ION INTERACTIONS AND RICE NUTRITION IN ACID SALINE POKKALI SOILS

By

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(2014-11-145)

THESIS

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DECLARATION

I, Aditya Mohan (2014-11-145) hereby declare that, this thesis entitled **"Ion interactions and rice nutrition in acid saline *Pokkali* soils"** is a bonafide record of research done by me during the course of research and that the thesis has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title of any other University or Society.

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LIST OF ABBREVIATIONS

%	-	Per cent
Al	-	Aluminium
B	-	Boron
BDL	-	Below detectable level
Ca	-	Calcium
CEC	-	Cation exchange capacity
Cu	-	Copper
DHA	-	Dehydrrogenase activity
ESP	-	Exchangeable sodium percentage
Fe	-	Iron
K	-	Potassium
MBC	-	Microbial biomass carbon
Mg	-	Magnesium
Mn	-	Manganese
Mo		Molybdenum
N	-	Nitrogen
Na	-	Sodium
opstat	-	Operational statistics
OC	-	Organic carbon
P	-	Phosphorus
PLDA	-	Pokkali land development agency
S	-	Sulphur
SAR	-	Sodium adsorption ratio
Se		Selenium
SPSS	-	Statistical Program for the social sciences

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INTRODUCTION

INTRODUCTION

A characteristic cultivation of rice along the coastal tract of Kerala in saline soils is called the '*Pokkali* cultivation' or 'saline farming'. Actually, it is named after a unique variety of rice called '*Pokkali*'. An organic way of cultivation is adopted for *Pokkali* rice and its cultivation extends to Alappuzha, Ernakulam and Thrissur districts. It is synonymous with *Kaipad* cultivation and *Kariland* cultivation in Kannur and Alapuzha respectively. *Pokkali* rice got geographical indication registration in the year 2008–2009. There are about 4000 hectares of paddy fields under *Pokkali* cultivation in Ernakulam district, while in Alappuzha and Thrissur, the extent of paddy cultivation is in about 3000 hectares and 2000 hectare respectively (Joy, 2013). The *Pokkali* fields of Kerala have been declining from 25,000 hectares to 9000 hectares (Dominic and Jithin, 2012). This area extends from 9°00' to10°40' N Latitude and 76°00' to77°30' E Longitude. These fields are low lying marshes situated near the estuaries of rivers and they are close to the sea. Other characteristics of lands include water-logging, poor drainage system and tidal action throughout the year. The rice cultivation is between June to early November when the fields have low salinity. From mid-November to mid-April, the salinity of fields becomes higher. Then prawn farming takes over. The average rainfall of the area is more than 2900 mm. The major part of which is received in the months of June, July and August. Heavy rain occurs continuously for 10-15 days and results in flash flooding.

Over the years, there is a decline in the area under *Pokkali* cultivation. Lands are converted for other purposes like coconut cultivation and construction purposes. In 1996, the *Pokkali* Land Development Agency [PLDA] was formed by the Government. The agency concentrated on the promotion of paddy cultivation in the wet lands. The agency gathered a lot of information regarding *Pokkali* padashekarams and their activities and it helped to undertake a highly disaggregated analysis. The agency found out that, the total area under *Pokkali* has decreased from 25,000 ha to a mere 8,500 ha. Out of this, rice cultivation is limited to 5,500 ha. The rest is either left fallow or used only for prawn cultivation.

Acidity, salinity and toxicity of ions are the major problems in *Pokkali* soils. The decline in the rice cultivation may be attributed to problems in rice nutrition, ill effects of salinity, unavailability of labour for harvest, losses and the difficulties experienced in paddy harvesting. Improper management of land can easily disturb the nutrient balance of *Pokkali* soils. Many works have been carried out to study the plant responses in saline soils. But, the nutritional constraints in plant growth of acid saline *Pokkali* soils have received little attention.

For minimizing the yield loss, proper and appropriate understanding of nutritional constraints and its management is required. Hence, the present study was undertaken on ion ineractions and rice nutrition in *Pokkali* soils, with the following objectives.

- Assessment of ion interactions in acid saline *Pokkali* soils
- Identification of the chemical constraints in plant nutrition of *Pokkali* soils
- Identification of emerging deficiency or toxicity of nutrients in *Pokkali* soils

REVIEW OF LITERATURE

REVIEW OF LITERATURE

The marshy *Pokkali* tracts typify a unique ecosystem, having a rich biodiversity and capacity to produce rotational rice and shrimp in an organic way. These lands have acid saline soils. They are prone to flooding and salinity since they are situated near to the mouth of the river and closer to sea. Salt water intrusion or deep flooding is common in these soils. The *Pokkali* soils have to confront multi stress due to acidity, salinity and flooding. Even though, the soil is rich in almost all the nutrients, toxicity of certain ions occurs. A better understanding of ion interactions is necessary to improve the plant growth in *Pokkali* soils.

2.1. Pokkali cultivation

A salt resistant variety of rice called *Pokkali* is cultivated in the coastal regions of Alappuzha, Ernakulam and Thrissur districts of Kerala. This variety has been given a status of registered Geographical Indication (GI) by the Geographical Indications Registry Office, Chennai, Tamil Nadu (Shylaraj *et al.,* 2013).

The *Pokkal*i fields are cultivated once in a year. The cultivation starts from April by strengthening of the outer bunds and setting up sluices. The flow of water to the fields is regulated by sluice gates. During low tide, the fields are drained and the sluices are closed at high tide. This helps in drying of the soil. Then mounds are formed. During May – June, salts are washed off from the mounds by the action of the rain water. Then the sprouted seeds are sown (Shylaraj *et al.,* 2013).

The rice plants grow up to two metres in the water-logged fields. However, at its maturity, the crop stoops and only the panicles stand upright. Rice is harvested by the end of September. During harvest, only the panicles are cut. The rest of the stalks are left in the field itself (Jayan and Sathyanathan, 2010). Rice cultivation is followed by shrimp filtration during the high saline phase (Sashidharan *et al.*, 2012).

The rice crop uses the nutrients from the prawns' excrement and other remnants. The remnants of paddy cultivation become feed for the prawns in turn. The tidal flows keep the fields highly fertile. Eventually no manure or fertilizer needs to be applied. These water logged fields are located below the mean sea level. These characteristics distinguish them from other farming practices in Kerala (Jayan and Sathyanathan, 2010).

2.2. Morphological characteristics of soil

The acid saline *Pokkali* soils belong to fine loamy, mixed, iso- hyperthermic acid family of sulfaqueptic tropofluents as per soil taxonomy. They are developed from lacustrine and alluvial deposits (Varghese *et al.*, 1970).

Varghese *et al.*, (1970) conducted a detailed study on profile characteristics of the *Pokkali* soils of Vyttila. Soil is light grey on the surface. The intensity of color increases with depth. Soil texture becomes finer with depth (Varghese *et al.*, 1970). Ground water table fluctuates up to 2 m due to tidal flows. The soil is stiff impervious clay. It is richly supplied with organic matter. It is hard in nature with impeded drainage conditions. Deep fissures are formed when dry. It shows stickiness when wet (Padmaja *et al.*, 1994). Samikutty (1977) reported that, concretions and mineral fragments were absent in the soil profile. Kaolinite is the dominant clay mineral in the soil. It contains fairly large amounts of smectite and small amounts of halloysite. The major components of fine sand and coarse sand fractions are quartz, mica, feldspar and chloritic minerals (Kuruvila, 1974).

2.3. Soil reaction

Majority of the saline soils of Kerala have acidic pH ranging from 3.0 to 6.8 despite high conductivity (Nair and Money, 1972). Bhaskaran and Varghese (2009) reported that, the wet land rice soils of Kerala can be arranged as Kari> Pokkali> Karapadom > Vellayani > Kayal > Kole > Wyanad > Pattambi > Kaipaid > Karamana > Kattampally > Chittoor, based on the severity of acidity. Under submergence, these wetlands showed an increase in pH to a fairly stable value. Kuruvila (1974) reported that, the increase in pH continued upto 20 days, and then the level was maintained. All the wetlands reached above a pH of 5.5 within two weeks of submergence except Pokkali, Kari, Kayal and Kole lands (Bhaskaran and Varghese, 2009). The inbuilt acidity of *Pokkali* soil becomes more dominant, when the salinity is washed away (Padmaja *et al.*, 1994).

2.4. Electrical conductivity

Sea and backwater tides make the soil saline. Most of the *Pokkali* soils have electrical conductivity higher than 14 dS m^{-1} (Varghese *et al.*, 1970). During monsoon season, rain water and fresh water from rivers enters the field. This removes salinity of the soil partially and soil attains electrical conductivity, ranging between 6-8 dS m^{-1} (Tomy *et al.*, 1984). During summer months (January - May), the electrical conductivity ranges between 12-24 dS m^{-1} and the average salt content reaches upto 1.8% (Shylaraj *et al.*, 2013).

2.5. Redox potential

Only during the sowing period of seeds, an aerobic condition prevails in the field. Later, anaerobic conditions take over the fields due to water logging. Prolonged and recurrent water logging conditions for more than 2 months causes distinct changes in soil properties (Chacon *et al.*, 2005).The redox potential can be used as a measure of electron availability within the soil system. It is determined from the concentration of oxidants and reductants in the soil environment. The wetland soils are usually characterized by the limited presence of electron acceptors and the abundant supply of electron donors. The reductants in these soils include organic matter and various organic compounds, reduced inorganic compounds *viz* NH_4^+, Mn^{2+}, S^{2-}-, CH_4 and H_2 (DeLaune and Reddy, 2005).

Typical Eh values of wetlands ranges from -300 to 700 mV and in aerobic soil, it is between 300 and 700 mV. The oxidation- reduction status of different redox couples can be understood from the redox potential of the soil. If a redox potential of 0 mV is considered, it indicates the absence of oxygen and nitrate and the reduced state of iron and manganese compounds (DeLaune and Reddy, 2005).

2.6. Organic matter

Soil organic matter is actually a repository of plant nutrients. It is important for maintaining physical, chemical and biological properties of the soil. It is also crucial for the soil for agricultural productivity and environmental functions (Izaurralde *et al.,* 2001). In *Pokkali* soils, the content of oxidizable organic matter increases during the first 10 days and is maintained thereafter (Samikutty, 1977). According to Annie *et al.,* (2014), the soil maintains medium to high organic carbon.

2.7. Cations and anions

In submerged soils, the prevalent form of inorganic nitrogen is ammonium. In anaerobic conditions, ammonium is not converted to NO_3^-. Mineralization in submerged soils includes the conversion of soil organic N to ammonium. This process supplies plant-available N in submerged agricultural soils (Waksman, 1929; Payne, 1970). The NH_4-N increased with the submergence period (Samikutty, 1977).

According to detailed fertility investigation conducted by Samikutty (1977) in *Pokkali* lands, the soil is extremely deficient in phosphorus. But, Snyder (2002) opined that, the availability of phosphorus is more in flooded conditions. This increase in P availability involves the reduction of ferric (Fe^{3+}) phosphate to ferrous (Fe^{2+}) phosphate and the release of P from insoluble Fe and Al compounds. Several weeks may be required for the release of phosphorus by these processes. This initially released P can be adsorbed into clay particles and aluminium hydroxide. It may result in temporary reduction in availability in some soils with high quantity of active Fe and Al (Snyder, 2002). The available P content is higher in the soil due to the tidal action (Sasidharan, 2004).

Ponnamperuma (1972) reported the changes occurring in submerged soils. As submergence advances, the potassium content of the soil was found to be increased. Upto 30 days of submergence, there was a steep increase in iron content in the *Pokkali* soil and it was maintained thereafter. Aluminium and manganese content increased upto 10 days and then it showed a fall. Ultimately, the availability of N P, K, Ca, Mg, Fe, Mn and Si is high due to submergence. The supply of micronutrients such as Cu and Mo was adequate (Ponnamperuma, 1972). Generally, there is a reduction in the availability of Zn, as result of submergence of the soil (Yoshida, 1981).

2.8. Ion exchange in *Pokkali* soils

The cation exchange capacity (CEC) of a soil is determined by the amount of organic matter as well as the type and amount of clay. It can be a measure of the reservoir of Ca, Mg, K, and other cations. According to Varghese *et al.*, (1970), cation exchange capacity of *Pokkali* soil tends to decrease with depth. The same trend is followed in the case of exchangeable magnesium. The upper horizon contained higher amount of exchangeable calcium than that of exchangeable magnesium. Santhosh (2013) reported a higher quantity of exchangeable sodium in *Pokkali* soils.

The order of dominance of exchangeable cations in *Pokkali* soils was reported by Aryalekshmi (2016), which is Ca = Na> Al> Mg>K > Fe.

The addition of marine derived salts enhances the acidity, due to exchange processes (Harriman *et al.,* 1995), especially, the concentrations of aqueous Fe^{2+}, Al^{3+} and Si are increased by this addition of salts (Portnoy and Giblin, 1997; Mkadam *et al.,* 2006) decreasing the pH (Wright *et al.,* 1988). Acidic conditions made metals such as Al and Fe more soluble. Then it became increasingly available for biogeochemical transformations (Dent, 1986).

A direct ion exchange process occurs due to the addition of Na^{+}saline solutions. This resulted in an exchange of Na^{+} ions with H^{+} and Al^{3+} ions, causing acidification (Hindar *et al.,* 1994). Earlier studies in wetland soils and sediments have reported a decrease in pH with increasing salt concentration (Khattak *et al.,* 1989). The release of H^{+} by cation exchange in the soils and the dissolution of organic material in organic-rich soils resulted in the rise of pH. Similarly, there is increase in acidity and acidic cations in solution with increased sea salt deposition (Harriman *et al.,* 1995; Farrell *et al.,* 1998). This was also attributed to exchange processes in variable charge soils.

The positive charge of variable charge soils was increased by decreasing pH. It enhances anion retention and cation desorption (Wiklander, 1975). The cationic and anionic composition revealed these soils were of Na- Mg- Cl- SO_4 type. During the first 10 days, there was an increase in concentration of sulphate-sulphur and thereafter it decreased (Samikutty, 1977).

2.9. Exchangeable sodium percentage, sodium adsorption ratio and percentage cation saturation

The sodium adsorption ratio (SAR) is utilized in the analysis of soil extracts (Saurez, 1981). It is an important water quality parameter as it is related to the exchangeable sodium percentage (ESP). ESP is the percentage of the cation exchange capacity occupied by sodium. The exchangeable sodium percentage of the *Pokkali* soil ranged between 13.7 and 83.3. Sodium adsorption ratio ranges from11.7 to 34.8 (Samikutty, 1977).

According to Bear and Toth (1948), Graham (1959) and Eckert (1987), ideal percent base saturation ranges for soils are 60–80, 10–25 and 3–5 for Ca, Mg and K, respectively. Soil values above these ranges indicate excessive levels while those below indicate deficiencies.

2.10. Biological properties of soil

Soil is not a dead mass. It is a home for millions of organisms (Pimentel, 1995). The soil is said to be healthy, if it has the capacity to function as a vital system to sustain the productivity of animals and plants, maintain the quality of water and air, and health of the plants and animals within the limits of an ecosystem (Doran and Zeiss, 2000). Incredibly complex linkages exist between soil organisms and soil functions.

