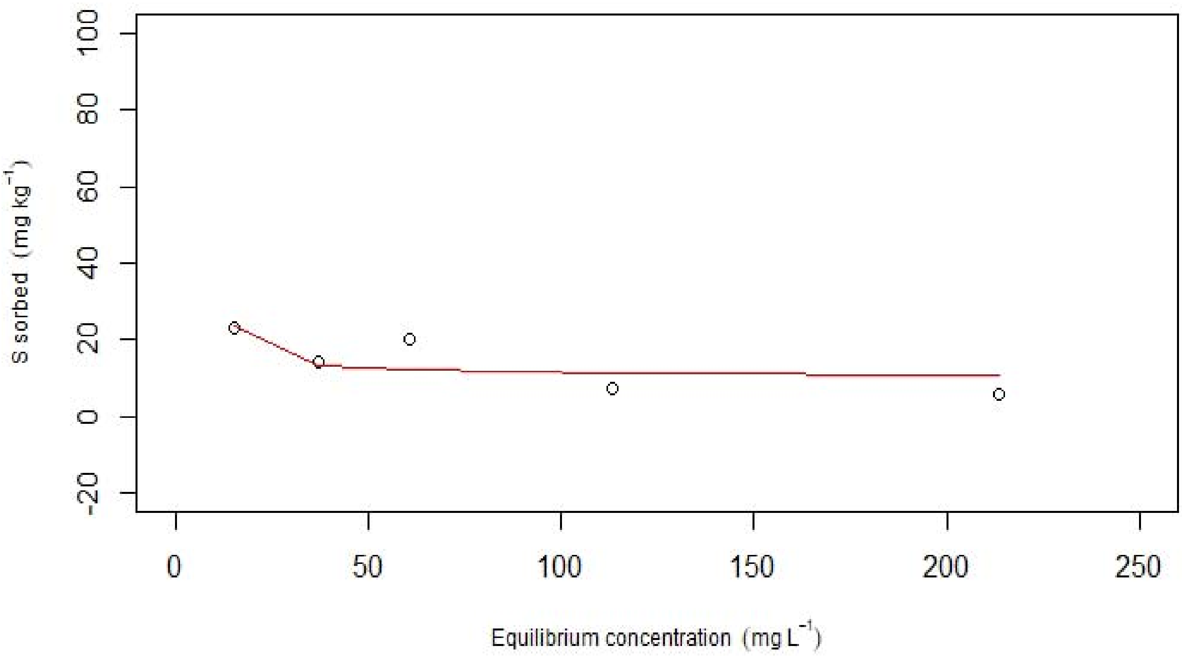
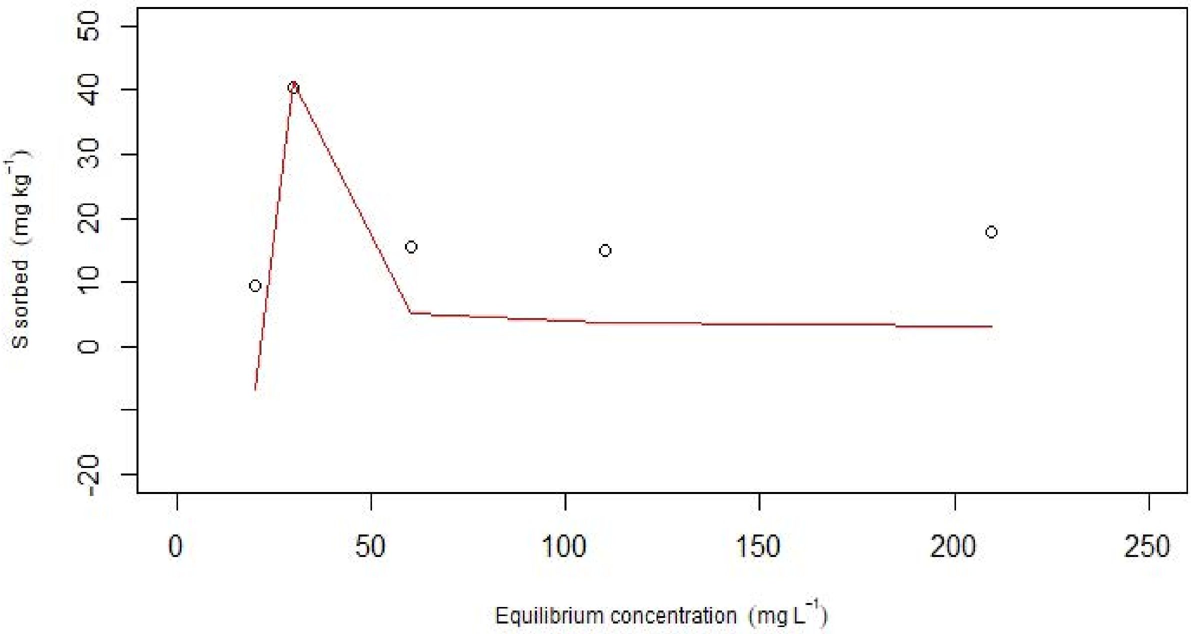


Fig 32. Langmuir adsorption isotherm40 °C

Laterite soil 1



Laterite soil 2

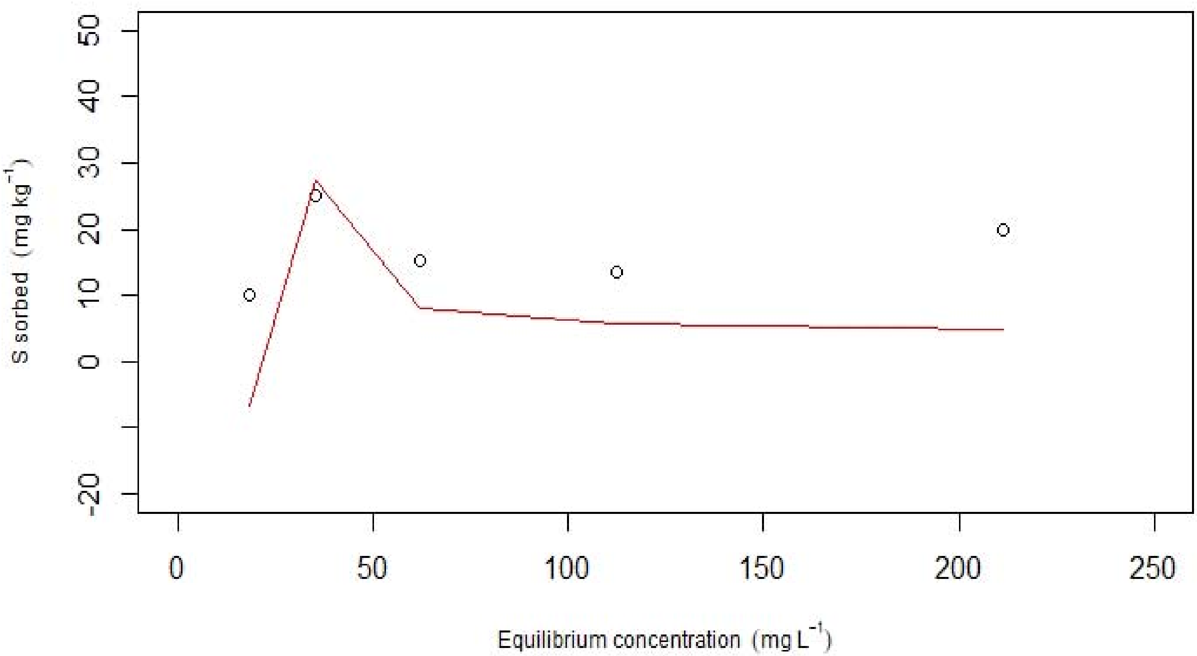
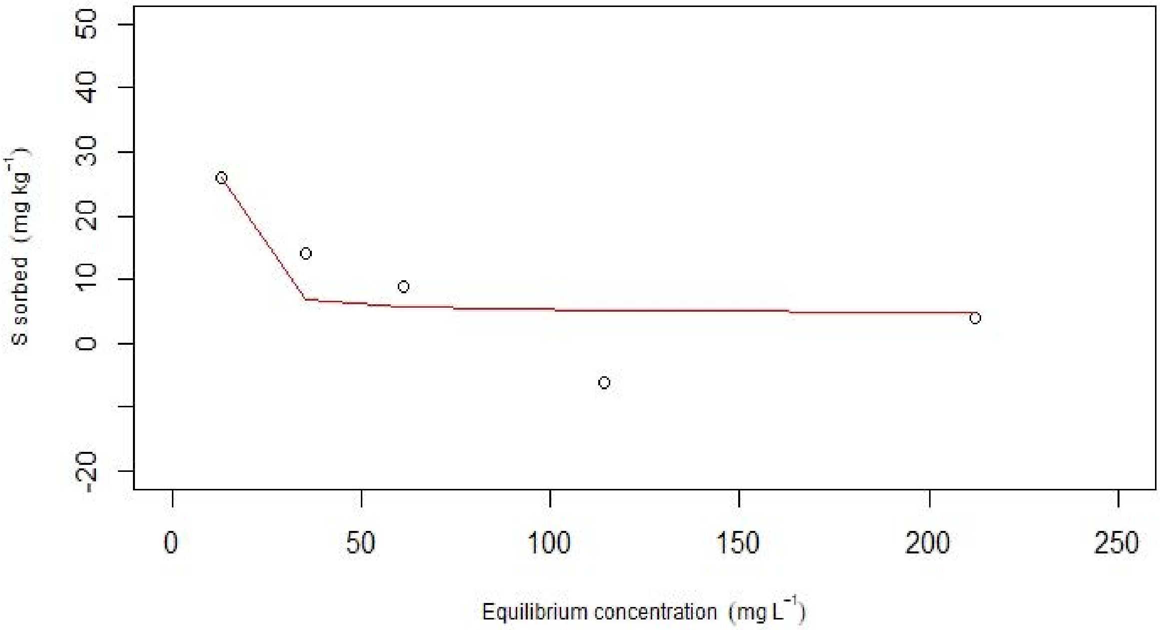