Flooded soils represent an unique situation. They are predominantly under anaerobic conditions. This causes a shift in the soil microflora. The aerobic microorganisms were replaced by facultative and obligate anaerobic ones, after the flooding of soil (Orten and Neuhaus, 1970). Fungi are usually active in aerobic conditions. Their growth is inhibited in wetland environment, as it is under anaerobic condition. This is because of absence of oxygen and change in pH (acid to neutral). Thus, microbial biomass is reduced under saturated conditions of soil, due to the shift from aerobic to anaerobic respiration. The decrease in microbial activity leads to the decline of rate of microbial mediated reactions and replacement of some reactions by new ones (Inglett *et al.*, 2005).

The heterotrophic soil microorganisms play a significant role in decomposition of organic materials. These decomposed materials act as a carbon source for microorganisms. Furthermore, the soil microbial biomass is a reservoir of many plant nutrients (Haider *et al.*, 1991).

The anaerobes in the wetland soil decompose carbohydrates and ends in the synthesis of fewer microbial cells per unit of organic C degraded. These organisms work at a lower energy level and their efficiency is lower than aerobes (Waksman, 1929; Payne, 1970). In the absence of oxygen, both facultative and obligate anaerobes use Mn^{4+}, Fe^{3+}, NO_3^-, and SO_4^{2-} in electron transfer reactions. These reactions produce Mn^{2+}, Fe^{2+}, N_2 and S^{2-} species. In some cases, it may increase the nutrient availability to the plants (Ponnamperuma, 1984). As per the opinion of Inglett *et al.*, (2005), the decomposition process lead to the production of bioavailable nitrogen and phosphorus. Furthermore, the extent of reduction of Fe^{3+} and/ or Mn^{4+} can influence the distribution of toxic trace metals and availability of phosphorus strongly (Inglett *et al.*, 2005).

According to Pedrazzini and McKee (1984), the activities of soil enzymes reflect the potential capacity of a soil to perform nutrient transformations. Dehydrogenase enzymes are the major component of soil enzymes that reflects the metabolic activity of the soil microbes (Casida *et al.*, 1964). Most dehydrogenases were of anaerobic origin (Orten and Neuhaus, 1970). Flooding cause a significant increase in the dehydrogenase activity of soils (Chendrayan *et al.*, 1980; Tate, 1979). This increase indicated an increased role for facultative anaerobic bacteria in flooded soils. An experiment conducted to study the effect of flooding on soil dehydrogenase enzyme revealed the fact that the non-flooded soil treatments showed negligible dehydrogenase activity. It was decreased soon after drainage of the flooded soils (Pedrazzini and McKee, 1984).

2.11. Ion interactions

The chemical composition of a soil solution is complex. It is determined by the solid phase, liquid phase, the gaseous phase and the complex exchange phase. The solid phase comprises clay minerals, amorphous inorganic compounds and organic materials. The liquid phase is made up of soil water and the gaseous phase consisted mainly of oxygen and carbon dioxide (Jurinak, 1990). A number of factors associated with the soil and its environment influences the activity of chemical species, particularly the nutrient ions (Jurinak, 1990; Deverel and Fujii, 1990). Microbial assimilation and excretion are important soil processes which may affect nutrient ion concentration in soil solution. Chelation and ligand complexing are vital reactions controlling the concentration of micronutrient ions in soils and soil extracts (Naidu and Rengasamy, 1994)

There are basically two kinds of interactions between nutrients such as synergism and antagonism. Synergism is a positive effect between nutrients and antagonism indicates negative effect between nutrients. These interactions depend on several factors *viz.,* soil type, physical properties, pH, ambient temperatures and proportion of participating nutrients. These interactions between two mineral nutrients become even more important when the contents of both elements are near deficiency range (Ujwala Ranade, 2011).

Anions like sulfates and carbonates are associated with multivalent cations. This association causes the formation of non-ionic species or ion pairs. It resulted in the reduced activity of the ionic species and the low availability of the nutrient ions (Adams, 1974). Such complexes may also reduce ion toxicity to plant growth. For example, formation of ion pairs of Al^{3+} with SO_4^{2-} or F^- reduces the ionic activity of

Al^{3+} and thus its toxicity to root growth (McCray and Sumner, 1990). In sodic soils, carbonate, bicarbonate and sulfate ion pairs reduced the activities of divalent ions (Alzubaidi and Webster, 1983). Under sufficiently reducing conditions, sulfate is reduced to sulfide and trace metal sulfides precipitate (Lindsay, 1979).

At low pH, positive charges are developed on the surfaces of hydrated oxides of iron and aluminium. Because of these developed charges, anions like Cl^-, NO_3^- etc. are adsorbed and get exchanged with each other. However, competition from organic anions restricts adsorption. This can be explained as due to the formation of surface complex between anion and a metal. Similar to phosphate ion, silicate, sulphate and probably fulvic acid were also adsorbed. But, sulphate formed a weak complex than phosphate (Smith, 1999).

Synergism, the positive interaction can be illustrated by the following examples (Ujwala Ranade, 2011):

- Optimum supply of nitrogen ensures optimum uptake of potassium as well as phosphorus, magnesium, iron, manganese and zinc from the soils.
- Optimum levels of copper and boron improve nitrogen uptake by plant.
- Uptake of phosphorus and potassium is improved by optimal levels of calcium and zinc.
- Optimal levels of sulphur increases uptake of zinc and manganese.
- Optimal levels of manganese improves copper uptake.

The examples below show the negative interrelationships between nutrients (Ujwala Ranade, 2011).

- Excessive amounts of nitrogen reduce the uptake of phosphorus, potassium, iron and almost all secondary and micronutrients like calcium and magnesium, iron, manganese, zinc and copper.

- Excessive quantity of phosphorus lowers uptake of micronutrients like iron, manganese, zinc and copper.
- Excessive amounts of potassium impairs uptake of magnesium to a greater extent and calcium to a lesser extent.
- Uptake of iron is reduced by the excessive amounts of calcium.
- Excessive Iron reduces zinc uptake and excess zinc decreases manganese uptake.

A long term fertilizer trial carried out by Watanable *et al.*, (2015) clearly revealed that, N deficiency decreased the uptake ability of many elements and Mo uptake was increased in maize.

Hakamata (1983) conducted a lysimeter experiment to determine the content and distribution of ions in a soil solution. The multiple regression analyses showed that, the amount of K present in the soil was controlled mainly by the anions. Ammonium concentration was controlled by Cl^- and SO_4^{2-} levels in soil solution.

Sasidharan (2004) reported that, in *Pokkali* soils, the organic carbon content correlated negatively with available phosphorus, potassium, calcium, sodium, magnesium, and iron and positively correlated with zinc, copper and manganese. Available nitrogen had significant negative correlation with available calcium. Available phosphorus had significant positive correlation with available copper and zinc but negatively correlated with available manganese.

2.12. Constraints in rice nutrition

Pokkali farmers have to face certain challenges in rice cultivation. The main constraints are acidity, salinity, toxicity and deficiency of nutrients. Crop failure is common in these soils. The reasons include salinisation and acidification during drought and intrusion of salt water or deep flooding (Joseph, 2014).

2.12.1. Salinity

Salinity refers to the concentration of salts in the soil that is sufficiently high to adversely affect crop yields or crop quality. Usually, saline soils have an electrical conductivity of more than 4 dS m^{-1} at 25°C and contain soluble salts, mainly chlorides and sulphates of sodium, calcium and magnesium. According to Padmaja *et al.,* (1994), there were three types of saline soils in Kerala. These soils were recognized based on their location, extent and intensity of salinity and crop season. *Pokkali* soils are the major one among them. It was formed when the influx of salt is greater than efflux. Ocean drifts, underground water, deposition by wind and mineral weathering are the major sources of salts in soil (Asiamah, 1995). Salinity alters soil physical properties by a process named flocculation. It causes fine particles to bind together to form aggregates and produces some positive effects on soil aeration, root penetration and root growth. However, high salinity conditions harm the plant growth. Excessive sodium concentrations can result in the breakdown of soil aggregates and can cause soil pore blockage. Ultimately, it will reduce the soil permeability (Allotey *et al.,* 2008). Sodium induced dispersion causes some problems such as reduced infiltration, reduced hydraulic conductivity and surface crusting (Frenkel *et. al.,* 1978; Van de Graaf and Patterson, 2001; Pearson, 2004).

According to Owens (2001), in aquatic ecosystems, increase in salinity affects most plants and lead to ionic and osmotic stresses. It also causes several biochemical and morphological alterations as well as nutrient imbalances (Muhammed *et al.,* 1987; Jampeetong and Brix, 2009). The plant exposure to salinity affects fundamental factors to plant life such as growth, photosynthesis, protein synthesis, lipid metabolism, productivity (Parida and Das, 2005) and nutritional balance (Grattan and Grieve, 1999). Nutrients have a major role in maintenance of plant structure, metabolism and osmoregulation of plant cells (Taiz and Zeiger, 2009). Munns and Tester (2008) opined that, salinity affects availability, absorption and transport of nutrients within the plant and results in nutritional disorders. Nutrient deficiency as well as ion toxicity and osmotic stress were the factors attributed to the deleterious effect of salinity on plant growth and productivity (Nublat *et al.*, 2001).

In saline soils, plants were adversely affected by low uptake of water by plant roots due to osmotic potential effects (Bernstein, 1975). The adverse responses were the results of high concentrations of salts or by high concentrations of specific ions. This can lead to salt toxicity in the plant. High concentration of certain ionic species such as Na and Cl may cause deficiencies of nutrient elements present at much lower concentrations. Thus, the performance of plant was weakened by salinity induced nutritional disorders, because of the effects of salinity on nutrient availability, competitive uptake, transport or partitioning within the plant (Grattan and Grieve, 1999).

The nitrate absorption may get inhibited by salinity. Aslam *et al.*, (1984) conducted short term experiments with barley seedlings and found that SO_4^{2-} and Cl^- diminished the rate of NO_3^- absorption. Sodium ions can cause disturbances in Ca nutrition. Elzam and Epstein (1969) carried out a study to compare two species of wheat grass, which were grown in nutrient solutions salinized with sodium chloride at concentrations ranging up to 500 mM. It is seen that salt concentration of 5.0 mM severely affected growth of the salt sensitive species of wheat grass and 100 mM affected the salt tolerant species. In each species, the Ca concentration in the roots dropped proportionally at the same concentrations of salt and it suggested a causal relationship between the salt induced Ca loss and failure of the plants.

Excessive soil salinity results in the yield reduction of many crops. A slight crop loss to complete crop failure may occur, depending on the type of crop and the severity of the salinity problem. If salt level ranges between 0 to 2 dS m^{-1}, there is no significant yield reduction. Generally a level of 2 to 4 dS m^{-1} affects some crops and many crops are affected by a range of 4 to 5 dS m^{-1}. However, salinity levels, above 8 dS m^{-1} affects all but very tolerant crops can yield satisfactorily (Grattan, 2002).

Ryan *et al.,* (1975) proposed that, seed germination in salt affected soils is influenced by the total concentration of dissolved salts and the type of salts involved. Egan *et al.,* (1997) studied the effect of different sodium and potassium salts on the germination of *Atriplex prostrate*. From the study, it was concluded that, inhibition of seed germination and early growth was primarily due to osmotic effect. It was not due to a specific ion toxicity of either the chloride or sulfate salts. Some studies showed the adverse effect of high salt levels on soybean through inhibiting seed germination and seedling growth, decrease in crop yields (Essa, 2002), reduction in the number and weight of root nodules (Lauter *et al.,* 1981), leaf area, root/shoot ratios (Rahman *et al.,* 2008), shoot height and fresh and dry weights (Cicek and Cakırlar, 2008).

Exchangeable Salinity level, denoted as EC, ESP value and exchangeable Na were generally higher, approximately 2.5 me.100 g^{-1} in paddy soils compared to non paddy soils as they can restrain saline water and mud, particularly compared to the surface layers (0-10 cm) (Maroeto *et al.*, 2007; Rahman *et al.*, 2008). Salinity can cause growth reduction in rice crop, resulting in stunted growth. Toxic ionic effects result in the excess $Na^{+}$and Cl^{-} uptake causing reduction in the uptake of K^{+} and Ca^{++} because of antagonistic effects (Dobermann and Fairhurst, 2000). The crops growing in saline soils showed a little vegetative growth and high sterility. Eventually, the crop yield was reduced (Shylaraj *et al.,* 2013). Ion balance, especially Na^{+}/K^{+} balance is essential for plant tolerance to salinity (Apse and Blumwald, 2007).

2.12.2. Acidity

Soil acidity is one of the major constraints that hinder rice production in many parts of the world. Plant growth and most soil processes, including nutrient availability and microbial activity, are favoured by a soil pH range of 5.5 – 8. Soil acidifies because the concentration of hydrogen ions in the soil increases. Iron reduction and carbon dioxide concentration in submerged soils play a key role in controlling the soil pH. This requires optimum temperature (between 25 and 35°C) and availability of easily decomposable organic matter, reducible iron and other electron acceptors such as sulphate and carbon dioxide (Ponnamperuma, 1972; Sahrawat, 2004).

A rapid change in soil environment influences the surface chemistry of the soil (Schofield, 1949; Nikiforroff, 1952; Cline, 1961). The poor plant growth on acid soils was attributed to several factors, such as aluminium toxicity (Barcelo *et al.*, 1996), manganese toxicity (Foy, 1984), low N supply (Foy, 1984), P deficiency (Foy, 1984) and Mo deficiency (Hafner *et al.*, 1992).

Aluminium ions play an important role in exchangeable acidity (Coleman and Thomas, 1967). According to Kamprath (1967), pH 4.5–5.8 in mineral soils indicates the presence of sufficient exchangeable Al to reduce plant growth. If exchangeable Al occupies more than 60 per cent of the CEC, it results in toxic levels of aluminium in soils (Nye *et al.*, 1961). The low fertility of acidified soils owes to the enrichment of Al^{3+} and Mn^{2+} and increased proportions of H^{+} ions in soil solution and on colloidal surfaces at the expense of basic cations. Simultaneously, the increase in pre disposition of soil minerals to weather in turn leads to release of both basic and acidic ions. The role of these ions points to its' buffering effects and capacity to prevent a rapid reduction in pH (Allotey *et al.*, 2008). When soil pH is reduced, aluminium becomes soluble. Even a small drop in pH can cause increase in the quantity of soluble aluminium, restricting access to water and nutrients, leading to retarded root growth. Poor crop, yield reduction and smaller grain size are the ultimate results. Aluminium in its ionic form is toxic to plant roots as it hinders cell division. Toxic levels of aluminum causes root pruning in plants. If manganese concentration reached toxic level, the normal growth processes of the above ground plant parts get affected. This results in stunted, discolored growth and poor yields (Allotey *et al.*, 2008).

Low pH is the one of the ill effects reported in *Pokkali* soil (Shylaraj *et al.*, 2013). The availability of plant nutrients is considerably affected by soil pH. The alkaline elements like calcium, potassium, and magnesium are lost with increase in acidity. Phosphorus is more available in acidic soil conditions. Acidity can also induce deficiencies of micronutrients *viz.*, molybdenum and copper. Acid soil will restrict root access to water and nutrients. Arnon and Johnson (1942) reported that, the poor growth of lettuce, tomato and Bermuda grass grown in low pH solution was the result of low calcium supply. Proctor (1999) demonstrated that, the growing of crops like maize, mung bean and rice in very acid soils causes complete root growth inhibition. In very acid soils, plants have to encounter the toxicity produced by H^+ ions initially. Then only, they have to face other opposing factors like Al, Mn, low N, low P and low Ca (Kidd and Proctor, 2001).

Low pH in topsoil may affect microbial activity, most notably decreasing legume nodulation. The resulting nitrogen deficiency may be indicated by reddening of stems and petioles on pasture legumes, or yellowing and death of oldest leaves on grain legumes. Rhizobia bacteria are greatly reduced in acid soils. Some pasture legumes may fail to persist due to the inability of reduced Rhizobia populations to successfully nodulate roots and affecting the functioning of symbiosis (Kidd and Proctor, 2001).

2.12.3. Toxicity and deficiencies

Essential nutrients are required by plants for their normal functioning and growth. Range of a nutrient is said to be sufficient, if it is present in amount that is necessary to meet the plant's nutritional needs and maximize growth. If nutrient levels are not sufficient, it causes a deficiency resulting in decline of overall crop growth and health. Nutrient deficiency occurs when an essential nutrient is not available in sufficient quantity to meet the requirements of a growing plant. Toxicity occurs when a nutrient is in excess of plant needs and decreases plant growth or quality (McCauley *et al.,* 2011).

Pokkali fields are characterized by the accumulation of sodium and toxic levels of iron and manganese (Padmaja *et al.,* 1994). Excess levels of sodium in soil solutions induce ion deficiencies (Chang and Dregne, 1955). Specific ion toxicity occurs when salinity is dominated by sodium chloride and it affects plant productivity (Chang and Dregne, 1955).

High Na^+ uptake also leads to deficiencies of elements such as K, Zn, Cu and Mn (Levitt, 1980). Excessive Na^+ uptake causes adverse effects on physiological processes of the crop. In the opinion of Rengasamy (1987), a threshold amount of $Ca^{2+}$and K^+ in the soil solution will be required to compensate these effects. Furthermore, concentration of certain trace elements such as B, Se or Mo may become high in the soil. It could lead to specific toxicities in some plants. If accumulation continues, it could become a health threat to the consumer. High Na concentrations may cause deficiencies of other elements, such as K or Ca in the plant. The toxic effects of Na^+ or Cl^- may not always be clearly distinguishable from deficiencies (Chang and Dregne, 1955).

When soil profiles are waterlogged, anoxic or suboxic conditions take over. It restricts plant growth. The submergence of the soil reduces the availability of zinc (Yoshidha, 1981). It is often combined with P deficiency. Under prolonged submergence, the availability of Ca, Mg, Cu, Fe, Mn and P is increased. This limits Zn availability and uptake by the crops (Das, 2014).

According to Das (2014), iron toxicity is one of the major constraints to lowland rice production. Iron is an essential microelement, which is quite abundant in the earth's crust. It is mainly present in the form of insoluble Fe (III). Therefore, it is unavailable to higher plants, especially in neutral and alkaline soils. Nevertheless, under saturated conditions in the acid soil, the ferrous form is stabilized and readily taken up by plants (Das, 2014). Iron toxicity and injurious concentrations of organic acids and sulphide may be present to cause toxicity to lowland rice. It occurs especially in soils with high organic matter and impeded drainage (Yoshidha, 1981). Rajendran *et al.,* (1993) observed that, in the anoxic post paddy soils, toxic gases like hydrogen sulphide were produced.

Aluminium toxicity is a major factor restricting crop performance on the acid soils (Barcelo and Porchenrieder, 2002). Shylaraj *et al.,* (2013) has reported aluminium toxicity in *Pokkali* soils. Aluminium interferes with the uptake, transport and use of essential elements such as Ca, Mg, P, K and Fe. It causes the inhibition of root elongation and restricts the absorption of mineral elements and water (Slaski, 1994). This leads to reduced growth and mineral deficiencies in shoots and leaves (Foy, 1988).

Boron and molybdenum are generally fixed in rice soil. Soils high in organic matter also have high boron. Boron deficiency occurs under moisture stress and dry conditions. Molybdenum is adsorbed strongly by iron/ aluminium oxides (Das, 2014). *Pokkali* soil was also affected by toxicity from carbon dioxide, salt injury and poor nutrient status (Shylaraj *et al.,* 2013).

2.13. Other challenges in Pokkali farming

In addition to the constraints in rice nutrition, there are several other factors challenging *Pokkali* farming. Recently, the unsustainable monoculture of prawn usurps the *Pokkali* lands from the rotational rice prawn cultivation. Even though it can provide immediate and higher returns, it is not sustainable in the long run. The State Government forbids monoculture of prawn. But, more area is being gradually brought under fallow-prawn and prawn-prawn systems illegally. The labour intensiveness of rice cultivation in *Pokkali* lands added to the pace of this shift. The shift to monoculture of prawn challenges the conservation of indigenous rice varieties and cultivation practices (Vijesh, 2006).

Pokkali fields confront some serious manmade threats too. These lands are being converted for other purposes like construction of roads, bridges, residential or commercial activities. Other reasons for the lands' decline include invasion of weed, over exploitation for fish and prawn farming and disposal of solid water, industrial and domestic effluents (Jayan and Sathyanathan, 2010)

2.14. Management in acid saline soils

Pokkali rice variety is a wonder crop cultivated in *Pokkali* soil. The organic way of cultivation is followed for *Pokkali* rice. These soils are naturally fertile due to tidal action (Shylaraj *et al.,* 2013). But, the nutrient balance in acid saline *Pokkali* soils is easily upset by improper land use management. Land uses had significant effect on measured physical, chemical and biological attributes except fine sand percentage, base saturation percent, dehydrogenase activity, organic carbon, available Mg and Zn. The study revealed that, highest soil quality index was observed in paddy- shrimp land use system and least in shrimp alone land use pattern (Joseph, 2014).

Chemical fertilizers have no role on the rice yield in these tracts. *Pokkali* soils are more suitable for organic farming. According to the study carried out in RRS, Vyttila, application of chemical fertilizers in the soil caused percentage yield reduction. This led to the withdrawal of fertilizer recommendation provided in the package of practice of Kerala Agricultural University (Annie *et al.,* 2014).

Sufficient native flora is present in *Pokkali* soils to solubilize the insoluble P in soil. Application of K solubilizers is not needed due to the high K content of the soil. Phosphate solubilizing organisms did not survive in the *Pokkali* soils which are acidic. Native flora of *Azospirillum* species and P solubilizers are present in the soil to solubilise the insoluble P in soil. Natural tidal inflow should not be hindered in *Pokkali* tract which in turn ensures the sustainability of the ecosystem (Annie *et al.*, 2014).

The natural tidal ingress of water should not be hindered for sustainable rice production in the *Pokkali* tract. This inflow is necessary for maintaining the fertility of the soil without the application of any external chemical inputs and aids in sustaining the unique *Pokkali* ecosystem (Annie *et al.*, 2014).

MATERIALS AND METHODS

MATERIALS AND METHODS

The present study was carried out to assess the ion interactions in acid saline *Pokkali* soils, thereby identifying the chemical constraints in plant nutrition and emerging deficiency or toxicity of nutrients in *Pokkali* soils. The *Pokkali* fields in Kottuvally pancnhayat of North Paravoor and RRS, Vyttila of Ernakulam district were selected for soil and plant samples' collection. The study was conducted at College of Horticulture, Vellanikkara during 2014 to 2016.

3.1. Details of location

The study was undertaken in selected *Pokkali* padasekharams of Kottuvally panchayath of Ernakulam district and in Rice Research Station, Vyttila. The soil samples were collected during three stages of *Pokkali* cultivation such as preparation of mounds, dismantling of mounds and harvesting. Plant samples were collected during maximum tillering and harvesting stages.

Table 1: Locations of study

Locations	**North latitude**	**East longitude**
Mundothuruth	10° 05' 730"	076° 15' 196"
Kalappumpadi	10° 06' 393"	076° 14' 654"
Muppathezhukettu	10° 06' 142"	076° 14 '680"
Periyali	10° 06' 345"	076° 14' 554"
Diamond	10° 06' 446"	076° 14' 576"
Kaitharam	10° 06' 765"	076° 14' 339"
Padinjare Kaitharam	10° 06' 345"	076° 13' 576"
Thathapilli	10° 06' 826"	076° 14' 002"
RRS, Vyttila	09° 58' 520"	076° 19' 329"

3.2. Collection of soil samples

The first set of soil samples were collected in June 2015, during the time of mound preparation. Soil samples were taken from a depth of 0-15 cm. The next sampling was carried out in July 2015, during mound dismantling stage. At the harvest stage, soil samples were collected in October, 2015. Three samples each were collected from each site and stored in clean polythene bags. Georeferenced representative soil samples were collected with the aid of GPS.

DIFFERENT STAGES OF RICE CULTIVATION

Plate 1: Mound preparation stage

Plate 2: Mound dismantling stage

Plate 3: Harvest stage

3.3. Characterization of soil samples

Collected soils samples were analyzed for physical, chemical, and biological properties. The soil samples collected during the mound preparation were dried and sieved and then analysis was carried out. The wet analysis was followed for soil samples collected during the stages such as dismantling of mounds and harvest.

3.3.1. Expression of results of wet analysis

Gravimetric method was used to find out moisture content in the soil sample. Initial weight of the sample (W_1) was taken. Then it was kept in the hot air oven at 105°C. After drying to a constant weight, the weight (W_2) of sample was again taken. The moisture content was calculated using the formula,

$$\text{Percent moisture} = [(W_1 - W_2)/W_1] \times 100$$

3.3.2. Physical characterization

3.3.2.1. Texture

The texture of the soil was determined by means of mechanical analysis. The International pipette method was followed for the analysis of particle size distribution (Robinson, 1922).

3.3.3. Chemical characterization

3.3.3.1. Soil pH

The soil pH was measured in 1: 2.5 soil water suspension, using a pH meter (Jackson, 1958).

3.3.3.2. Electrical conductivity

Electrical conductivity was determined using a conductivity meter. The supernatant liquid of the 1:2.5 soil water suspension used for measuring soil pH was utilized for estimating electrical conductivity (Jackson, 1958).

3.3.3.3. Redox potential

Redox potential was estimated with the help of multi- parameter PCS Tester TM 35 (Eutech instruments).

3.3.3.4. Cation exchange capacity

The cation exchange capacity was estimated using the method proposed by Hendershot and Duquette (1986). Barium chloride solution (0.1 M) was used to replace the exchangeable cations (Ca, Mg, Na, K, Al, Fe, Mn, Cu and Zn) in the soil. The extract was utilized for cation estimation. Forty ml of 0.1M $BaCl_2$ was added to 4 gram of soil sample. It was shaken for two hours and filtered through Whatman No.42 filter paper. Exchangeable Ca, Mg, Fe, Mn, Cu, Zn and Al were determined using Atomic Absorption Spectrophotometer. Using flame photometer exchangeable Na and K were estimated.

3.3.3.5. Available nitrogen

Available nitrogen in soil was estimated using alkaline potassium permanganate method. Potassium permanganate oxidizes the soil organic matter and hydrolyses the liberated ammonia. It is absorbed in boric acid and titrated against standard acid (Subbiah and Asija, 1956).

3.3.3.6. Available phosphorus

Available phosphorus in the soil samples was extracted using Bray No.1 reagent (Bray and Kurtz, 1945) and determined colorimetrically by the reduced molybdate ascorbic acid blue colour method proposed by Watanabe and Olsen (1965), using a spectrophotometer.

3.3.3.7. Available potassium

Available potassium in the soil samples was extracted using neutral normal ammonium acetate and it was estimated by flame photometry (Jackson, 1958).

3.3.3.8. Available calcium and magnesium

Available calcium and magnesium in the soil samples were extracted using neutral normal ammonium acetate estimated using atomic absorption spectrophotometer.

3.3.3.9. Available sulphur

Available sulphur in the soil samples were estimated using spectrophotometer through turbidimetry, after the extraction using $CaCl_2$ (0.15 per cent) (Tabatabai, 1982).

3.3.3.10. Available micronutrients (Fe, Cu, Mn and Zn)

The method proposed by Sims and Johnson (1991) was followed for estimating available micronutrients in soil samples. Forty ml of 0.1M HCl was added to four gram soil. Then it was shaken for 5 minutes and filtered through Whatmann No.1 filter paper. The micronutrients Fe, Cu, Mn and Zn content in the filtrate were analysed using atomic absorption spectrophotometer.

3.3.3.11. Available boron

Available boron in soil samples was estimated with hot water method (Gupta, 1972), followed by the colorimetric estimation using azomethine – H in spectrophotometer.

3.3.3.12. Available aluminium

Available aluminium was estimated from soil samples using 0.1 M $BaCl_2$ as the extracting agent and analysed using atomic absorption spectrophotometer (Ciesielski *et al.,* 1997).

3.3.3.13. Anions

3.3.3.13.1. Chloride

The chloride content in soil samples was estimated using the method proposed by Reitemeier (1943). Four drops of potassium chromate solution (5%) was added to the sample aliquot and it was titrated with silver nitrate (0.005 N), to the first permanent reddish brown colour. Chloride content was estimated using amount of silver nitrate used for titration.

3.3.3.13.2. Carbonate and bicarbonate

Carbonate and bicarbonate ions in the soil samples were determined by titrating it against standard sulphuric acid using phenolphthalein and methyl orange as indicators (Reitemeier, 1943). One drop of phenolphthalein was added to the sample aliquot to check the presence of carbonate. Two drops of methyl orange was added and titrated using sulphuric acid (0.01N) to estimate bicarbonate content.

3.3.3.13.3. Phosphate

The air dried soil sample (1g) was taken in a 15 ml centrifuge tube and 7 ml of extraction solution (Bray no.1) was added. It was shaken for one minute on a mechanical shaker, after which the solution was filtered. The soil extract (5 ml) was transferred to a 25 ml volumetric flask and 10ml of distilled water was added. Then the phosphate content was determined using a spectrophotometer by ascorbic acid method at a wavelength of 882 nm (Doreen *et al.*, 2014).

3.3.3.13.4. Sulphate

Sulphate content was determined using the method proposed by Bower and Huss (1948). A 10 ml volume of 1:1 soil extract was diluted to 20 ml. Then 1ml of calcium chloride and 20 ml of acetone was added to the sample and centrifuged for 3 minutes. The supernatant liquid was decanted and again 10 ml of acetone was added and centrifuged. A volume of 40 ml distilled water was added and then it was shaken to dissolve the precipitate completely. Electrical conductivity of the solution was measured. The concentration of SO_4 was determined in reference to a graph showing the relationship between the concentration and electrical conductivity of $CaSO_4$ solution. The graph is constructed by means of international critical tables.

3.3.3.14. Sodium adsorption ratio

Sodium adsorption ratio (SAR) was calculated from the formula

SAR= Na^+/ (Ca+ Mg/2)½ where the concentrations Na^+, Ca^{2+} and Mg^{2+} were measured in mmol L^{-1} (U. S. Salinity Laboratory Staff, 1954).

3.3.3.15. Exchangeable sodium percentage

Exchangeable Sodium Percentage (ESP) is the percentage of the total cation exchange capacity occupied by sodium ions (U. S. Salinity Laboratory Staff, 1954).