Fig 32. Continued

Laterite soil 3



Laterite soil 4

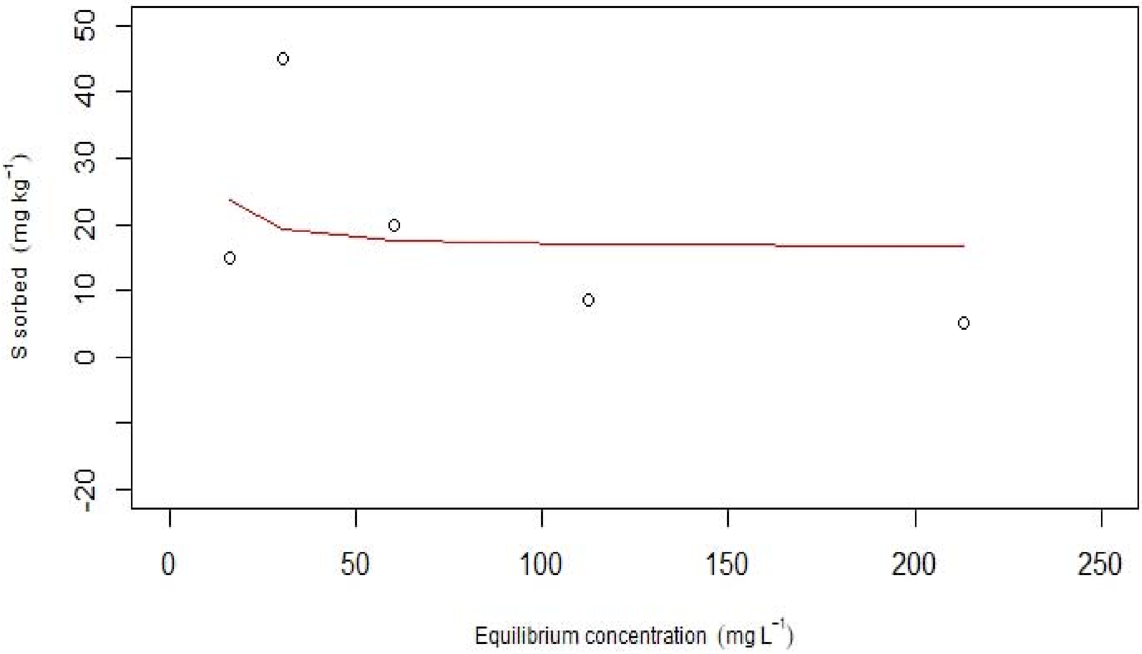
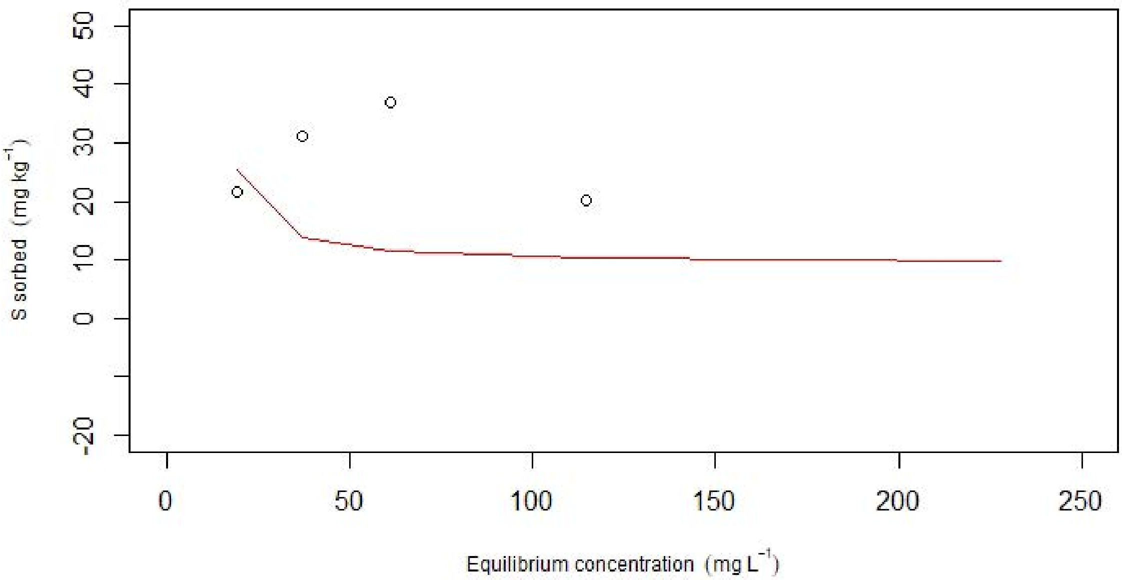
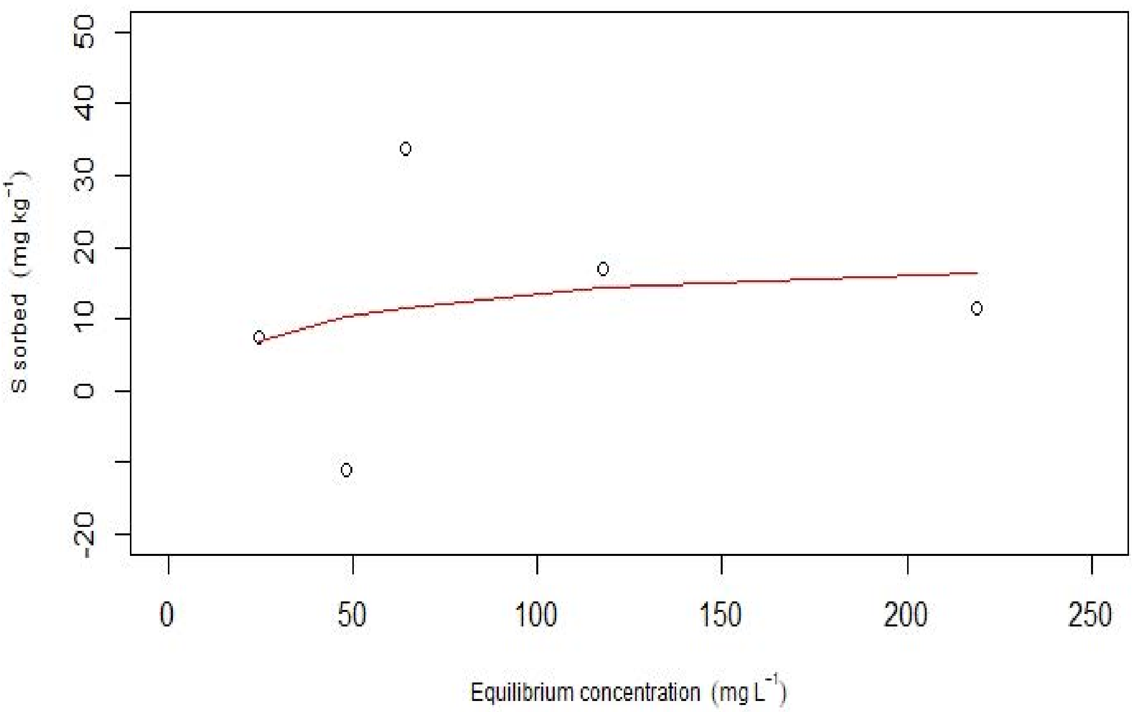