ESP= (Na^+/ CEC) ×100

3.3.3.16. Per cent cation saturation

The percentage of cation saturation was calculated using the formula,

Per cent cation saturation = (Cation concentration/ CEC) x 100

Where cation concentration is given in milli equivalents of basic cation in 100 g soil and CEC, the cation exchange capacity is expressed in cmol (p^+) kg^{-1} (U. S. Salinity Laboratory Staff, 1954).

3.3.4. Biological characterization

3.3.4.1. Organic carbon

Organic carbon of the soil was estimated by wet digestion method (Walkley and Black, 1934).

3.3.4.2. Dehydrogenase activity

The method proposed by Klien *et al.,* (1971) was used to estimate dehydrogenase activity. Dehydrogenase assays based on the reduction of 2, 3, 5-triphenyl tetrazolium chloride (TTC) to the creaming red-colored formazan (TPF) was used to determine microbial activity in soil. It was estimated colorimetrically using spectrophotometer.

3.3.4.3. Microbial biomass carbon

The chloroform fumigation and extraction method was used to estimate microbial biomass carbon in soil. A total of five sets of 10 g soil samples were taken. One set was kept in an oven at 105° C and the moisture was determined using gravimetric method. Vacuum was created inside desiccator using a vacuum pump. Two sets of soil samples and a beaker with ethanol free chloroform were kept in vacuum desiccator for 24 hours. Then the extract was taken using 0.5 M potassium sulphate from the fumigated and non- fumigated samples to determine organic carbon. Potassium dichromate (0.2 M), concentrated sulphuric acid and orthophosphoric acid were added to 10 ml extract. It was kept on a hot plate at 100°C for half an hour under refluxing condition. Then, 250 mL water was added. It was titrated against standard ferrous ammonium sulphate (Jenkinson and Powlson, 1976).

3.4. Collection and analysis of plant samples

Plant samples were collected during stages such as panicle initiation and harvest and dry weight was recorded. Plant samples were analysed for nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, copper, manganese, iron, zinc, boron and aluminium, following standard analytical procedures (Chesnin and Yein, 1951; Piper, 1966; Gupta, 1975).

DIFFERENT STAGES OF RICE GROWTH

Plate 4: Maximum tillering stage of rice

Plate 5: Harvest stage of rice

Table 2: Analytical methods for plant samples

Sl. No.	Element	Method
1	Nitrogen	Microkjeldhal method (Piper, 1966)
2	Phosphorus	Digestion of plant samples using nitric acid followed by colorimetric estimation in spectrophotometer by Vanadomolybdate yellow color method (Piper, 1966)
3	Potassium and Sodium	Digestion of plant samples using concentrated nitric acid followed by filtration and determined by flame photometer (Piper, 1966)
4	Calcium and Magnesium	Determination using atomic absorption spectrophotometer (Piper, 1966)
5	Sulphur	Turbidimetric method using spectrophotometer (Chesnin and Yein, 1951)
6	Copper , Zinc, Iron and Mangnese	Nitric acid extract method using atomic absorption spectrophotometer (Piper, 1966)
7	Boron	Dry ashing of plant tissue followed by determination using Spectrophotometer (Gupta, 1975)
8	Aluminium	Digestion of plant sample using nitric acid followed by filtration and analysed using ICP-OES (Model: Optima 8000) (Piper, 1966)

3.5. Yield and dry matter content

The yield of rice from each location was recorded. The dry matter content was also recorded.

3.6. Statistical analysis

The statistical analysis was performed with statistical softwares such as opstat (operational statistics) and SPSS (Statistical Program for the Social Sciences). Statistical tools such as correlation, t test, canonical analysis and regression were used to analyse the results.

RESULTS

RESULTS

The present study comprised of the analysis of the various physical, chemical and biological parameters of *Pokkali* soil and its effect on plant nutrition. The data generated were subjected to statistical analysis and the experimental results obtained are presented below.

4.1. SOIL ANALYSIS

The soil samples were characterized for physical (soil texture), electrochemical (pH, EC and redox potential), chemical (CEC, exchangeable cations, ESP, SAR, cation saturation, available N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, Al and Na) and biological attributes (microbial biomass carbon, dehydrogenase activity and organic carbon).

4.1. 1. Physical attributes

4.1. 1.1. Soil texture

The soil texture observed in *Pokkali* fields were sandy loam, sandy clay loam and clayey. Sandy loam texture was found in Mundothuruth and Diamond padashekarams. Sandy clay loam was observed in four padashekarams and those include Kalappumpadi, Muppathezhukettu, Periyali and Padinjare Kaitharam. Kaitharam, Thathapilli and RRS, Vyttila was found to have clayey texture. Clay content was higher in the soils of Thathapilli, Kaitharam and RRS, Vyttila. The lowest clay content was seen in Mundothuruth. The highest silt perentage was recorded in Kalappumpadi and least in RRS, Vyttila. The coarse sand and fine sand fractions were more in Diamond and Padinjare Kaitharam. The coarse sand fraction was recorded as lowest in Thathapilli. The fine sand proportion was least in Periyali (Table 3).

Table 3: Soil texture of nine locations

SITE	Sample No.	Clay	Silt	Coarse sand	Fine sand	Texture
		Per cent				
Mundothuruth	1	15.00	14.20	33.5	37.20	**Sandy loam**
Kalappumpadi	2	20.41	19.82	10.01	49.76	**Sandy clay loam**
Muppethezhukettu	3	50.73	12.11	0.37	37.01	**Sandy clay loam**
Periyali	4	46.88	14.80	27.61	10.71	**Sand clay loam**
Diamond	5	19.60	9.73	53.25	19.44	**Sandy loam**
Kaitharam	6	60.71	16.82	4.05	18.51	**Clayey**
Padinjare Kaitharam	7	31.90	10.17	2.94	54.99	**Sandy clay loam**
Thathapilli	8	60.87	17.01	0.74	21.38	**Clayey**
RRS, Vyttila	9	59.74	6.04	6.09	28.13	**Clayey**

4.1. 2. Electrochemical properties

The soil reaction of samples in different locations during three stages of cultivation has been given in Table 4. The soil pH during 3 stages ranged from 3.12 (mound preparation stage) to 5.64 (mound dismantling stage), which comes under acidic range. The pH of the soil ranged from 3.39 (Thathapilli) to 4.75 (Muppathezhukettu) in 9 different locations. The pH of soils was significantly different in the 9 locations as well as during the 3 stages of cultivation.

The electrical conductivity (EC) of samples in different locations varied significantly during 3 different stages of cultivation. The EC during 3 stages ranged from 2.21 (mound dismantling) to 5.61 dS m^{-1} (mound preparation). Among the 9 locations, there was a significant variation in electrical conductivity of the samples. The highest EC was observed in Diamond (5.0 dS m^{-1}) (Table 5).

The redox potential of samples in different locations during three stages of cultivation has been presented in Table 6. The oxidation- reduction potential recorded in mound preparation, mound dismantling and harvest stages were found to be 181.48 mV, 219.34 mV and 358.51 mV respectively, indicating the effect on submergence on *Pokkali* soils. Redox potential showed significant difference between these three stages.

4.1.3. Chemical attributes

4.1. 3.1. Available nitrogen

The available N content of soil samples in different locations differed significantly during the three stages of cultivation Available N varied from 78.52 (harvest) to 174.22 kg ha^{-1} (mound preparation). No significant variation was observed in available N content among different locations (Table 7).

Table 4: Soil pH in different locations during the three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	3.08	5.59	3.59	4.09
Kalappumpadi	2.84	6.09	3.72	4.22
Muppathezhukettu	3.29	6.70	4.19	4.75
Periyali	3.28	5.94	3.65	4.29
Diamond	2.93	5.21	3.45	3.86
Kaitharam	3.12	4.62	3.75	3.83
Padinjare Kaitharam	2.84	6.02	3.24	4.03
Thathapilli	2.84	4.63	2.72	3.39
RRS, Vyttila	3.90	5.90	4.25	4.68
Mean	3.12	5.64	3.62	–
CD (0.05)	Stages of growth	0.07		
	Location	0.13		
	Interaction	0.23		

Table 5: Electrical conductivity (dS m^{-1}) of the soil samples from different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	5.70	1.90	2.03	3.21
Kalappumpadi	5.53	2.26	2.63	3.47
Muppathezhukettu	5.13	1.76	2.10	3.00
Periyali	5.23	2.63	2.33	3.40
Diamond	8.06	3.36	3.56	5.00
Kaitharam	5.63	2.50	2.23	3.45
Padinjare Kaitharam	6.33	2.50	2.90	3.91
Thathapilli	5.06	2.30	2.73	3.36
RRS, Vyttila	3.80	0.66	0.84	1.77
Mean	5.61	2.21	2.37	
CD (0.05)	Stages of growth	0.52		
	Location	0.96		
	Interaction	NS		

Table 6: Redox potential (mV) of soil samples from different locations during the three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	173.00	209.66	412.33	265.00
Kalappumpadi	178.33	222.33	344.66	248.44
Muppathezhukettu	190.66	215.33	259.00	221.66
Periyali	187.33	214.33	271.66	224.44
Diamond	190.66	215.66	278.00	228.11
Kaitharam	170.00	204.66	432.00	268.88
Padinjare Kaitharam	189.00	239.33	407.33	278.55
Thathapilli	169.33	242.33	407.33	273.00
RRS, Vyttila	185.00	210.43	414.33	269.92
Mean	181.48	219.34	358.51	–
CD (0.05)	Stages of growth	7.53		
	Location	13.05		
	Interaction	22.61		

Table 7: Available nitrogen (kg ha^{-1} soil) content of soil samples of different locations during the three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	179.79	223.79	64.81	156.13
Kalappumpadi	181.88	223.70	56.44	154.01
Muppathezhukettu	160.97	104.53	73.17	112.89
Periyali	160.98	125.44	58.53	114.98
Diamond	190.25	104.53	52.26	115.68
Kaitharam	142.16	104.53	39.72	95.47
Padinjare Kaitharam	173.52	209.06	64.81	149.13
Thathapilli	163.07	146.36	140.17	149.87
RRS, Vyttila	215.33	209.06	156.80	193.73
Mean	174.22	161.22	78.52	–
CD (0.05)	Stages of growth	35.42		
	Location	NS		
	Interaction	NS		

4.1.3.2. Available phosphorus

The available P content showed significant difference during three stages among different locations. Harvest stage recorded highest value of available P (47.04 kg ha^{-1}). The least content was observed at mound dismantling stage (31.12 kg ha^{-1}). Among the nine locations, RRS, Vyttila recorded the highest P content. During mound preparation stage, highest content was observed in Mundothuruth padashekaram (63.21 kg ha^{-1}) and least in Thathapilli (14.63 kg ha^{-1}). The highest P content (70.38 kg ha^{-1}) was recorded in RRS and least in Periyali, during mound dismantling stage. The highest value of P (119.26 kg ha^{-1}) was registered at the time of harvest, in RRS, Vyttila (Table 8).

4.1.3.4. Available potassium

The available K content of samples during three stages of cultivation varied significantly. The highest K content was seen at mound dismantling stage (1392.28 kg ha^{-1}). The Kcontent of mound preparation and harvest stages were 75.911 kg ha^{-1} and 1286.51 kg ha^{-1} respectively. The available K content did not differ significantly among locations (Table 9).

4.1. 3.5. Available calcium

The available Ca content of soil samples showed significant difference among mound preparation, mound dismantling and harvest stages. The highest Ca content was observed during mound dismantling stage (8.82 meq $100g^{-1}$). The least content (5.58 meq $100g^{-1}$) was seen at mound preparation stage of cultivation. Among the nine locations, Kaitharam recorded the highest available Ca content (Table 10).

Table 8: Available phosphorus (kg ha^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	63.21	17.42	31.45	37.36
Kalappumpadi	52.96	30.71	30.96	38.21
Muppathezhukettu	48.38	24.11	46.09	39.53
Periyali	48.88	16.49	27.47	30.95
Diamond	54.85	27.37	64.90	49.04
Kaitharam	24.19	26.41	53.36	34.65
Padinjare Kaitharam	41.41	37.69	30.16	36.42
Thathapilli	14.63	29.52	19.71	21.29
RRS, Vyttila	38.92	70.38	119.26	76.19
Mean	43.05	31.12	47.04	–
CD (0.05)	Stages of growth	11.08		
	Location	19.19		
	Interaction	33.25		

Table 9: Available potassium (kg ha^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	29.86	874.32	599.63	501.27
Kalappumpadi	48.16	1210.44	1616.92	958.50
Muppathezhukettu	45.92	1565.56	1406.50	1005.99
Periyali	94.08	2,011.44	1389.11	1164.88
Diamond	53.01	1,710.33	1288.02	1017.12
Kaitharam	77.65	1634.68	2334.13	1348.82
Padinjare Kaitharam	42.56	1667.31	1108.38	939.41
Thathapilli	4.85	1001.44	779.282	595.19
RRS, Vyttila	287.09	855.01	1056.65	732.91
Mean	75.91	1392.28	1286.51	–
CD (0.05)	Stages of growth	306.43		
	Location	NS		
	Interaction	NS		

Table 10: Available calcium (meq 100g $^{-1}$ soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	6.01	4.61	3.99	4.87
Kalappumpadi	6.10	6.53	5.62	6.08
Muppathezhukettu	6.38	8.63	6.88	7.29
Periyali	7.20	11.84	8.71	9.25
Diamond	7.78	9.33	8.21	8.44
Kaitharam	8.26	10.29	11.44	10.00
Padinjare Kaitharam	2.87	9.49	10.15	7.51
Thathapilli	3.55	14.16	8.26	8.66
RRS, Vyttila	2.11	4.52	3.05	3.23
Mean	5.58	8.82	7.37	–
CD (0.05)	Stages of growth	1.53		
	Location	NS		
	Interaction	NS		

4.1. 3.6. Available magnesium

The available Mgcontent of soil samples during three stages of cultivation showed significant difference. The highest concentration was registered in mound preparation stage (1.11 meq 100g $^{-1}$ soil). Mound dismantling stage (0.40 meq 100g $^{-1}$ soil) marked the lowest Mg content among three stages of cultivation. The available Mg content did not vary significantly among the locations (Table 11).

4.1. 3.7. Available sulphur

The available Scontent of soil showed significant difference during 3 stages of cultivation. The S content ranged from 83.49 mg kg^{-1} to 310.80 mg kg^{-1}. The highest value was recorded in mound dismantling stage. The nine locations varied significantly in the available S content of soil. The highest and least content were observed in Thathapilli and RRS, Vyttila respectively (Table 12).

4.1. 3.8. Available iron

The available Fe content was significantly different between three stages of cultivation. The content recorded was 299.14 mg kg^{-1}, 852.95 mg kg^{-1} and 1371.72 mg kg^{-1} during mound preparation, mound dismantling and harvest stages respectively. The interaction effect was not significant. The available Fe content of soil samples was significantly different among the nine locations (Table 13).

4.1. 3.9. Available manganese

The available Mn content of soil samples in nine locations during three stages of cultivation are shown in Table 14. The stages of cultivation did not show any significant variation. But the locations varied significantly in Mn content. Thathapilli recorded the highest available Mn content (54.23 mg kg^{-1}) in soil. The least content (0.931 mg kg^{-1}) was observed in RRS, Vyttila.

Table 11: Available magnesium (meq 100g $^{-1}$ soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	1.21	0.27	0.36	0.62
Kalappumpadi	0.77	0.34	0.43	0.52
Muppathezhukettu	1.25	0.40	0.53	0.73
Periyali	1.44	0.45	0.62	0.83
Diamond	1.84	0.41	0.55	0.93
Kaitharam	1.25	0.41	0.79	0.82
Padinjare Kaitharam	0.78	0.43	0.66	0.62
Thathapilli	0.76	0.46	0.96	0.73
RRS, Vyttila	0.73	0.38	0.52	0.54
Mean	1.11	0.40	0.60	–
CD (0.05)	Stages of growth	2.55		
	Location	NS		
	Interaction	NS		

Table 12: Available sulphur (mg kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	80.07	51.41	196.08	109.19
Kalappumpadi	94.27	128.60	274.82	165.90
Muppathezhukettu	82.03	101.52	259.21	147.59
Periyali	82.13	198.16	328.0	202.77
Diamond	94.31	202.00	401.93	232.75
Kaitharam	94.40	188.93	365.49	216.27
Padinjare Kaitharam	103.13	223.43	303.14	209.90
Thathapilli	94.31	231.63	556.86	294.27
RRS, Vyttila	26.75	47.47	111.68	61.97
Mean	83.49	152.57	310.80	–
CD(0.05)	Stages of growth	54.76		
	Location	94.85		
	Interaction	NS		

Table 13: Available iron (mg kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	**Stages of cultivation**			**Mean**
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	304.16	450.19	584.71	446.36
Kalappumpadi	286.00	517.57	763.12	522.23
Muppathezhukettu	305.16	666.28	959.61	643.68
Periyali	301.33	848.90	1061.83	737.35
Diamond	300.86	643.23	3904.33	1616.14
Kaitharam	302.33	676.02	1379.68	786.012
Padinjare Kaitharam	296.73	697.88	954.07	649.56
Thathapilli	308.96	1802.39	1855.63	1322.33
RRS, Vyttila	286.76	1374.12	882.46	847.78
Mean	299.14	852.95	1371.72	–
CD (0.05)	Stages of growth	590.04		
	Location	NS		
	Interaction	NS		

Table 14: Available manganese (mg kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	15.38	8.19	7.21	10.26
Kalappumpadi	18.47	4.97	8.64	10.69
Muppathezhukettu	11.00	9.11	8.22	9.44
Periyali	10.49	14.17	8.28	10.98
Diamond	5.99	11.11	9.05	8.72
Kaitharam	13.43	13.05	18.52	15.00
Padinjare Kaitharam	12.93	12.58	8.63	11.38
Thathapilli	27.62	32.23	102.84	54.23
RRS, Vyttila	1.94	0.84	BDL	0.93
Mean	13.03	11.80	19.04	
CD(0.05)	Stages of growth	NS		
	Location	13.06		
	Interaction	22.62		

BDL: Below detectable level

4.1. 3.10. Available zinc

The available Zn content of samples registered no significant variation between the stages of cultivation. But, a significant variation in Zn content was observed among nine locations. The Zn content ranged between 8.68 mg kg^{-1} to 50.77 mg kg^{-1} among nine locations. Highest content was observed in Thathapilli padashekaram. Interaction effect was also not significantly different (Table 15).

4.1. 3.11. Available copper

The available Cu content of soil samples collected from nine different locations did not differ significantly during the three stages of cultivation. The nine locations were found to be significantly different between each other with respect to available Cu content. The available Cu content varied from 1.14 to 2.35 mg kg^{-1} soil among nine locations. The highest and least content were observed in Kalappumpadi and Thathapilli padashekarams (Table 16).

4.1. 3.12. Available boron

The available B content differed significantly among the three stages of cultivation as well as among the nine locations. Available B varied between 0.001 to 1.59 mg kg^{-1} soil during the three stages. The B content followed an increasing trend from mound preparation to harvest stage. The B content showed a range of 0.29-1.90 mg kg^{-1} soil among the nine locations. The highest content was observed in Thathapilli padashekaram (Table 17).

4.1.3.13. Available aluminium

The available Al content of soil of nine locations during three different stages of cultivation has been presented in Table18. Significant difference was seen between Al content during three stages. The highest content was observed during harvest (1037.14 mg kg^{-1} soil). Mound preparation stage recorded the least

Table 15: Available zinc (mg kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	45.09	32.54	19.19	32.28
Kalappumpadi	26.91	19.66	21.68	22.75
Muppathezhukettu	32.41	30.76	50.10	37.76
Periyali	31.84	33.13	20.11	28.36
Diamond	28.08	15.07	20.24	21.13
Kaitharam	19.04	16.03	17.16	17.41
Padinjare Kaitharam	18.34	11.74	19.63	16.57
Thathapilli	29.78	55.91	66.63	50.77
RRS, Vyttila	6.99	5.36	13.68	8.68
Mean	26.50	24.47	27.60	–
CD (0.05)	Stages of growth	NS		
	Location	13.69		
	Interaction	NS		

Table 16: Available copper (mg kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	1.92	0.98	0.64	1.18
Kalappumpadi	1.19	1.53	0.70	1.14
Muppathezhukettu	1.28	1.48	1.21	1.32
Periyali	1.42	1.98	0.62	1.34
Diamond	1.50	1.58	1.00	1.36
Kaitharam	1.38	1.60	0.86	1.28
Padinjare Kaitharam	1.37	1.52	1.00	1.30
Thathapilli	1.70	1.72	3.64	2.35
RRS, Vyttila	1.02	2.39	2.24	1.88
Mean	1.42	1.64	1.32	–
CD(0.05)	Stages of growth	NS		
	Location	0.70		
	Interaction	1.21		

Table 17: Available boron (mg kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	0.004	0.17	0.78	0.32
Kalappumpadi	BDL	0.01	0.85	0.29
Muppathezhukettu	BDL	0.04	2.18	0.74
Periyali	BDL	0.24	2.92	1.05
Diamond	BDL	BDL	1.71	0.57
Kaitharam	BDL	0.80	1.65	0.82
Padinjare Kaitharam	BDL	1.10	1.44	0.84
Thathapilli	0.006	3.86	1.83	1.90
RRS, Vyttila	BDL	0.21	0.97	0.39
Mean	0.001	0.71	1.59	–
CD(0.05)	Stages of growth	0.46		
	Location	0.81		
	Interaction	1.40		

BDL: Below detectable level

Table18: Available aluminium (mg kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	**Stages of cultivation**			**Mean**
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	5.37	568.94	496.76	357.02
Kalappumpadi	4.83	732.8	687.63	475.09
Muppathezhukettu	6.81	607.21	755.76	456.59
Periyali	5.93	1138.60	943.16	695.90
Diamond	4.73	891.84	1028.85	641.80
Kaitharam	4.24	1041.76	1202.64	749.54
Padinjare Kaitharam	4.83	1146.46	1137.86	763.05
Thathapilli	4.80	1941.27	2317.82	1421.30
RRS, Vyttila	5.03	674.44	763.753	481.07
Mean	5.18	971.48	1037.14	–
CD (0.05)	Stages of growth	245.96		
	Location	426.02		
	Interaction	NS		

content. Among the nine locations, Thathapilli (1421.30 mg kg^{-1} soil) and Mundothuruth (357.02 mg kg^{-1} soil) recorded the highest and lowest Al content respectively among the nine locations.

4.1.3.14. Available sodium

The available Na content of soil samples showed significant variation among nine locations. It varied between 12.03 to 26.69 meq 100 g^{-1} soil. The highest and least content was observed at harvest and mound preparation stages respectively. Among the locations, the highest content was observed in Diamond padashekaram (Table 19).

4.1.3.15. Anions

The chloride content of soil samples varied significantly among nine locations during three different stages of cultivation. The content ranged between 86.02 and 265.53 mg kg^{-1} soil. The highest content was seen during mound preparation stage. Among the nine locations, RRS (364.7 mg kg^{-1} soil) recorded the highest chloride content (Table 20).

The bicarbonate content did not show significant difference during different stages of cultivation. The content registered highest during mound preparation stage (41.11 mg kg^{-1} soil). The least content was observed at the time of mound dismantling stage. No significant difference was observed among nine locations (Table 21).

The sulphate content of soil samples in nine locations during three stages of cultivation is presented in Table 22. Significant variation was observed in sulphate content, considering mound preparation, mound dismantling and harvest stages. The highest content was registered in mound dismantling stage (1997.36 mg kg^{-1} soil)

Table 19: Available sodium (meq 100 g^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	15.99	8.46	8.46	12.03
Kalappumpadi	15.91	15.11	15.11	16.00
Muppathezhukettu	18.41	21.20	21.20	21.49
Periyali	20.73	20.81	20.81	24.80
Diamond	31.03	20.19	20.19	27.59
Kaitharam	22.10	15.19	15.19	26.69
Padinjare Kaitharam	24.57	17.47	17.47	23.73
Thathapilli	12.74	12.01	12.01	17.94
RRS, Vyttila	21.18	9.61	9.61	15.21
Mean	20.30	15.56	15.56	_
CD (0.05)	Stages of growth	5.81		
	Location	10.06		
	Interaction	NS		

Table 20: Chloride (mg kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	99.29	43.73	96.92	79.98
Kalappumpadi	BDL	42.55	235.18	92.57
Muppathezhukettu	241.12	36.64	167.84	148.53
Periyali	563.81	56.73	333.32	317.95
Diamond	309.68	148.93	453.88	304.16
Kaitharam	212.76	60.28	243.49	172.17
Padinjare Kaitharam	BDL	78.012	250.58	109.53
Thathapilli	BDL	260.04	232.85	164.29
RRS, Vyttila	963.16	47.28	83.92	364.78
Mean	265.53	86.02	233.11	–
CD (0.05)	Stages of growth	96.18		
	Location	166.60		
	Interaction	288.56		

Table 21: Bicarbonate (mg kg^{-1}) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	24.4	BDL	BDL	8.13
Kalappumpadi	20.33	BDL	65.06	28.46
Muppathezhukettu	28.46	12.2	40.66	27.11
Periyali	32.53	BDL	24.4	18.97
Diamond	24.4	BDL	BDL	8.13
Kaitharam	69.13	BDL	52.86	40.66
Padinjare Kaitharam	73.2	BDL	56.93	43.37
Thathapilli	52.86	BDL	8.13	20.33
RRS, Vyttila	44.73	24.4	116.39	61.84
Mean	41.11	4.06	40.49	–
CD (0.05)	Stages of growth	19.84		
	Location	NS		
	Interaction	NS		

BDL: Below detectable level

Table 22: Sulphate (mg kg^{-1}) of content soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	1042.25	1807.15	1848.75	1566.05
Kalappumpadi	2148.54	1861.59	1864.81	1958.31
Muppathezhukettu	1793.09	1874.34	1852.03	1839.82
Periyali	1951.62	2428.30	2092.07	2157.33
Diamond	1503.32	3334.52	1847.20	2228.35
Kaitharam	1592.99	1877.55	1725.54	1732.03
Padinjare Kaitharam	1809.13	1876.05	1658.26	1781.15
Thathapilli	1381.66	1410.22	1504.78	1432.22
RRS, Vyttila	1468.10	1506.54	589.71	1188.12
Mean	1632.30	1997.36	1664.79	
CD (0.05)	Stages of growth	258.50		
	Location	447.74		
	Interaction	775.50		

Table 23: Phosphate (mg kg^{-1}) content of soil samples of different locations collected during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	63.25	16.86	25.30	35.14
Kalappumpadi	75.90	16.86	33.73	42.16
Muppathezhukettu	25.30	19.67	14.05	19.67
Periyali	18.97	16.86	20.38	18.74
Diamond	14.05	8.43	15.46	12.65
Kaitharam	10.54	21.08	17.57	16.39
Padinjare Kaitharam	1.40	10.54	9.13	7.02
Thathapilli	17.57	18.27	23.89	19.91
RRS, Vyttila	31.07	24.59	16.86	24.17
Mean	28.67	17.02	19.60	–
CD (0.05)	Stages of growth	8.89		
	Location	15.40		
	Interaction	26.68		

and least in harvest stage (1632.30 mg kg^{-1} soil). The locations differed significantly in sulphate content. The least content was observed in RRS and highest in Diamond.

The phosphate content varied significantly between different locations during three different stages of cultivation. The highest phosphate content was found in mound dismantling stage (38.73 mg kg^{-1} soil). During mound preparation stage, phosphate content was present below detectable level in Muppathezhukettu and Diamond. Mundothuruth and Periyali marked the higher status of phosphate during mound dismantling stage (Table 23).

4.1. 3.16. Cation exchange capacity and exchangeable cations

The cation exchange capacity (CEC) of soil in nine locations during three stages of cultivation is given in Table 24. The CEC varied significantly between three stages of cultivation and nine locations. Among the three stages, mound preparation stage has the lowest CEC and highest CEC was recorded during harvest stage. Among locations, Diamond registered highest CEC.

Exchangeable Ca and Na were significantly different among nine locations. But exchangeable Mg, K, Al, Fe and Mn were found ignificantly different among three stages of cultivation as well as nine locations. There was no significant variation in the concentration of exchangeable Cu and Zn, considering both the stages of cultivation and locations (Table 25 to 33). For the exchangeable cations namely, Mg, Fe and Mn, highest and least contents were recorded during mound preparation and harvest stages respectively. The exchangeable Ca and Mg content recorded highest in Diamond padashekaram (Table 25 and 26). The exchangeable Al was highest in Thathapilli (Table 29). Soil samples collected during harvest stage had the highest exchangeable K (0.655 cmol (P^{+}) kg^{-1}soil).