Fig 32. Continued

***Onattukara* sandy soil 1**



***Onattukara* sandy soil 2**



Results of the present investigation indicate that the secondary nutrient element sulphur is present in sufficient amounts (>5 mg ha^{-}) in a good majority of the rice growing regions covered. Available sulphur content was remarkably the highest (2030 mg ha^{-1}) in Pokkali soils as opposed to low land brown hydromorphic laterite and *Onattukara* sandy soils wherein it was relatively lower (10.464 and 11.698 mg ha^{-1} respectively).

Sulphur fractions were studied in the soil samples collected before cropping with rice and at active tillering and harvest stages of the crop. Sulphate sulphur constituted 1.15 – 25.61 per cent of total S. Another major observation was that 53.74 to 89.52 per cent of total S remained in organic form. These soils had very narrow C: S (38.75: 1, being the maximum) and N:S ratio (6.45: 1, being the maximum), indicating mineralization of sulphur in soil. Sulphur showed an antagonistic relation with the nutrients P, K and Mn.

The samples from *Pokkali* and *Kari* soils exhibited sulphur desorption at both the temperatures studied, whereas laterite and *Onattukara* sandy soil showed adsorption of sulphur, which could be best explained using Langmuir and Freundlich adsorption isotherms.

Sufficiency of sulphur in larger part of the rice growing soils investigated during the period 2016-2019, suggest that application of fertilizers containing sulphur in these soils need to be essentially based on soil testing and crop requirement. However in low sulphur soils, like the low land brown hydromorphic laterite and *Onattukara* sandy soils, crop demand for sulphur has to be catered creditably through organic manures and sulphur fertilizers. In any case, it is always ideal to adopt soil test based fertiliser recommendation for sustaining soil health, crop productivity and environmental wholesomeness.

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Summary

6. SUMMARY

Representative soil samples were collected from seven different rice growing tracts falling under different agro-ecological units (AEU) of Kerala for the study on 'Sulphur dynamics in major rice-growing soils of Kerala' undertaken during the period 2016-2019.

Five samples each were collected from various locations pertaining to a particular soil type during three stages viz; before cropping, at active tillering stage and after harvest. In addition three plant samples each were also collected from all the locations at active tillering stage of rice crop and after harvest.

The samples collected before crop raising were characterized with respect to pH, EC, OC, CEC, texture, bulk density, temperature, available nutrients, MBC, Dehydrogenase activity and Aryl sulphatase activity.

The changes in pH, EC, OC and available nutrients were analysed at active tillering stage and after harvest. Nutrient content in plant samples were also analysed at active tillering stage of the rice crop and after harvest.

Fractionation of sulphur was done to assess their contribution to plant availability at three stages viz before crop raising, at active tillering stage and after harvest.

Total C, Total N, Total P, Total S, C:S ratio, N:S ratios were also estimated before crop raising, at active tillering stage and after harvest.

Adsorption study of sulphur wad carried out at 25 °C and 40 °C. The quantity-intensity relationships were characterized to understand buffer power and intercept from the quantity-intensity curve.

The salient results of the study are summarised herewith

Electrochemical properties before cropping

- Sixteen samples out of 35 samples belonged to the category of strongly acidic (<4.5) to moderately acidic (4.5 -5.5) and 10 samples were under the category of slightly acidic (5.5-6.5), which mainly comprised of all soils except the Black cotton soil which were slightly alkaline in nature

- The highest value for EC was reported from *Pokkali* soil because of sea water intrusion. The EC of *Kari* and *Kole* land soils ware relatively lower than that of *Pokkali* soil
- The highest CEC was reported from *Kari* soil and the least from *Onattukara* sandy soil
- Forty per cent of collected soil samples reported high in terms of organic carbon status.
- The least value for bulk density was observed in Black cotton soils and highest in *Onattukara* sandy soil
- The least temperature was recorded from *Pokkali* soils and highest from *Kari* soil
- The *Kari* soil reported significantly higher value for Microbial Biomass Carbon which remained the lowest in *Onattukara* sandy soil
- The dehydrogenase activity was significantly higher in Laterite soil as against the *Kole* land which reported the least value
- The aryl sulphatase activity was estimated as significantly higher in *Kari* soil and lower in Laterite soil
- The *Kole* land recorded significantly higher value for Av.N whereas *Onattukara* sandy soils recorded the least value which was on par with *Poonthalpadam* soil.
- The significantly highest value for Av.P was identified to be from Black *cotton* soils and the lowest was a part of *Kole* lands.
- It was conspicuous from the analysed values that the *Pokkali* soil had significantly higher value for Av. K contrasted to *Onattukara* sandy soil that recorded the lowest for this parameter
- The significantly highest value for Av. Ca was estimated from Black cotton soil it was least from *Onattukara* sandy soil
- The data revealed that Black cotton soil had significantly highest value in comparison to the *Onattukara* sandy that recorded the lowest amount of Av.Mg .

- It gets reflected from the recorded values of Av .S that a significantly higher value was reported from *Pokkali* soil whereas least sulphur status was associated with Laterite soils
- The significantly higher value for Av. Cu was obtained from *Kari* soil and the least from *Onattukara sandy* soils
- The *Kole* land had significantly highest value for Av. Mn while *Onattukara* sandy soil had the least value
- The available zinc was estimated to be significantly high in *Pokkali* soils whereas the Lowest value was typical to *Onattukara* sandy soil
- The *Pokkali* soil reported significantly higher value for Av. Cu and *Onattukara* sandy soils the lowest
- It gets reflected from the analytical values that the significantly highest value for Av. B was observed to be from *Pokkali* soil whereas all other soils did not expose any significant differences among them
- The pH correlated significantly and positively with Av. Ca and negatively with Av. Fe
- Electrical conductivity (EC) was significantly and positively correlated with OC, Av. K, Av. S, Av. Mg, and Av. Fe,
- Organic carbon had showed a significant and positive correlation with temperature, Av. N, Av. S, Av. Fe.
- Microbial biomass carbon (MBC) had significant positive correlation with aryl sulphatase activity EC, CEC, OC and temperature
- Dehydrogenase activity had shown a negative correlation with pH
- Aryl sulphatase activity seemed to be significantly and positively correlated with CEC, OC, temperature and negatively correlated with pH
- The microbial biomass carbon and aryl sulphatase activity significantly and positively correlated with Av. N and Av. S

Active tillering stage

- The soil pH showed slightly elevated values at active tillering when compared to initial sampling except Black cotton soils

- The EC values at active tillering stage has shown a decreasing trend when compared to the initial sampling
- The available nitrogen status exhibited a declining trend at active tillering stage from the initial stage
- Other than *Pokkali* soils all other soil types reported an increase Av. P at active tillering stage as against the initial values.
- It was found that Black cotton soil had significantly highest value of Av. K and *Kole* land had the least value.
- The *Pokkali* soil recorded significantly higher value for Av. Ca whereas *Onattukara* sandy soil recorded the least value.
- The significantly highest value for Av. Mg was identified to be from *Pokkali* soil and the lowest for *Onnatukara* sandy soil.
- At active tillering stage, all the soil types recorded a reduction Av. S content when compared to the initial values.
- The Av. Fe content has decreased at active tillering stage for all the soil types other than *Onattukara* sandy soils when compared to the initial values.
- Av. Mn content evinced a declining trend at active tillering stage for all the soil types other than *Onattukara* sandy soils from the initial values.
- The *Pokkali* soils pictured a significantly higher mean value for Av. Zn whereas the least value was reported from *Onnatukara sandy* soil.
- The Av. Cu content got decreased at active tillering stage from the initial values in all the soils except *Pokkali* soils.
- At active tillering stage, the Av. B had decreased in all the soil types when compared to the initial values.
- The rice crop raised in Black cotton soils reported significantly highest total N content whereas that in *Poonthalpadam* soil reported the least value.