Table 24: Cation exchange capacity (cmol (p^+) $^{-1}$ kg soil) of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	7.99	12.57	11.53	10.70
Kalappumpadi	7.73	16.86	19.30	14.63
Muppathezhukettu	7.26	16.59	23.84	15.90
Periyali	9.13	21.29	30.01	20.14
Diamond	11.23	22.13	30.76	21.37
Kaitharam	8.91	16.51	35.21	20.21
Padinjare Kaitharam	11.04	20.65	28.57	20.09
Thathapilli	9.42	21.81	29.20	20.14
RRS, Vyttila	11.89	11.34	14.34	12.52
Mean	9.40	17.75	24.75	
CD (0.05)	Stages of growth	4.32		
	Location	7.49		
	Interaction	NS		

Table 25: Exchangeable calcium (cmol (p^+) kg^{-1}soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	2.13	2.09	1.28	1.83
Kalappumpadi	1.99	1.92	2.03	1.98
Muppathezhukettu	2.08	2.14	1.93	2.05
Periyali	2.34	1.87	2.01	2.07
Diamond	3.33	2.34	2.31	2.66
Kaitharam	2.34	1.98	2.33	2.21
Padinjare Kaitharam	1.88	1.42	1.99	1.76
Thathapilli	2.32	2.07	2.35	2.25
RRS, Vyttila	0.87	1.20	1.32	1.13
Mean	2.14	1.89	1.95	–
CD (0.05)	Stages of growth	NS		
	Location	0.49		
	Interaction	NS		

Table 26: Exchangeable magnesium (cmol (p^+) kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	0.38	0.31	0.29	0.33
Kalappumpadi	0.37	0.31	0.30	0.33
Muppathezhukettu	0.37	0.31	0.30	0.33
Periyali	0.37	0.32	0.31	0.34
Diamond	0.39	0.32	0.32	0.34
Kaitharam	0.37	0.32	0.31	0.34
Padinjare Kaitharam	0.37	0.32	0.32	0.33
Thathapilli	0.36	0.31	0.31	0.33
RRS, Vyttila	0.35	0.28	0.28	0.31
Mean	0.37	0.31	0.30	
CD (0.05)	Stages of growth	0.004		
	Location	0.006		
	Interaction	NS		

Table 27: Exchangeable sodium (cmol (p^+) kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	4.23	6.16	6.82	5.74
Kalappumpadi	4.28	10.33	13.52	9.37
Muppathezhukettu	4.39	10.65	18.21	11.08
Periyali	5.04	14.82	24.13	14.66
Diamond	6.44	15.01	23.84	15.1
Kaitharam	5.37	9.018	28.67	14.35
Padinjare Kaitharam	7.66	13.82	22.24	14.57
Thathapilli	5.65	10.78	21.62	12.68
RRS, Vyttila	9.66	6.53	9.61	8.60
Mean	5.86	10.79	18.74	–
CD (0.05)	Stages of growth	4.22		
	Location	NS		
	Interaction	NS		

Table 28: Exchangeable potassium (cmol (p^+) kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	0.31	0.54	0.71	0.52
Kalappumpadi	0.13	0.54	0.80	0.49
Muppathezhukettu	0.15	0.72	0.94	0.60
Periyali	0.20	0.53	0.93	0.55
Diamond	0.12	0.58	0.93	0.54
Kaitharam	0.17	0.54	0.94	0.55
Padinjare Kaitharam	0.12	0.53	0.96	0.54
Thathapilli	0.03	0.52	0.63	0.39
RRS, Vyttila	0.91	0.72	0.77	0.80
Mean	0.24	0.58	0.84	–
CD (0.05)	Stages of growth	0.05		
	Location	0.09		
	Interaction	0.16		

Table 29: Exchangeable aluminium (cmol (p^+) kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	0.06	3.28	2.29	1.87
Kalappumpadi	0.05	3.45	2.49	2.00
Muppathezhukettu	0.07	2.43	2.28	1.59
Periyali	0.06	3.43	2.49	1.99
Diamond	0.05	3.56	3.14	2.25
Kaitharam	0.04	4.22	2.63	2.30
Padinjare Kaitharam	0.05	4.30	2.85	2.40
Thathapilli	0.05	7.03	3.90	3.66
RRS, Vyttila	0.05	2.64	2.31	1.67
Mean	0.05	3.82	2.71	–
CD (0.05)	Stages of growth	0.28		
	Location	0.49		
	Interaction	0.85		

Table 30: Exchangeable iron (cmol (p$^+$) kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	0.76	0.12	0.08	0.32
Kalappumpadi	0.81	0.24	0.11	0.39
Muppathezhukettu	0.61	0.12	0.14	0.29
Periyali	0.65	0.26	0.10	0.34
Diamond	0.83	0.25	0.18	0.42
Kaitharam	0.73	0.38	0.19	0.43
Padinjare Kaitharam	0.88	0.22	0.18	0.43
Thathapilli	0.87	0.32	0.34	0.51
RRS, Vyttila	0.02	BDL	0.04	0.02
Mean	0.68	0.21	0.15	–
CD (0.05)	Stages of growth	0.07		
	Location	0.12		
	Interaction	0.21		

Table 31: Exchangeable manganese (cmol (p^+) kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	0.076	0.018	0.007	0.034
Kalappumpadi	0.071	0.016	0.011	0.032
Muppathezhukettu	0.051	0.013	0.009	0.024
Periyali	0.042	0.019	0.006	0.022
Diamond	0.057	0.022	0.013	0.031
Kaitharam	0.048	0.029	0.013	0.03
Padinjare Kaitharam	0.045	0.026	0.01	0.027
Thathapilli	0.345	0.058	0.033	0.145
RRS, Vyttila	0.01	0.003	0.002	0.005
Mean	0.083	0.023	0.012	–
CD (0.05)	Stages of growth	0.041		
	Location	0.071		
	Interaction	NS		

Table 32: Exchangeable copper (cmol (p^+) kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	0.001	0.016	0.008	0.008
Kalappumpadi	BDL	0.003	0.005	0.003
Muppathezhukettu	0.001	0.004	0.001	0.002
Periyali	0.001	0.002	0.015	0.006
Diamond	0.001	0.001	0.004	0.002
Kaitharam	0.002	0.001	0.003	0.002
Padinjare Kaitharam	0.002	BDL	BDL	0.001
Thathapilli	0.002	0.01	BDL	0.004
RRS, Vyttila	0.001	0.002	BDL	0.001
Mean	0.001	0.004	0.004	–
CD (0.05)	Stages of growth	NS		
	Location	NS		
	Interaction	NS		

BDL: Below detectable level

Table 33: Exchangeable zinc (cmol (p^+) kg^{-1} soil) content of soil samples of different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	0.22	0.024	0.024	0.089
Kalappumpadi	1.305	0.018	0.012	0.445
Muppathezhukettu	0.001	0.143	0.013	0.053
Periyali	0.001	0.015	0.006	0.008
Diamond	0.003	0.013	0.011	0.009
Kaitharam	0.001	0.011	0.007	0.006
Padinjare Kaitharam	0.004	0.014	0.008	0.009
Thathapilli	0.001	0.067	0.02	0.029
RRS, Vyttila	0.001	0.006	0.005	0.004
Mean	0.171	0.035	0.012	
CD (0.05)	Stages of growth	NS		
	Location	NS		
	Interaction	NS		

4.1. 3.17. Exchangeable Sodium Percentage

The Exchangeable Sodium Percentage (ESP) of soil samples in nine locations during three stages of cultivation is presented in Table 34. There was significant difference in ESP among three stages under study. The highest and least ESP was observed at harvest (69.17 per cent) and mound dismantling stage (59.35per cent).Nine locations also varied significantly in ESP. The interaction between the stages and nine locations was found to be significant.

4.1.3.19. Sodium Adsorption Ratio

The sodium adsorption ratio (SAR) differed significantly among mound preparation, mound dismantling and harvest stages. The ratios ranged between 2.81 to 6.92 during three stages. The locations also showed significant difference in SAR. The highest and lowest contents were reported in Padinjare Kaitharam and Thathapilli respectively (Table 35).

4.1. 3.22. Percent cation saturation

The percent cation saturation refers to the estimate of the percentage of the soil CEC that is occupied by a particular cation. The percent saturation of cations such as Ca, Mg, Na, K, Fe and Al were found to be significant during three stages of cultivation. Among three stages, highest percent K saturation (3.63 per cent) was observed during mound dismantling stage. The Ca and Mg followed a decreasing trend from mound preparation to harvest stage. The per cent Na saturation was highest during the harvest stage. The Zn and Cu did not show any significant difference among three stages (Table 36- 44).

4.1. 3.23. Percent base saturation

The percent base saturation refers to the percent of the exchange sites occupied by the basic cations (Ca, Mg, Na and K). Significant difference was observed in percent base saturation of three stages of cultivation as well as nine locations. Among the stages, mound dismantling recorded the least (76.02 per cent) and mound preparation recorded the highest (91.45 per cent). Among the locations, Muppathezhukettu possessed the highest base saturation (Table 45).

4.1.4. Biological attributes

The organic carbon content of samples in different locations during three stages of cultivation has been shown in Table 46. The organic carbon status showed significant difference among different stages as well as different locations. Mound dismantling stage possessed 2.14 per cent organic carbon. Among locations, RRS recorded the highest organic carbon content (2.16 per cent).

The microbial biomass carbon (MBC) of samples in different locations was not found significantly different during the three different stages of cultivation. The observed contents were 169 µg TPF g^{-1} soil, 189.59 µg TPF g^{-1} soil and 185.29 µg TPF g^{-1} soil in mound preparation, mound dismantling and harvest stages (Table 47).

The dehydrogenase activity(DHA) differed among different locations at different stages of cultivation. Among different stages of cultivation considered, highest DHA activity was observed during harvest stage (1849.42 µg g^{-1} soil), followed by mound preparation (1366.31 µg g^{-1} soil). Thathapilli recorded the highest activity among the nine locations (Table 48).

4.2. Plant analysis and nutrient uptake

The plant samples were analyzed for nutrient content and uptake. The nutrients such as P, K, Ca, Mg, Fe, Mn, Cu, Zn, B and Na were found significantly varying among the three stages of cultivation. The plant samples at maximum tillering stage (4.45 per cent) possessed higher K content than that in the harvest stage. The content was recorded high during harvest stage for Fe, Mn, Cu, Na and B. Higher Zn content was observed in plant samples of maximum tillering stage than that of harvest. The nutrients such as N, S and Al did not show any significant difference among the two stages of growth.

The uptake of P, K, Ca, Fe, Mn, Cu, Zn, B and Na were found to be significantly different between the two growth stages. Considering the two growth stages, the K uptake was found to be higher in maximum tillering stage (84.96 kg ha^{-1}). More Ca uptake was observed in maximum tillering stage (10.58 kg ha^{-1}) than harvest stage (5.002 kg ha^{-1}). The Mg uptake of maximum tillering and harvest stages were recorded as 1.95 kg ha^{-1} and 1.75 kg ha^{-1} respectively. The iron uptake was found to be more in harvest stage (7.42 kg ha^{-1}). The uptake of S did not show any significant difference between the two stages of growth (Table 49 to 76).

4.3. Rice yield

The rice yield of different locations is presented in Table 75. The yield differed significantly among the nine locations. The highest yield (3483.3 kg ha^{-1}) was recorded in Padinjare Kaitharam padashekaram, followed by RRS, Vyttila (3450 kg ha^{-1}). The lowest yield (950 kg ha^{-1}) was noted in Periyali padashekaram.

4.3.1. Correlation of rice yield with available nutrients

The rice yield was significantly correlated with available K, Ca, Zn and Cu at the mound preparation stage. Except potassium, the other three showed a strong negative correlation with Ca, Zn and Cu. Multiple regression equations for yield with available content of different nutrients are given below.

$$\text{Yield} = 3161.244 + 2.550K - 0.692\,Ca - 22.935\,Zn - 5.481Cu \qquad (R^2 = 0.45) \qquad (1)$$

$$\text{Yield} = 3161.244 + 2.550K - 0.692\,Ca - 22.935\,Zn \qquad (R^2 = 0.47) \qquad (2)$$

The variation in yield (45 per cent) can be mainly accounted for potassium, calcium, zinc and copper content in soil. When Copper was excluded from the equation, R^2 was increased to 0.47. (Equation 1 and 2).

The yield was found to be positively correlated with available P content and negatively correlated with available Zn content in the soil at the mound dismantling stage. The multiple regression equation revealed that 45 per cent variation in yield can be attributed to available P and Zn content in the soil at mound dismantling stage (Equation 3).

Multiple regression equations for yield with available content of different nutrients during the mound dismantling stage are represented as follows:

$$\text{Yield} = 1424.71 + 26.82\,P - 12.01\,Zn \qquad (R^2 = 0.45) \qquad (3)$$

During the harvest stage, only available P content was significantly correlated with the yield. The multiple regression equation is given below:

$$\text{Yield} = 1450.292 + 10.957\,P \qquad (R^2 = 0.17) \qquad (4)$$

The available P in soil was related to 17 per cent variation in rice yield.

Table 34: Exchangeable sodium percentage (%) of soil samples at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	53.45	47.69	54.98	52.04
Kalappumpadi	53.79	61.01	62.93	59.24
Muppathezhukettu	62.18	64.08	66.69	64.32
Periyali	55.21	68.36	74.44	66.00
Diamond	57.42	67.90	77.38	67.57
Kaitharam	60.40	54.38	77.50	64.09
Padinjare Kaitharam	66.78	66.58	75.03	69.46
Thathapilli	60.10	47.15	67.32	58.19
RRS, Vyttila	81.28	56.99	66.23	68.17
Mean	61.18	59.35	69.17	–
CD (0.05)	Stages of growth	0.96		
	Location	1.66		
	Interaction	2.90		

Table 35: Sodium adsorption ratio (SAR) of soil samples at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	5.14	2.24	3.20	3.53
Kalappumpadi	5.36	3.37	3.48	4.07
Muppathezhukettu	4.87	3.77	3.92	4.19
Periyali	6.29	3.07	4.70	4.69
Diamond	9.12	3.49	4.99	5.86
Kaitharam	6.39	2.50	4.63	4.51
Padinjare Kaitharam	11.45	2.88	4.07	6.14
Thathapilli	5.46	1.48	2.40	3.11
RRS, Vyttila	8.19	2.46	3.76	4.80
Mean	6.92	2.81	3.90	–
CD (0.05)	Stages of growth	0.70		
	Location	1.22		
	Interaction	2.11		

Table 36: Percent calcium saturation (%) of soil at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	25.39	16.67	11.80	17.96
Kalappumpadi	26.52	11.58	13.82	17.31
Muppathezhukettu	28.65	12.82	11.27	17.58
Periyali	25.52	9.10	8.79	14.47
Diamond	29.41	10.59	7.54	15.85
Kaitharam	26.22	12.03	8.24	15.50
Padinjare Kaitharam	18.24	6.70	7.88	10.94
Thathapilli	24.52	9.73	10.09	14.78
RRS, Vyttila	7.29	10.79	9.53	9.20
Mean	23.53	11.11	9.89	–
CD (0.05)	Stages of growth	2.37		
	Location	4.10		
	Interaction	7.11		

Table 37: Percent magnesium saturation (%) of soil at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	5.06	2.58	3.07	3.57
Kalappumpadi	5.11	1.89	2.07	3.02
Muppathezhukettu	5.54	1.96	1.94	3.15
Periyali	4.14	1.60	1.41	2.38
Diamond	3.51	1.48	1.06	2.02
Kaitharam	4.28	2.00	1.07	2.45
Padinjare Kaitharam	3.80	1.61	1.25	2.22
Thathapilli	3.95	1.51	1.44	2.30
RRS, Vyttila	3.00	2.57	2.02	2.53
Mean	4.27	1.91	1.70	–
CD (0.05)	Stages of growth	0.42		
	Location	0.74		
	Interaction	NS		

Table 38: Percent sodium saturation (%) of soil at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	53.45	47.69	54.98	52.04
Kalappumpadi	53.79	61.01	62.93	59.24
Muppathezhukettu	62.18	64.08	66.69	64.32
Periyali	55.21	68.36	74.44	66.00
Diamond	57.42	67.90	77.38	67.57
Kaitharam	60.40	54.38	77.50	64.09
Padinjare Kaitharam	66.78	66.58	75.03	69.46
Thathapilli	60.10	47.15	67.32	58.19
RRS, Vyttila	81.28	56.99	66.23	68.17
Mean	61.18	59.35	69.17	–
CD (0.05)	Stages of growth	5.32		
	Location	9.22		
	Interaction	NS		

Table 39: Percent potassium saturation (%) of soil at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	3.47	4.46	6.72	4.88
Kalappumpadi	1.80	3.23	5.05	3.36
Muppathezhukettu	2.24	4.53	5.53	4.10
Periyali	2.22	2.65	4.16	3.01
Diamond	1.15	2.67	3.00	2.27
Kaitharam	1.95	3.34	3.15	2.81
Padinjare Kaitharam	1.27	2.69	3.80	2.59
Thathapilli	0.35	2.50	2.92	1.92
RRS, Vyttila	7.67	6.60	5.59	6.62
Mean	2.46	3.63	4.44	–
CD (0.05)	Stages of growth	0.77		
	Location	1.35		
	Interaction	NS		

Table 40: Percent iron saturation (%) of soil at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	9.57	0.98	0.83	3.79
Kalappumpadi	10.99	1.47	0.64	4.36
Muppathezhukettu	8.66	0.70	0.89	3.42
Periyali	7.13	1.24	0.39	2.92
Diamond	7.49	1.11	0.60	3.07
Kaitharam	8.22	2.25	0.74	3.74
Padinjare Kaitharam	8.84	1.10	0.71	3.55
Thathapilli	9.2	1.5	1.57	4.14
RRS, Vyttila	0.17	0	0.31	0.16
Mean	7.82	1.16	0.74	–
CD (0.05)	Stages of growth	0.66		
	Location	1.14		
	Interaction	1.97		

Table 41: Percent manganese saturation (%) of soil at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	0.907	0.143	0.062	0.37
Kalappumpadi	0.93	0.09	0.08	0.37
Muppathezhukettu	0.77	0.07	0.06	0.30
Periyali	0.45	0.09	0.03	0.19
Diamond	0.50	0.09	0.04	0.21
Kaitharam	0.54	0.17	0.05	0.25
Padinjare Kaitharam	0.45	0.12	0.04	0.20
Thathapilli	3.94	0.28	0.13	1.45
RRS, Vyttila	0.08	0.02	0.01	0.04
Mean	0.95	0.12	0.05	–
CD (0.05)	Stages of growth	0.49		
	Location	NS		
	Interaction	NS		

Table 42: Percent zinc saturation (%) of soil at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	3.09	0.19	0.26	1.18
Kalappumpadi	15.77	0.10	0.06	5.31
Muppathezhukettu	0.02	0.96	0.08	0.35
Periyali	0.01	0.07	0.02	0.04
Diamond	0.02	0.06	0.03	0.04
Kaitharam	0.008	0.07	0.02	0.03
Padinjare Kaitharam	0.02	0.06	0.03	0.04
Thathapilli	0.01	0.30	0.08	0.13
RRS, Vyttila	0.009	0.05	0.03	0.03
Mean	2.1	0.21	0.07	–
CD (0.05)	Stages of growth	NS		
	Location	NS		
	Interaction	NS		

Table 43: Percent copper saturation (%) of soil at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	3.09	0.194	0.263	1.18
Kalappumpadi	15.77	0.103	0.069	5.31
Muppathezhukettu	0.02	0.965	0.084	0.35
Periyali	0.014	0.078	0.026	0.04
Diamond	0.028	0.061	0.035	0.04
Kaitharam	0.008	0.073	0.024	0.03
Padinjare Kaitharam	0.029	0.068	0.031	0.04
Thathapilli	0.012	0.3	0.08	0.13
RRS, Vyttila	0.009	0.055	0.033	0.03
Mean	2.11	0.211	0.072	–
CD (0.05)	Stages of growth	NS		
	Location	0.03		
	Interaction	NS		

Table 44: Percent aluminium saturation (%) of soil at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	0.81	27.11	22.38	16.77
Kalappumpadi	0.73	20.56	15.38	12.23
Muppathezhukettu	1.01	14.59	13.56	9.72
Periyali	0.70	16.86	10.73	9.43
Diamond	0.46	16.06	10.33	8.95
Kaitharam	0.53	25.72	8.89	11.71
Padinjare Kaitharam	0.54	21.15	11.27	10.99
Thathapilli	0.57	34.43	16.53	17.17
RRS, Vyttila	0.47	23.57	16.36	13.46
Mean	0.64	22.23	13.94	–
CD (0.05)	Stages of growth	2.80		
	Location	4.85		
	Interaction	NS		

Table 45: Percent base saturation (%) of soil at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	87.39	71.42	76.39	78.40
Kalappumpadi	87.23	77.72	83.79	82.91
Muppathezhukettu	98.63	83.40	85.38	89.14
Periyali	87.11	81.71	88.77	85.86
Diamond	91.51	82.65	88.98	87.71
Kaitharam	92.86	71.76	89.97	84.86
Padinjare Kaitharam	90.11	77.59	87.96	85.22
Thathapilli	88.94	60.89	81.75	77.20
RRS, Vyttila	99.25	76.96	83.40	86.54
Mean	91.45	76.01	85.16	–
CD (0.05)	Stages of growth	3.52		
	Location	6.10		
	Interaction	NS		

Table 46: Organic carbon (%) of soil samples at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	2.34	1.93	0.74	1.67
Kalappumpadi	0.77	2.29	1.4	1.49
Muppathezhukettu	1.52	1.87	0.75	1.38
Periyali	1.85	2.30	1.22	1.79
Diamond	2.06	2.04	1.38	1.83
Kaitharam	1.78	2.16	1.21	1.72
Padinjare Kaitharam	1.80	1.84	1.41	1.68
Thathapilli	2.59	2.41	1.03	2.01
RRS, Vyttila	2.41	2.45	1.63	2.16
Mean	1.90	2.14	1.20	_
CD (0.05)	Stages of growth	0.23		
	Location	0.40		
	Interaction	0.70		

Table 47: Microbial biomass carbon (µg g^{-1} soil) of soil samples at different locations during three stages of cultivation

Locations	Stages of cultivation			Mean
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	190	216	211	206
Kalappumpadi	126	135	139	133
Muppathezhukettu	194	198	227	206
Periyali	212.	198	154	188
Diamond	179	175	161	172
Kaitharam	194	161	176	177
Padinjare Kaitharam	227	238	171	212
Thathapilli	100	231	235	189
RRS, Vyttila	95	152	190	146
Mean	169	189	185	–
CD (0.05)	Stages of growth	NS		
	Location	NS		
	Interaction	NS		

Table 48: Dehydrogenase activity (µg TPF g^{-1} soil) of soil samples at different locations during three stages of cultivation

Locations	**Stages of cultivation**			**Mean**
	Mound preparation	Mound dismantling	Harvest	
Mundothuruth	1725	1389	1695	1603
Kalappumpadi	1266	2840	2732	2280
Muppathezhukettu	1154	1106	1544	1268
Periyali	1029	683	2279	1330
Diamond	821	1543	2350	1572
Kaitharam	1035	985	1793	1271
Padinjare Kaitharam	2378	856	1325	1520
Thathapilli	2560	1796	2517	2291
RRS, Vyttila	324	281	404	336
Mean	1366	1276	1849	–
CD (0.05)	Stages of growth	145.12		
	Location	251.36		
	Interaction	435.37		

Table 49: Dry weight of plant samples at two growth stages

Location	Maximum tillering stage (g/ hill)	Harvest stage (g/ hill)
Mundothuruth	117.09	173.47
Kalappumpadi	106.05	118.84
Muppathezhukettu	104.50	125.06
Periyali	100.50	165.79
Diamond	113.31	138.49
Kaitharam	106.39	139.05
Padinjare Kaitharam	109.65	144.06
Thathapilli	116.00	145.38
RRS, Vyttila	116.12	140.50

Table 50: Plant nitrogen content (%) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	3.91	3.31	3.61
Kalappumpadi	5.33	4.66	4.99
Muppathezhukettu	5.37	5.45	5.41
Periyali	2.73	2.93	2.83
Diamond	4.26	4.57	4.41
Kaitharam	3.73	3.45	3.59
Padinjare Kaitharam	5.06	5.37	5.22
Thathapilli	5.06	4.97	5.02
RRS, Vyttila	3.51	3.67	3.59
Mean	4.33	4.26	–
CD (0.05)	Stages of growth	NS	
	Location	0.54	
	Interaction	NS	

Table 51: Nitrogen uptake (kg ha^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	48.97	41.39	45.18
Kalappumpadi	50.65	44.30	47.48
Muppathezhukettu	67.23	51.84	59.53
Periyali	53.27	37.91	45.59
Diamond	85.23	91.41	88.32
Kaitharam	93.27	86.24	89.76
Padinjare Kaitharam	177.31	188.17	182.74
Thathapilli	75.98	74.62	75.30
RRS, Vyttila	123.02	128.47	125.74
Mean	86.10	82.70	–
CD (0.05)	Stages of growth	NS	
	Location	13.25	
	Interaction	NS	

Table 52: Plant phosphorus content (%) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	0.59	0.98	0.79
Kalappumpadi	0.60	0.56	0.58
Muppathezhukettu	0.59	0.58	0.59
Periyali	0.58	0.61	0.60
Diamond	0.90	0.85	0.87
Kaitharam	0.81	0.95	0.88
Padinjare Kaitharam	0.24	0.31	0.27
Thathapilli	0.81	0.79	0.80
RRS, Vyttila	0.36	0.63	0.50
Mean	0.61	0.70	–
CD (0.05)	Stages of growth	0.07	
	Location	0.15	
	Interaction	NS	

Table 53: Phosphorus uptake (kg ha^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	7.47	12.36	9.92
Kalappumpadi	5.75	5.37	5.56
Muppathezhukettu	7.44	7.31	7.37
Periyali	11.78	12.33	12.05
Diamond	16.86	16.00	16.43
Kaitharam	20.32	23.89	22.10
Padinjare Kaitharam	8.59	10.86	9.73
Thathapilli	12.17	15.97	14.07
RRS, Vyttila	12.82	22.37	17.60
Mean	11.47	14.05	–
CD (0.05)	Stages of growth	1.87	
	Location	3.98	
	Interaction	NS	

Table 54: Plant potassium content (%) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	4.84	0.35	2.59
Kalappumpadi	4.86	1.62	3.24
Muppathezhukettu	3.42	0.84	2.13
Periyali	3.60	1.94	2.77
Diamond	7.18	0.25	3.71
Kaitharam	4.97	1.22	3.10
Padinjare Kaitharam	4.22	1.05	2.64
Thathapilli	5.39	1.39	3.39
RRS, Vyttila	1.57	0.68	1.13
Mean	4.45	1.04	–
CD (0.05)	Stages of growth	0.28	
	Location	0.59	
	Interaction	0.84	

Table 55: Potassium uptake (kg ha^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	60.52	4.43	32.47
Kalappumpadi	46.18	15.46	30.82
Muppathezhukettu	42.75	10.54	26.64
Periyali	72.12	38.94	55.53
Diamond	134.77	4.68	69.73
Kaitharam	124.45	30.60	77.53
Padinjare Kaitharam	147.86	36.90	92.38
Thathapilli	80.95	20.91	50.93
RRS, Vyttila	55.14	19.5	37.36
Mean	84.97	20.23	–
CD (0.05)	Stages of growth	4.76	
	Location	10.10	
	Interaction	14.28	

Table 56: Plant calcium content (%) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	0.22	0.57	0.40
Kalappumpadi	0.26	0.41	0.33
Muppathezhukettu	0.19	0.50	0.34
Periyali	0.13	0.48	0.30
Diamond	0.16	0.59	0.37
Kaitharam	0.20	0.11	0.15
Padinjare Kaitharam	0.07	0.10	0.08
Thathapilli	0.16	0.15	0.16
RRS, Vyttila	0.44	0.56	0.50
Mean	0.20	0.38	–
CD (0.05)	Stages of growth	0.07	
	Location	0.16	
	Interaction	0.22	

Table 57: Calcium uptake (kg ha^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	2.86	35.76	19.31
Kalappumpadi	2.46	3.95	3.21
Muppathezhukettu	2.41	6.26	4.33
Periyali	2.73	9.59	6.16
Diamond	3.09	11.12	7.11
Kaitharam	5.01	2.77	3.89
Padinjare Kaitharam	2.57	3.68	3.12
Thathapilli	2.50	2.34	2.42
RRS, Vyttila	15.41	19.72	17.56
Mean	4.34	10.58	
CD (0.05)	Stages of growth	1.31	
	Location	2.78	
	Interaction	3.94	

Table 58: Plant magnesium content (%) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	0.10	0.06	0.08
Kalappumpadi	0.11	0.06	0.08
Muppathezhukettu	0.10	0.06	0.08
Periyali	0.09	0.06	0.07
Diamond	0.10	0.10	0.10
Kaitharam	0.11	0.09	0.10
Padinjare Kaitharam	0.04	0.09	0.07
Thathapilli	0.11	0.09	0.10
RRS, Vyttila	0.11	0.09	0.10
Mean	0.10	0.08	
CD (0.05)	Stages of growth	0.008	
	Location	0.016	
	Interaction	0.023	

Table 59: Magnesium uptake (kg ha^{-1}) of at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	1.33	0.76	1.04
Kalappumpadi	1.06	1.18	1.12
Muppathezhukettu	1.32	0.76	1.04
Periyali	1.94	1.19	1.56
Diamond	1.99	1.87	1.93
Kaitharam	2.74	2.39	2.57
Padinjare Kaitharam	1.67	3.27	2.47
Thathapilli	1.72	1.45	1.59
RRS, Vyttila	3.75	3.25	3.50
Mean	1.95	1.79	–
CD (0.05)	Stages of growth	NS	
	Location	0.46	
	Interaction	0.65	

Table 60: Plant sulphur content (%) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	0.03	0.04	0.04
Kalappumpadi	0.04	0.04	0.04
Muppathezhukettu	0.04	0.04	0.04
Periyali	0.04	0.06	0.05
Diamond	0.05	0.05	0.05
Kaitharam	0.04	0.07	0.05
Padinjare Kaitharam	0.02	0.02	0.02
Thathapilli	0.07	0.04	0.06
RRS, Vyttila	0.05	0.04	0.04
Mean	0.04	0.05	–
CD (0.05)	Stages of growth	NS	
	Location	0.01	
	Interaction	NS	

Table 61: Sulphur uptake (kg ha^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	0.40	0.59	0.50
Kalappumpadi	0.41	0.44	0.43
Muppathezhukettu	0.60	0.55	0.57
Periyali	0.96	1.35	1.16
Diamond	1.04	1.08	1.06
Kaitharam	1.12	1.77	1.44
Padinjare Kaitharam	0.68	0.70	0.69
Thathapilli	1.07	0.74	0.90
RRS, Vyttila	1.78	1.64	1.71
Mean	0.90	0.98	–
CD (0.05)	Stages of growth	NS	
	Location	0.28	
	Interaction	NS	

Table 62: Plant iron content (mg kg^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	1064.13	2211.57	1637.85
Kalappumpadi	1161.87	3275.00	2218.43
Muppathezhukettu	736.66	3496.00	2116.33
Periyali	303.63	1660.33	981.98
Diamond	1314.00	5562.00	3438.00
Kaitharam	364.43	2826.00	1595.22
Padinjare Kaitharam	327.76	5185.00	2756.38
Thathapilli	4034.3	3592.67	3813.50
RRS, Vyttila	1961.3	3497.47	2729.40
Mean	1252.02	3478.45	–
CD (0.05)	Stages of growth	450.92	
	Location	956.54	
	Interaction	1352.75	

Table 63: Iron uptake (kg ha^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	1.33	2.76	2.04
Kalappumpadi	1.10	3.11	2.10
Muppathezhukettu	0.92	4.37	2.64
Periyali	0.60	3.32	1.96
Diamond	2.46	10.42	6.44
Kaitharam	0.91	7.06	3.98
Padinjare Kaitharam	1.14	18.14	9.64
Thathapilli	6.05	5.38	5.72
RRS, Vyttila	6.86	12.24	9.55
Mean	2.37	7.42	
CD (0.05)	Stages of growth	1.32	
	Location	2.80	
	Interaction	3.96	