- It gets reflected from the analysed data on total P that the significantly highest value was reported from Laterite soil. The least value was associated with *Kari* soil.
- The Laterite soils contributed to significantly highest total plant K content. The *Pokkali* soil recorded the least value.
- The total calcium content was significantly highest in Black cotton soils whereas the least was evidenced in Laterite soil.
- It was evidenced from the analysed values that the *Pokkali* soils had significantly higher total plant Mg as against the *Onnatukara* sandy soils that registered the lowest value for total plant Mg.
- The significantly highest total plant S content was estimated to be from *Pokkali* soils and the least from *Onnatukara sandy* soil.
- The significantly highest value for total plant Fe was concluded to be from *Kole* land and the lowest from Black cotton soil.
- The significantly highest total plant Mn value was reported from *Poonthalpadam* soils. The minimal value was obtained from *Kari* soils.
- The analysed data revealed the significantly highest value for total plant Zn from *Kole* land and the lowest from *Poonthalpadam* soil.
- The *Poonthalpadam* soil was found to have significantly higher value for total Cu. The minimal value was obtained from Black cotton soils.
- The *Kari* soils accounted for significantly higher total plant B content in contrast to *Poonthalpadam* soils that accounted the least value.
- The soil pH had a significant and positive correlation with total plant N, total plant Ca and negative correlation with total plant Cu.
- The higher electrical conductivity value was found to reduce the uptake of P, K and Mn.
- Organic carbon was found to have a significant and positive correlation with plant total Zn, plant total Cu and plant total B.

Harvest stage

- The analytical results on soil pH indicated that that the significantly highest value was recorded in Black cotton soil and least in *Kari* soil.
- The significantly highest value for electrical conductivity was concluded to be from *Pokkali* soil. The EC values were lower in *Kole* land.
- It gets revealed from the analysis on organic carbon that the *Kari* soil accounted for significantly higher value whereas the *Onattukara* sandy soil contained the lowest amount of organic carbon.
- The *Kole land*s were identified to possess significantly highest quantity of Av. N as against *Pokkali* soils.
- It was clear from the data obtained that the significantly highest values for Av. P was associated with *Onnatukara* sandy soils and least with *Pokkali* soils.
- The *Pokkali* soil registered significantly highest mean value of Av. K whereas the least value was registered with *Onattukara* sandy soil.
- It was clear from the observation that the Av. Ca was significantly higher in *Poonthalpadam* soils. The least value was observed in *Onnatukara sandy* soil.
- The *Pokkali* soils accounted for significantly higher Av. Mg whereas the lower value was reported in *Onnatukara* sandy soils.
- In terms of available S, the *Pokkali* soil type revealed significantly higher value Than all others
- A significantly higher amount of Av. Fe was contained in *Kari* soil as opposed to Black cotton soils.
- The analysed data on Av. Mn showed that it was significantly highest in Black cotton soils as against *Onattukara* sandy soils.
- The significantly highest value for Av. Zn was reported in *Pokkali* soils and the least in *Onattukara* sandy soil.
- The Av. Cu was significantly highest in *Pokkali* soils. The content was lowest *Onnatukara sandy* soils.

- The significantly highest value for Av. B was reported from *Pokkali* soils and the least from laterite soils.
- It could be concluded from the data on total plant N that, It was significantly higher in Black cotton soils.
- The *Kole* land accounted for significantly higher value of total plant P.
- The significantly highest value for total plant K was observed in Laterite soils and the least in *Pokkali* soils.
- The analysed data on total plant Ca at harvest stage revealed it as significantly the highest in Black cotton soil.
- The total plant Mg content for all the soil types were observed to be the same.
- The Black cotton soil was found to have the significantly highest value for total plant S. The lowest value was obtained from *Poonthalpaadam* soils.
- The *Kole* land soils reported significantly higher mean value for total Fe.
- The analysed data on total Mn showed the significantly highest value from *Kole* land.
- It was evident from the data that mean total Zn was significantly high in *Kole* land and minimum in Black *cotton* soils.
- The significantly highest value for total Cu was identified to be from *Poonthalpaadam* soils.
- It gets revealed from the analysis on total B that the *Poonthalpaadam* soils recorded the highest.
- The analysed data on total N in grain explained that the Black cotton soil accounted for a significantly higher value
- The significantly highest mean total P in grain was observed to be from Black cotton soil and least from *Pokkali* soil.
- It was noticeable evident from the analysis on mean total K status in grain that the significantly highest value was from *Poonthalpadam* soil with *Kari soils* registering the lowest.

- The significantly higher mean total Ca in grainwas concluded to be from Black cotton soils.
- The significantly higher mean total Mg in grain was reported from *Kole* land soils and the lower from *Onattukara* sandy soils.
- The highest mean value for total S in grain was recorded from *Kari* soils and the least from *Poonthalpaadam* soils.
- From the results, it could be concluded that the significantly higher value for total iron in grain was reported in *Kole* land while the least was observed to be from Black cotton soil.
- In respect of total Mn, a significantly higher value was associated with *Kole* land.
- Total Zn content in grain was significantly high in *Onattukara* sandy soil.
- The *Poonthalpadam* soils reported significantly higher total grain Cu.
- Based on the Data, total B content in grain was maximum when rice was cropped in *Poonthalpadam* soil. The lowest content was linked with Laterite soil.
- It gets revealed from the data on correlation that an increase in soil pH enhanced the total Ca uptake same time limiting that of Cu.

Sulphur fractions

- All the S fractions were very high in *Pokkali* soils.
- All the fractions of S had very high significant as well as positive correlation among themselves
- It could be inferred from the study on S fractions in various soil types that the *Onattukara* sandy soil exhibited lowest values for all fractions of S.

Sulphur fractions at active tillering stage

- The significantly highest value for sulphate S, water soluble S and heat soluble S was recorded from *Pokkali* soil and the least from Laterite soil.
- *Pokkali* soil reported significantly highest value for sulphate soluble after ignition while the *Onattukara* sandy soils, the lowest.

- The *Kari* soils showed significantly higher value for total organic and total S whereas the *Onattukara sandy* soils had the least value.

Sulphur fractions at harvest stage

- The significantly highest mean sulphate S was estimated to be from *Pokkali* soil whereas the least value was observed in Laterite soil.
- The *Pokkali* soil reported significantly higher value for total water soluble S whereas laterite soils reported the least value.
- It gets revealed from the data on S fractions that the *Pokkali* soils had significantly highest mean heat soluble sulphur and Laterite soils the lowest value.
- The significantly highest sulphate soluble after ignition was identified to be from *Pokkali* soils. The least value was reported from laterite soil.
- Based on the study conducted on S fractions, it could be concluded that the significantly highest mean total organic sulphur was recorded in *Kari* soil with *Onattukara* sandy soil registering the lowest value for total organic sulphur.
- The significantly highest value for total S was observed in *Kari* soil and least in *Onattukara* sandy soils.
- All the fractions of S had significant and positive correlation with EC, CEC, organic carbon.
- The microbial biomass carbon and aryl sulphatase activity exhibited significant positive correlation with all the sulphur fractions.
- The available N established significant positive correlation with total organic S and total S.
- The *Kari* soil reported significantly higher total C wherein in contrast to *Onattukara* sandy soil reported the lowest value before crop raising, at active tillering stage and harvest stage.
- *Kari* soils recorded significantly higher value of total P. The least value was obtained from *Onattukara* sandy soil before crop raising as well as at active tillering stage

- The significantly highest total P was reported from *Kari* soil and the lowest from Black cotton soil at harvest stage

C:S and N:S ratio

- The analytical values disclosed that laterite soils recorded significantly highest mean C:S ratio while Pokkali soils the lowest before crop raising, at active tillering stage and harvest stage.
- The significantly higher mean N:S ratio was obtained in laterite soil which was on par with *Onattukara* sandy soil. The ratio remained lowest in *Pokkali* soil before crop raising.
- At active tillering stage the mean N:S ratio was significantly highest in *Onattukara* sandy soil whereas *Kari* soil accounted the lowest.
- The significantly highest mean N:S ratio was identified to be from laterite soil whereas the *Kari* soils displayed the minimal value at harvest stage.
- The total C significantly and positively correlated with EC, CEC, organic carbon and temperature
- EC significantly and negatively correlated with C:S ratio
- C:S and N:S ratio had negative correlation with sulphur fractions in soil
- Microbial biomass carbon and aryl sulphatase activity significantly and negatively correlated with the N:S ratio
- While Pokkali and Kari soil exhibited desorption of sulphur at both the temperatures (25 ℃ and 40 ℃) studied, it was found to get adsorbed in the case of Laterite soil and *Onattukara* sandy soils at both 25 ℃ and 40 ℃.

References

References

Aggarwal, V. and Nayyar, V.K. l998. Available soil sulphur status and sulphur nutrient of wheat crop. *J. Indian Soc. Soil Sci.* 46: 71- 75.

Ahmad, N and Jones, R.L. 1969. A Plinthaquult of the Aripo savannas, North Trinidad, II. Mineralogy and genesis. *Soil Sci Soc.am Proc*., 33 (5): 766-768

Alharbi, S.A., Hajomer, S., Wainwright, M., Marraiki, N.A. and Eifan, S.A. 2012. L-cysteine desulfhydrase-an enzyme which can be assayed in soil but is unlikely to function in the environment. *African Journal of Microbiology Research*, *6*(24): 5086-5090.

Al-Khafaji, A.A. and Tabatabai, M.A. 1979. Effects of trace elements on arylsulfatase activity in soils. *Soil Science*, *127*(3): 129-133.

Allan, J.D., Castillo, M. M. and Capps, K.A. 2021. *Stream ecology: structure and function of running waters*. Springer Nature, Swizerland.481p

Aparna, B., Gladis, R., Aryanath, V., and Thampatti, K.C.M. 2020. Studies on the Acid Sulphate Soils of Kuttanad of Kerala, *Ind. J. Pure App. Biosci. 8*(2): 421-428.

Armstrong, W. 1969. Rhizosphere oxidation in rice: An analysis of intervarietal differences in oxygen flux from the roots. *Physiologia Plantarum*, *22*(2): 296-303.

Aulakh, M.S., Sidhu, B.S., Arora, B.R., and Singh, B. 1985. Content and uptake of nutrients by pulses and oilseed crops, *Indian J. Ecol.* 12 (2): 238-242.

Balanagoudar, S.R. and Satyanarayana, T. 1991. Depth distribution of different forms of sulphur in Vertisols and Alfisols. *J Indian Soc Soil Sci* 38: 634-640.

Banerjee, M.R., Chapman, S.J., and Killham, K. (1993) Factors influencing the determination of microbial biomass sulphur in soil. *Commun Soil Sci Plant Anal* 24: 939-950.

Barber, D.A., Ebert, M., and Evans, N.T.S. 1962 The movement of O_2 through barley and rice plants. *J. Exp. Bot*. 13: 397-403.

Beena, V.I. and Thampatti, K.C. 2013. Characterization of acid sulphate soils in Kerala. *J. Life sci. 7*(8): 907 – 912

Benedycka, Z. 1983. Response of radish to potassium chloride versus potassium sulphate under field conditions. Part II. Effect on chemical composition. *Zesz. Nauk. ART Olszt. Rol.* 36: 205-212.

Berger, K.C. and Truog, E. 1939. Boron determination in soils and plants. *Indian Eng. Chem. Anal.* Ed. 11: 540-542.

Bhan. C, Tripathi. B.R. 1973. The forms and contents of sulphur in some soils of U.P. *J Indian Soc Soil Sci* 21: 499-504.

Bhatnagar, R.K., Bansal, K.N., and Trivedi, S.K. 2003. Distribution of sulphur in some profiles of Shivpuri district of Madhya Pradesh. *J. Indian Soc. Soil Sci.* 51: 74-76.

Bhindhu, P.S. 2017. Chemistry and transformations of calcium and magnesium in tropical acid soils of Kerala. PhD (Ag) Thesis, Kerala Agricultural University, Thrissur, 277p

Biswas, B.C., Sarkar, M.C., Tanwar, S.P.S., Das, S., and Kalwe, S. P. 2004. Sulphur deficiency in soils and crop responses to fertilizer sulphur in India. *Fertil. News* 49: 13-33.

Bloem, E.M., 1998. Sulphur balance of agro-ecosystems with special regard to site hydrology and physical soil characteristics. PhD Thesis Technische Universität Carolo-Wilhelmina, 156p

Bolle-Jones, E.W. 1964. Incidence of sulphur deficiency in Africa. *Emp. J. Exp. Agric*. 32: 241-248.

Boreczek, B. 2001. The use of plant tests for the estimation of plants sulphur supply. *Fragm. Agron*. 18(4): 136-146.

Bornemisza, E. 1959. Sulphur Categories in the Soils of the Meseta Central of Costa Rica. Ministry of Agriculture and Industry, San Jose, Costa Rica, Lab. 8-59.

Bray, R.H. and Kurtz, L.T. 1945. Determining total, organic and available forms of phosphate in soils. *Soil Sci.* 59: 39-45.

Bristow, J.M. 1975 The structure and function of roots in aquatic vascular plants. In: Torrey, J.G. and C1ardson, D.T. (eds.), *The Development and Function of Roots*, Academic Press, New York. 221-236.

Brunauer S., Copeland, L. E., and Kantr, D.L. 1967. *The Solid-Gas Interface.* Marcel Dekker Publishers, New York, 280p

Carter, M.R. and Gregorich, E.G. 2007. *Soil sampling and methods of soil analysis* (2nd Ed.). CRC Press, Taylor and Francis Group 6000 Broken Sound Parkway NW. 1224p.

Casida, L.E, Klein, D.A. and Santoro, T. 1964. Soil dehydrogenase activity. *Soil Sci.*, 98: 371-376.

Castellano, S.D, Dick, R.P. 1991. Cropping and sulphur fertilization influence on sulphur transformations in soil. *Soil Sci. Soc. Am* 155: 114-121.

Ceccotti, S.P., Morris, R.J., and Messick, D.L 1998. A global overview of the sulphur situation: industry's background, market trends, and commercial aspects of sulphur fertilizers. In: Schug, E. (ed.) *Sulphur Agroecosystems. Nutrients in Ecosystems. Vol 2. Springer.* 175-202.

Chao, T.T., Harward, M.E., and Fang, S.C. 1962. Adsorption and desorption phenomenon of sulphate ions in soils. Soil Sci. Soc. Am. Proc. 26: 234-237.

Chaudhary, D.R. and Shukla, L.M. 2002. Sulphur status of arid soils of Western Rajasthan. *Ann. Agrl. Res.* 23: 371-376.

Cheema, H.S. and Arora, C.I. 1984. Sulphur status of soil, tube well waters and plants in some areas of Ludhiana under groundnut-wheat cropping system. *Fertil. News.* 29(3): 28-31.

Cicy, M.P. 1989. Sulphur status of the Kuttanad soils of Kerala. MSc. (Ag) Thesis, Kerala Agricultural University, p148.

Cox, F.R. 1987. Micronutrient soil tests. Correlation and calibration. In: Brown, J. R. (ed.), *Soil Testing: Sampling, Correlation, Calibration and Interpretations*. SSSA, Madison. 97-117.

Coyle, E.A. and McAleese, D.M. 1970. Aspects of sulphur uptake and distribution in cereals. In: *Sulphur Agric.* 158-176.

Dick, W.A., Cheng, L., and Wang, P. (2000). Soil acid and alkaline phosphatase activity as pH adjustment indicators. *Soil Biol., & Biochem. 32*(3): 1915 – 1919.

Dijkshoorn, W. and Wijk. V.A.L. 1967. The sulphur requirements of plants as evidenced by the sulphur-nitrogen ratio in the organic matter-A review of published data. *Plant. Soil* 26: 129-157.

Dolui A.K and Nandi, S. 1989. Adsorption and Desorption of sulphate in some soils of West Bengal. *Proc. Indian Natn. Sci. Acad*.; 55(5&6):483-488.

Donald, C.M. and Williams, C.H. 1954. Fertility and productivity of a podzolic soil as influenced by subterranean clover (Trifolium subterraneum L.) and superphosphate. *Aust J. of Agric Research*, *5*(4), 664-687.

Dutta, J. 2009. Long term effect of chemical fertilisers and amendments on sulphur sorption under maize-wheat system M.Sc. (Ag.) thesis, Kerala Agricultural University, Thrissur, 63p.

Ensminger, L.E. 1954. Some factors affecting the adsorption of sulphate by Alabama soils. *Soil Sci. Soc. Am. Proc.* 18: 259-264.

Erikson, J. 1996. Incorporation of sulphur into soil organic matter in the field as determined by the natural abundance of stable sulphur isotopes. *Biol. Fertil. Soils* 22:149-155.

Fazli, I.S., Jamal, A., Ahmed, S., Masoodi, M., Khan, J.S. and Abdin, M.Z. 2008. Interactive effect of sulphur and nitrogen on nitrogen accumulation and harvest in oilseed crops differing in nitrogen assimilation potential. *J. Plant. Nutri*. 31: 1203-1220.

Fitzgerald, J.W. 1978. Naturally occurring organosulfur compounds in soil. In J.O. Nriagu (ed.) *Sulfur in the environment. Part 2.* John Wiley & Sons, New York. 391-443.

Fox, R.L. 1969. Fertilization of Volcanic Ash Soils in Hawaii. In: *Panel on volcanic ash soils in Latin America,* Turrialba, Costa Rica. 6-13.

Fox, R.L., Moore, D.G., Wang, J.M., Plucknett, D.L., and Furr, R.D. 1965. Sulphur in soils, rainwater and forage plants of Hawaii. *Hawaiian Farm Sci.* 14 (3): 9-12.

Germida, J.J., Wainwright, M. and Gupta, V.V.S.R. 1992. Biochemistry of sulfur cycling in soil. In G. Stotzky and J.M. Bollag (ed.) *Soil Biochem. Vol. 7.* Marcel Dekker, New York. 1-38.

Gill, M.S. and Singh, V.K. 2009. Macro role of nutrients. *Indian J. Fert.* 5(4): 59-66.

Gopinath (2021). grapesAgri1: Collection of Shiny Apps for Data Analysis in Agriculture. Journal of Open Source Software, 6(63), 3437, https://doi.org/10.21105/joss.03437

Grygierzec, B., Luty, L., and Musiał, K. 2015. The efficiency of nitrogen and sulphur fertilization on yields and value of N: S ratio for Lolium × boucheanum. *Plant Soil Environ*. 61(3): 137-143.

Gupta, U.C. 1972. Effects of boron and limestone on cereal yields and on B and N concentrations of plant tissue. *Commun. Soil Sci. Plant Anal*. 6: 439-450.

Haldar, B.R., and Barthakur, H.P. 1976. Sulphide production in some typical rice soils of Assam. *J. of the Indian Soc of Soil Sci*, *24*(4), 387-395.

Haneklaus, S. Bloem, E. and Schnug, E. 2007. Sulfur and plant disease. In: *Mineral nutrition and plant diseases*. Am Phyto pathological Socy, St. Paul, MN, 101–118.

Haque, I. and Walmsley, D. 1973 Adsorption and desorption of sulphate in some soils of West Indies. *Geoderma.* 9: 269-278.

Harward. M.E., and Reisenaur, H.M. 1966. Reactions and movement of inorganic soil sulphur. *Soil Sci* 101 326-335.

Hasan, S.M., Fox, R.L., and Boyd, C.C. 1970. Solubility and availability of sorbed sulphate in Hawaiian soils. *Soil Sci. Soc. Am. Pro.* 34: 897-901.

Hegde, T.M. 1980. Evaluation of S status of different rice soils. *J Agric. Sci.* 14: 171-176.

Hingston, F., Atkinson, R., Posner, A.M., and Qurik, P. 1968. Specific adsorption of anions of goethite. *Trans Intern. Congr. Soil Sci.* 1: 669-678.

Hua-Yun, X.I.A.O., Nan, L.I. and Cong-Qiang, L.I.U., 2015. Source identification of sulfur in uncultivated surface soils from four Chinese provinces. *Pedosphere*, *25*(1): 140-149.

Irene, E. J. 2014. Wet soil analysis for nutrient prescription in paddy soils. M.Sc, (Ag) thesis, Kerala Agricultural University, Thrissur, 277p

Islam, M.N., Hoque, S. and Islam, A., 2006. Effect of P× S interactions on nutrient concentration and yield of wheat, rice and mungbean. *J Indian Soc of Soil Sci,* 54(1): 86-91.

Jackson, M. L. 1958. *Soil Chemical Analysis.* Prentice Hall of India Private Ltd., New Delhi, 498p

Jackson, M.L., 1973. Soil chemical analysis, pentice hall of India Pvt. *Ltd., New Delhi, India*, *498*:.151-154.

Jacob, C.I. 1966. Sulphur status of Kerala soil Msc. (Ag) thesis, Kerala Agricultural University, 82p

Jakubus, M. 2006. Sulphur in environment. AR Poznan press, 49p.

Jamal, A., Fazli, I.S., Ahmad, S. and Abdin, M.Z. 2006. Interactive effect of nitrogen and sulphur on yield and quality of groundnut (Arachis hypogea L.). *Korean J Crop Sci*, *51*(6): 519-522

Jamal, A., Fazli, I.S., Ahmad, S., Abdin, M.Z. and Yun, S.J., 2005. Effect of sulphur and nitrogen application on growth characteristics, seed and oil yields of soybean cultivars. *Korean Journal of Crop Science*, *50*(5): 340-345.

Jamal, A., Ko, K., Kim, H.S., Choo, Y.K., Joung, H. and Ko, K. 2009. Role of genetic factors and environmental conditions in recombinant protein production for molecular farming. *Biotechnology Adv. 27*(6): 914-923.

Jansen, H.H. and Bettany. 1984. Sulfur nutrition of rapeseed. Influence of fertilizer nitrogen and sulphur rates. *Soil Sci Soc Am J* 48:100-107.

Jat, J.R. and Yadav, B. L. 2006. Different forms of sulphur and their relationship with properties of Entisols of Jaipur District (Rajasthan) under mustard cultivation. *J. Indian Soc. Soil Sci.* 54: 208-212.

Joshi, D.C., 1984. Relationship of carbon, nitrogen, phosphorus and sulphur in major soils of Rajasthan and in their humus fractions. *J. Indian Soc Soil Sci*, *32*(1): 35-38.

Kannan, V.M., Augustine, T., Navya, and Mahesh. 2014. Geochemistry and heavy metals in the soils of unique tropical rice agricultural ecosystem. *J. Environ*. *3*(1): 5-11.

Kertesz, M.A. and Mirleau, P., 2004. The role of soil microbes in plant sulphur nutrition. *Journal of experimental botany*, *55*(404): 1939-1945.

Kertesz, M.A. and Mirleau, P., 2004. The role of soil microbes in plant sulphur nutrition. *J experimental botany*, *55*(404):1939-1945.

Kimsey, M., McDaniel, P., Strawn, D., and Moore, J. 2005. Fate of applied sulphate in volcanic ash-influenced forest soils. *Soil Sci. Soc. Am. J.* 69: 1507-1515.

Klose, S., Moore, J.M. and Tabatabai, M.A., 1999. Arylsulfatase activity of microbial biomass in soils as affected by cropping systems. *Biology and Fertil. soils*, *29*(1): 46-54.

Knights, J.S., Zhao, F.J., McGrath, and S.P. Magan, N. 2001. Long term of land use and fertilizer treatments on sulphur transformations in soils from the Broadbalk experiment. Soil Biology Biochem 33: 12-13

Kowalenko, C.G. and Lowe 1975. Mineralisation of sulphur from four soils and its relationship to soil carbon, nitrogen and phosphorous. *Can. J. Soil Sci*. 55: 9-14

Langmuir, I. 1918. The adsorption of gases on plane surfaces of glass, mica and platinum. *J. Am. Chem. Soc*. 40: 1361-1403.

Larson, W.E., Clapp, C.E., Pierre, W.H., and Morachan. Y.B. 1972. Effects of increasing amounts of organic residues on continuous corn: II. Organic carbon, nitrogen, phosphorus, and sulfur. *Agron. J.* 64: 205-208.

Lindsay, W. L. and Norvell, W. A. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Sci. Soc. Am. J.* 42: 421-428.

M.A., Zablotowicz, R.M., Krutz, L.J., Bryson, C.T. and Locke, M.A., 2012. Microbial and vegetative changes associated with development of a constructed wetland. *Ecological Indicators*, *13*(1): 37-45.

MacKenzie, D. 1995. Killing Crops with Cleanliness. *New Scientist*. 44p.

Mahto, S. N., Singh, K. P., and Singh, S. 1992. Total and available Sulphur in some soils of Chotanagpur area of Bihar in relation to soil properties. *J. Indian Soc. Soil Sci.* 40: 846-847

Massoumi, J. and Cornfield, A.H. 1963. A rapid method for determination sulphate in water extracts of soils. *Analyst* 88: 321-322.

McClung, A.C., DeFreitas, L.M., and Lott, W.L. 1959. Analysis of several Brazilian soils in relation to plant responses to sulphur. *Soil Sci. Soc. Am. Prec*. 23(3): 221-224.

McGill, W.B. and Cole, C.V. 1981. Comparative aspects of cycling of organic C, N, S and P through soil organic matter. *Geoderma* 26: 267-286.

Misal, N.B., Polara, K.B., and Shirgire, S.T. 2017. Dynamics of sulphur fractions in calcareous soils of Saurashtra region of Gujarat. *Int. J. Agricul. Sci.* 8: 20-30.

Mohanty, S. and Yamano, T. 2017. Rice food security in India: emerging challenges and opportunities. In *The Future Rice Strategy for India*. Academic Press: 1-3

Mukhopadhyay, P. and Mukhopadhyay, A.K. 1980. Status and distribution of different S forms in some typical soil profiles West Bengal. *J. Indian Soc. Soil Sci.* 28(4): 454-459.

Muller, L.E. 1965. Deficiencia de azufra en algunos suelos de Centre America. *Turrialba* 15: 208-215.

Murthy,. 2004. Sulphate sorption studies in some shrink swell soils. *Agropedology* 14: 55-59.

Naik, M.S. and Das, N.B. 1964. Fertilizer sulphur and food production. *J. Indian Soc. Soil. Sci.* 12(3): 151-155.

Niknahad, G.H., Machet. J.M., Beaudoin, N., and Recous, S. 2008. Estimation of sulfur mineralization and relationships with nitrogen and carbon in soils. *Biol Fertil Soils* 45: 297-304.

Olsen, S.R., Cole, C.V., Watanabe, I., and Dean, L.A. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circ. 939. USDA, Washington DC. 19p.

Parton, W.J., Stewart, J.W. and Cole, C.V., 1988. Dynamics of C, N, P and S in grassland soils: a model. *Biogeochem*, 5(1): 109-131.

Pigna, M. and Violante, A. 2003. Adsorption of Sulfate and Phosphate on Andisols. *Commun. Soil Sci. Plant Anal.* 34 (15–16): 2099–2113.

Piper, C. S. 1966. *Soil and Plant Analysis*. Hans publishers, Mumbai, 365p.

Ponnamperuma F. N. 1972. The chemistry of submerged soils. Adv Agron. 24:29-96.

Prasad, R. 2007. *Crop Nutrition-Principles and Practices*. New Vishal Publications, New Delhi, 290p.

Rahman, M.N., Islam, M.B., Sayem, S.M., Rahman, M.A., and Masud, M.M. 2007. Effect of different rates of sulphur on the yield and yield attributes of rice in old Brahmaputra floodplain soil. *J. Soil Nat.* 1(1): 22-26.

Rajasekharan, P., Nair, K. M., Rajasree, G., Sureshkumar, P., & Narayanan Kutty, M. C. (eds). (2013). Soil fertility assessment and information management for enhancing crop productivity in Kerala. Kerala state planning board. Thiruvananthapuram, 514p.

Reddy, K.B., Rajagopal, V., and Sitaramayya, M. 1988. Response of groundnut to Sulphur application in some soils of Ananthpur district of Andhra Pradesh, *Andhra Agric. J.* 35: 86-91.

Reshma, M.R. 2020. Anionic equilibria in major soil types of Kerala. PhD (Ag) Thesis, Kerala Agricultural University, Thrissur, 301p

Robinson, G.W. 1922. A new method for the mechanical analysis of soils and other dispersions. *J. Agri. Sci.* 12: 306-321.

Santhosh, C. 2013. Chemistry and transformation of boron in soils of Kerala. PhD (Ag) thesis, Kerala Agricultural University, Thrissur, 257p.

Scherer, H.W., 2001. Sulphur in crop production. *Eur. J. Agron*, 14(2), pp.81-111.

Schnug, E. 1992. Baking quality and sulphur content of wheat I. Influence of grain sulphur and protein concentrations on loaf volume. *Sulphur Agric.* 16: 31-34.

Sharma, A. and Sankhyan, N K. 2020. Sorption studies on sulphur in cultivated soils of Himachal Pradesh. *Int. J. Curr. Microbiol. App. Sci*, *9*(8): 3376-3384.

Sharma, A. and Sankhyan, N.K. 2020. Sorption studies on Sulphur in Cultivated Soils of Himachal Pradesh. *Int. J. Curr. Microbiol. App. Sci* (2020) 9(8): 3376-3384

Sharma, Y.K. and Gangwar, M.S. 1997. Distribution of different forms of sulphur and their relationship with some properties in Alfisols, lnceptisols and Molisols of Moradabad district, U.P. *J. Indian Soc. Soil Sci.* 45: 480-485.

Shivay, Y.S., Prasad, R., and Pal, M. 2014. Effect of levels and sources of sulphur on yield, sulphur and concentration and uptake and S-use efficiency in Basmati rice. *Commun. Soil Sci. Plant Anal.* 001-12p.

Sims, J. R. and Johnson, G. V. 1991. Micronutrient soil tests. In: Mortvedt, J. J., Cox, F. R., Shuman, L. M. and Welch, R. M. (eds), *Micronutrient in Agriculture (2nd Ed.). Soil Sci. So.c Am., Madison*, USA, pp. 427-476.

Singh, B.R., Yang, Z. and Hansen, S., 2006, July. Aggregate Associated Sulphur Fractions in Soils under Long-Term Fertilization Experiment. *In The 18th World Congress of Soil Science.*

Singh, M.V. 2001. Importance of sulphur in balanced fertilizer use in India. *Fertil. News* 46 (10): 13-35.

Singh, S.B. and Rao, C.B. 2001. Availability of micronutrient in some alluvial soils of Kanpur region. *Indian J. Pulses Res.* 14(1):65-66.

Siwik-Ziomek, A., Lemanowicz, J., and Koper, J. (2016). Arylsulphatase activity and sulphate content in relation to crop rotation and fertilization of soil. Int. *Agrophys*., 30(3): 359-367.

Srinivasarao, C., Ganeshamurthy, A.N., Ali, M., Singh, R.N. and Singh, K.K., 2004. Sulphur fractions, distribution, and their relationships with soil properties in different soil types of major pulse-growing regions of India. *Commun. soil Sci. plant Anal*, 35(19-20): 2757-2769.

Stevenson, S.J. 1986. Cycles of soil: Carbon, Nitrogen, Phosphorous, Sulfur, Micronutrients. *John Wiley & Sons, New York 2nd Edn*

Subbiah, B. and G.L. Asija. 1956. Alkaline permanganate method of available nitrogen determination. *Curr. Sci.* 25: 259.

Sutar, R.K., Pujar, A.M., Kumar, B.A., and Hebsur, N.S. 2017. Sulphur nutrition in maize-A critical review. *Int. J. Pure App. Biosci*, *5*(6): 1582-1596.

Sutaria, G.S., Vora, V.D. M., Talpada, M., Hirpara, D.S., Vekaria, P.D., and Akbari, K.N. 2016. Studies on sulphur fractions in soils of Rajkot district, Gujarat. *Inter. J. Agric. Sci*. Res. 6(1): 61-68.

Tabatabai, M. A. and Al-Khafaji. 1980. Comparison of nitrogen and sulphur mineralization in soil. *Soil Sci. Soc. Am. J.* 44: 1000-1006

Tabatabai, M. A., Dick, W. A., 2002. Soil enzymes ; research developments in measuring activities .Enzymes in the environment: activity, ecology, and applications pp.567-596

Tabatabai, M.A. 1982. Sulfur. In: Page, A.L. Keeney, D.R., Baker, D.E., Miller, R.H., Roscoe Ellis Jr., and Rhoades, J. D. (eds), *Methods of Soil Analysis Part 2. Chemical and Microbiological Properties* (2nd Ed.). *Am. Soc. Agron*, Madison, Wisconsin, USA : 501-538.

Tabatabai, M.A., 1994. Soil enzymes. *Methods of soil analysis: Part 2 Microbiological and biochemical properties*, *5*: 775-833.

Takkar, P. N. 1988. Sulphur status of Indian soils. In: TSI-FAI symposium on sulphur on Indian agriculture: The sulphur Institute Washington, USA and *Fertil Assoc India*, New Delhi, pp.1-31.

Tandon, H. L. S. 1991. Sulphur Research and Agricultural Production in India (3rded.), The Sulphur Institute, Washington, D.C, 308p.

Tandon, H. L. S. 2011. Sulphur in Soils, Crops and Fertilizers. Fertilizer Development and Consultation Organization (FDCO), New Delhi, 204p.

Tandon, H. L. S. and Tiwari, K. N. 2007. Fertiliser use in Indian agriculture-an eventful half century. *Better Crops* 1(1): 3 -5.

Tandon, H.L.S., 1986. *Sulphur: Research and agricultural production in India* (No. REP-3982. CIMMYT.).

Tisdale, S.L., Nelson, W.L., and Beaton, J.D. 1985. *Soil fertility and fertilizers*, Mac millan Publishing Company: New York, ; 75-79.

Trasar-Cepeda, C., Gil-Sotres, F. and Leirós, M.C., 2007. Thermodynamic parameters of enzymes in grassland soils from Galicia, *Soil Biology and Biochemistry*, *39*(1): 311-319.

Trivedi, S.K., Bansal, K.N., and Singh, V.B. 1998. Important forms of sulphur in profiles of some soil series of northern M.P. *J. Indian Soc. Soil Sci.* 46: 579-583.

Uziak, Z., Szymańska, M., and Trojanowska-Solecka, A. 1982. The influence of varied nitrogen sulphur nutrition on the productivity and biological value of fodder plants. *Ann. UMCS Lublin, Sect.* 37(12): 125-133.

Von, T.S., Hörndl, D., and Schmidhalter, U., 2018. Interaction of soil pH and phosphorus efficacy: Long-term effects of P fertilizer and lime applications on wheat, barley, and sugar beet. *Ambio,* 47(1), :41-49.

Walkley, A.J. and Black, I.A. 1934. Estimation of soil organic carbon by chromic acid titration method. *Soil Sci.* 31: 29-38.

Wang, C.H. 1978. Sulphur fertilization of rice. Sulphur in Agriculture 2,: 13 -16.

Watanabe, F.S. and Olsen, S.R. 1965. Test of an ascorbic acid method for determining phosphorus in water and sodium bicarbonate extracts from soil. *Soil Sci. Soc. Am. Proc.* 29: 39-45.

Weaver, M.A., Zablotowicz, R.M., Krutz, L.J., Bryson, C.T. and Locke, M.A., 2012. Microbial and vegetative changes associated with development of a constructed wetland. *Ecological Indicators*, *13*(1): 37-45.

Westermann, D.T., 1974. Indexes of Sulfur Deficiency in Alfalfa. I. Extractable Soil SO_4-S 1. *Agron. J. 66*(4), pp.578-581.

Williams, C.H. and Steinbergs, A. 1959. Soil sulphur fractions as chemical indices of available sulphur in some Australian soils. *Aust. J. Agric. Res.* 10(3): 340-352.

Williams, C.H. and Steinbergs, A., 1962. The evaluation of plant-available sulphur in soils. Plant and soil, 17(3): 279-294.

Williams, C.H., 1975. The chemical nature of sulphur compounds in soils. In *'Sulphur in Australasian Agriculture*: 21-30.

Young, E.G., Smith, D.G. and Langille, W.M., 1959. The chemical composition of sea water in the vicinity of the Atlantic provinces of Canada. *J. Fisheries Board of Canada,* 16(1): .7-12.

Zhang, H., Jiao, H., Jiang, C.-X, Wang, S.-H., Wei, Z.-J.; L, J.-P.; Jones, R.L. Hydrogen sulfide protects soybean seedlings against drought-induced oxidative stress. *Acta Physiol. Plant*. 2010, 32, 849–857.

Sulphur dynamics in major rice-growing soils of Kerala

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ABSTRACT OF THE THESIS

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ABSTRACT

Sulphur has been recognized as an essential nutrient to plants and it is ranked as fourth among major plant nutrients after nitrogen, phosphorus, and potassium. Most of the soils in Kerala are rich in total S and the maximum amount of sulphates has been reported in *Kari* and *Pokkali* soils. Representative soil samples were collected from seven different rice growing tracts falling under different agro-ecological units (AEU) of Kerala for the study entitled Sulphur dynamics in major rice-growing soils of Kerala. Five samples each were collected from various locations pertaining to a particular soil type for initial characterisation. In addition three soil and plant samples were also collected from each soil type at active tillering and harvest stage of rice crop.

The study aims at understanding sulphur dynamics in major rice soils of Kerala and its relationship with that of carbon, nitrogen and phosphorus. It also envisages at unfolding the antagonism/ synergism between sulphur and other nutrients, if any. Sixteen out of 35 samples belonged to the category of strongly acidic to moderately acidic. It can be concluded from characterisation study that the sandy soils of *Onattukara* was low in terms of fertility wherein *Pokkali* soils, *Kole* land and *Kari* soils of Kuttanad were high with respect to soil fertility. None of the soils were found deficient in available sulphur with *Pokkali* soils being the remarkably highest. The low land brown hydromorphic laterite and *Onattukara* sandy soils had relatively lower sulphur content. The *Kari* soils accounted for highest microbial biomass carbon and aryl sulphatase activity.

The estimated soil pH was slightly elevated at active tillering and harvest stage. The sulphur exhibited an antagonistic relationship with phosphorous, potassium as well as manganese

Fractionation of S was conducted at three stages to find out the dominant different forms of sulphur. The *Pokkali* soils and *Onattukara* sandy soils had the highest as well as lowest value for all the sulphur fractions before cropping. The *Kari* soil concluded the highest total organic sulphur at active tillering and harvest stage. All the sulphur fractions were positively influenced by microbial biomass

carbon and aryl sulphatase activity. An identifiable positive relation existed between available nitrogen and total organic sulphur as well.

The C:S ratio was high in Laterite soil and lowest in *Pokkali* soil at all the three stages.

The Onattukara sandy soil and Laterite soil accounted for the highest N:S ratio wherein *Kari* soil and *Pokkali* soil had the lowest ratio. The decreased C:S and N:S ratio contributed to the raised plant available sulphur in soil.

Sulphur adsorption experiment was conducted at 25 ℃ as well as 40℃ and quantity-intensity relations were carried out based on data. While The samples from *Pokkali* and *Kari* soil exhibited desorption of sulphur at both the temperatures (25 ℃ and 40 ℃) studied, it was found to get adsorbed in the case of Laterite soil and *Onattukara* sandy soils at both 25 ℃ and 40 ℃.