Table 64: Plant manganese content (mg kg $^{-1}$) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	83.33	453.75	268.54
Kalappumpadi	84.16	447.15	265.65
Muppathezhukettu	36.08	262.69	149.39
Periyali	28.93	143.16	86.04
Diamond	64.00	218.91	141.45
Kaitharam	100.55	82.14	91.34
Padinjare Kaitharam	133.35	136.52	134.93
Thathapilli	382.03	181.11	281.57
RRS, Vyttila	38.36	65.93	52.15
Mean	105.64	221.26	–
CD (0.05)	Stages of growth	13.37	
	Location	28.36	
	Interaction	40.11	

Table 65: Manganese uptake (kg ha^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	0.10	0.56	0.33
Kalappumpadi	0.08	0.42	0.25
Muppathezhukettu	0.04	0.32	0.18
Periyali	0.05	0.28	0.17
Diamond	0.12	0.41	0.26
Kaitharam	0.25	0.20	0.22
Padinjare Kaitharam	0.46	0.47	0.47
Thathapilli	0.57	0.27	0.42
RRS, Vyttila	0.13	0.23	0.18
Mean	0.20	0.35	–
CD (0.05)	Stages of growth	0.04	
	Location	0.08	
	Interaction	0.12	

Table 66: Plant copper content (mg kg^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	24.25	10.63	17.44
Kalappumpadi	25.55	23.50	24.52
Muppathezhukettu	22.07	20.55	21.31
Periyali	36.50	22.38	29.44
Diamond	15.88	32.46	24.17
Kaitharam	13.28	33.97	23.63
Padinjare Kaitharam	10.10	30.72	20.41
Thathapilli	17.52	31.65	24.59
RRS, Vyttila	48.86	46.00	47.43
Mean	23.78	27.98	–
CD (0.05)	Stages of growth	2.83	
	Location	6.01	
	Interaction	8.50	

Table 67: Copper uptake (g ha^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	30.00	10.00	20.00
Kalappumpadi	20.00	20.00	20.00
Muppathezhukettu	20.00	20.00	20.00
Periyali	70.00	40.00	50.00
Diamond	30.00	60.00	40.00
Kaitharam	30.00	80.00	50.00
Padinjare Kaitharam	30.00	10.00	70.00
Thathapilli	20.00	40.00	30.00
RRS, Vyttila	17.00	16.00	16.00
Mean	50.00	60.00	–
CD (0.05)	Stages of growth	8.00	
	Location	20.00	
	Interaction	20.00	

Table 68: Plant zinc content (mg kg^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	0.02	0.01	0.01
Kalappumpadi	0.01	0.01	0.01
Muppathezhukettu	0.13	0.01	0.07
Periyali	0.009	0.009	0.009
Diamond	0.29	0.01	0.15
Kaitharam	0.36	0.01	0.19
Padinjare Kaitharam	0.04	0.01	0.02
Thathapilli	0.45	0.01	0.23
RRS, Vyttila	0.20	0.01	0.11
Mean	0.17	0.01	–
CD (0.05)	Stages of growth	0.04	
	Location	0.10	
	Interaction	0.14	

Table 69: Zinc uptake (kg ha^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	0.19	0.15	0.17
Kalappumpadi	0.14	0.11	0.12
Muppathezhukettu	1.64	0.13	0.89
Periyali	0.18	0.17	0.18
Diamond	5.54	0.28	2.914
Kaitharam	9.22	0.26	4.74
Padinjare Kaitharam	1.40	0.36	0.88
Thathapilli	6.78	0.17	3.47
RRS, Vyttila	7.33	0.42	3.87
Mean	3.60	0.23	–
CD (0.05)	Stages of growth	1.08	
	Location	2.30	
	Interaction	3.26	

Table 70: Plant aluminium content (mg kg^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	315.30	462.40	388.85
Kalappumpadi	292.43	442.00	367.21
Muppathezhukettu	212.93	683.33	448.13
Periyali	555.50	613.23	584.36
Diamond	2568.30	1037.60	1802.95
Kaitharam	304.00	1007.93	655.96
Padinjare Kaitharam	167.03	1428.83	797.93
Thathapilli	39.00	1627.70	833.35
RRS, Vyttila	39.00	979.63	509.31
Mean	499.27	920.29	–
CD (0.05)	Stages of growth	NS	
	Location	NS	
	Interaction	NS	

Table 71: Aluminium uptake (kg ha^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	0.39	0.57	0.48
Kalappumpadi	0.27	0.42	0.34
Muppathezhukettu	0.26	0.85	0.56
Periyali	1.11	1.22	1.16
Diamond	4.81	1.94	3.38
Kaitharam	0.76	2.52	1.64
Padinjare Kaitharam	0.58	5.00	2.79
Thathapilli	0.05	2.44	1.25
RRS, Vyttila	0.13	3.42	1.78
Mean	0.93	2.04	
CD (0.05)	Stages of growth	1.04	
	Location	NS	
	Interaction	NS	

Table 72: Plant boron content (%) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	5.32	4.81	5.06
Kalappumpadi	7.76	6.13	6.95
Muppathezhukettu	3.91	6.11	5.01
Periyali	4.64	511	4.87
Diamond	4.51	7.59	6.05
Kaitharam	5.35	7.55	6.45
Padinjare Kaitharam	5.10	5.53	5.32
Thathapilli	6.58	5.25	5.92
RRS, Vyttila	5.44	6.22	5.83
Mean	5.40	6.03	–
CD (0.05)	Stages of growth	0.26	
	Location	0.56	
	Interaction	0.79	

Table 73: Boron uptake (kg ha^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	66.51	60.19	63.35
Kalappumpadi	73.80	58.30	66.05
Muppathezhukettu	48.91	76.44	62.68
Periyali	92.85	102.23	97.54
Diamond	84.74	142.41	113.58
Kaitharam	133.90	188.80	161.35
Padinjare Kaitharam	178.66	193.82	186.24
Thathapilli	98.77	78.84	88.80
RRS, Vyttila	190.54	217.83	204.18
Mean	107.63	124.32	–
CD (0.05)	Stages of growth	7.25	
	Location	15.39	
	Interaction	21.77	

Table 74: Plant sodium content (%) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	0.33	0.03	0.18
Kalappumpadi	0.34	0.61	0.47
Muppathezhukettu	0.22	0.26	0.24
Periyali	0.10	1.58	0.84
Diamond	0.81	0.04	0.43
Kaitharam	0.24	1.28	0.76
Padinjare Kaitharam	0.08	1.25	0.67
Thathapilli	0.92	0.58	0.75
RRS, Vyttila	0.37	0.38	0.37
Mean	0.38	0.67	--
CD (0.05)	Stages of growth	0.13	
	Location	0.28	
	Interaction	0.40	

Table 75: Sodium uptake (kg ha^{-1}) at different locations

Location	Stages of growth		Mean
	Maximum tillering	Harvest	
Mundothuruth	4.24	0.47	2.35
Kalappumpadi	5.34	9.50	7.42
Muppathezhukettu	2.83	3.33	3.08
Periyali	1.00	15.03	8.01
Diamond	15.29	0.93	8.11
Kaitharam	6.07	32.03	19.05
Padinjare Kaitharam	2.92	43.99	23.46
Thathapilli	13.84	8.72	11.28
RRS, Vyttila	13.20	13.36	13.28
Mean	7.19	14.15	–
CD (0.05)	Stages of growth	4.11	
	Location	8.72	
	Interaction	12.34	

Table 76: Rice yield of different locations

Sites	Yield (kg ha^{-1})
Mundothuruth	1250.00
Kalappumpadi	1500.00
Muppethezhukettu	1250.00
Periyali	950.00
Diamond	1858.33
Kaitharam	2450.00
Padinjare Kaitharam	3483.33
Thathapilli	1500.00
RRS, Vyttila	3450.00
CD (0.05)	88.13

4.3.1. Correlation of rice yield with plant nutrients

The rice yield showed a significant negative correlation with plant P and Mg content during the maximum tillering stage of rice. The yield was negatively correlated to plant N, K, Mg, S, Fe, Al, B and Na during the maximum tillering stage, but which were not significant. Multiple regression equations of yield are provided below:

Yield= 3962.199-1535.243 P -10453.696 Mg ($R^2 = 0.25$) (5)

Yield= 3962.199-1535.243 P ($R^2 = 0.23$) (6)

By the exclusion of Mg, the R^2 was decreased to 0.23 from 0.25 (Equation 5 and 6).

The yield showed significant correlations with Mg, Cu, Mn and Fe content of plant at harvest stage. It was positively correlated to Mg, Cu and Fe content. Multiple regression equations of yield with nutrient content of plant at harvest are represented as follows:

Yield= 1489.01 - 4652.88 Mg + 30.19 Cu-2.43 Mn + 0.15 Fe ($R^2 = 0.400$) (7)

Yield= 1489.01 + 30.19 Cu-2.43 Mn + 0.15 Fe ($R^2 = 0.423$) (8)

Yield= 1489.01 - 4652.88 Mg + 30.19 Cu-2.43 Mn ($R^2 = 0.421$) (9)

Yield= 1489.01 -2.43 Mn ($R^2 = 0.403$) (10)

4.4. Canonical analysis

The cations identified in the *Pokkali* soil were K, Ca, Mg, Fe, Mn, Zn, Cu, Al and Na. Among these cations, the decisive cations were K, Mg, Cu and Na. The anions like bicarbonate and chloride were present in limited quantities in the soil. *Pokkali* soils recorded the absence of carbonate ions. The predominant anions existing in the soil were SO_4 and PO_4. The SO_4 ion showed a positive correlation with the K, Ca, Mg, Fe, Mn, Zn, Al and Na ions. But SO_4 ion was negatively correlated with Cu and Zn ions. Another dominant anion namely PO_4 was found to be positively correlated with Mg and Zn ions. It showed negative correlation to the rest of the cations namely K, Ca, Fe, Mn, Cu, Al and Na (Annexure III).

4.5. Canonical regression

Stepwise regression was conducted with sulphate to identify the various ions that are associated with sulphate as also potassium of the soil. The cations under consideration were K, Ca, Mg, Fe, Mn, Zn, Cu, Al and Na. Step down regression identified 'K' having predictive ability towards the presence of sulphate ion. Hence, a linear relationship was identified. The linear relationship could be described as

$$SUL = 1575.033 + 0.206\,K \qquad (t = 2.66^{*})$$

Where SUL = Quantity of sulphate

K = Quantity of potassium present in the soil

4.6. Soil fertility status

Organic carbon in *Pokkali* soils showed a high fertility status. The observed mean was 1.75 per cent. The mean value of available nitrogen (137.99 kg ha^{-1}) came under low nitrogen status. The available P content was very much higher in the soil samples. It showed a mean value of 40.40 kg ha^{-1}, can be classified as high. The available K was present in very high quantities in soil. Available Ca and S were present in high concentrations in the soil samples. But Mg was observed only in low levels (< 120 mg kg^{-1}). Micronutrients (Fe, Mn, Zn, and Cu) were present in very high concentrations in soil samples, compared to the sufficiency range. Nutrients namely, Al (581.09 mg kg^{-1}) and B (32.50 mg kg^{-1}) also exceeded the sufficiency range (Annexure IV).

4.7. Plant nutrient status

The nitrogen content in plant samples was found to be sufficient. The mean value recorded was 4.30 per cent, which lies within the sufficiency range (1-5 per cent). The mean value of phosphorus obtained was a little greater than sufficiency range (0.1- 0.4 per cent). Adequate amount of potassium and calcium was found to be present in the plant samples. The observed mean of magnesium (1.87 per cent) exceeded the sufficiency limit (0.1- 0.4 per cent). Micronutrients such as Fe, Mn and Cu were present in adequate quantities. Zinc, boron and aluminium showed toxic concentrations in plant samples (AnnexureV).

4.8. Correlation between soil and plant nutrients

Plant manganese content showed a positive significant correlation with available iron content of soil (Annexure VI). But the multiple regression equation revealed that only 3.6 per cent variation in plant manganese content could be attributed to soil iron content.

$$\text{Plant P} = 0.665 + 0.002\ \text{Mn} \qquad (R^2 = 0.036) \qquad (12)$$

Plant Ca was positively correlated to available P and Ca content of soil. Available Mg, Na and Al were having significant negative correlations with plant Ca, with "r "value as 0.701. Plant Mg and S showed significant correlation only with available iron content of soil.

Plant copper was positively correlated to organic carbon as well as the available P content in the soil. Only available Na was significantly correlated to Plant Mn (Annexure IV). Multiple regression equations with respect to plant Cu and Mn are given below:

$$\text{Plant Cu} = 12.83 + 6.70\ \text{OC} + 0.15\ \text{P} \qquad (R^2 = 0.38) \qquad (13)$$

$$\text{Plant Mn} = 304.65 - 0.014\ \text{Na} \qquad (R^2 = 0.11) \qquad (14)$$

Plant Zn and Al were significantly correlated to available iron and organic carbon respectively. Plant B and Na showed significant positive correlations with available P and Mn contents of soil respectively (Annexure IV). Multiple regression equations with respect to plant Zn, Al and Na are represented below:

$$\text{Plant Zn} = 105.92 + 0.007\ \text{Fe} \qquad (R^2 = 0.16) \qquad (15)$$

$$\text{Plant Al} = 153.50 + 635.85\ \text{OC} \qquad (R^2 = 0.27) \qquad (16)$$

$$\text{Plant Na} = 2964 + 46.18\ \text{Mn} \qquad (R^2 = 0.28) \qquad (17)$$

4.8. Correlation of Net Ionic Equilibrium ratios with soil parameters

The correlations of the Net Ionic Equilibrium (NIE) ratios with different soil parameters are shown in Annexure VII. The NIE ratio K/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ was positively correlated with the ratio Na/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$. The third ratio Mg/ $[(Ca+ Mg+ Fe+ Mn) + (Al)^{2/3}]$ showed negative correlation with the first two ratios.

The ratios K/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ and Na/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ were negatively correlated with pH of the soil. The other two ratios, Mg/ $[(Ca+ Mg+ Fe+ Mn) + (Al)^{2/3}]$ and Cu/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ showed a significant positive correlation with pH. The cation exchange capacity of soil showed significant positive correlations with K/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ and Na/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$, and strong negative correlation with Cu/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$. The exchangeable Mg content was significantly correlated to Cu/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3]}$. The Na content showed significant positive correlations with K/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ and Na/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$.

The ratio Cu/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ was found to have significant negative correlations with K and Na. The same ratio showed significant positive correlations with exchangeable Fe and Mn. Copper and zinc were negatively correlated with the ratios K/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ and Na/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$. Chloride and bicarbonate were negatively correlated to the ratios Mg/ $[(Ca+ Mg+ Fe+ Mn) + (Al)^{2/3}]$ and Cu/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$. All the four ratios were significantly correlated to the phosphate content of the soil. The ratios K/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ and Na/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ showed negative correlation, and the other two ratios showed positive correlation with the phosphate content of soil.

$K/[(Ca+Mg+Fe+Mn)^{1/2}+(Al)^{1/3}]$: Ratio 1

$Na/[(Ca+Mg+Fe+Mn)^{1/2}+(Al)^{1/3}]$: Ratio 2

$Mg/[(Ca+Mg+Fe+Mn)^{+}(Al)^{2/3}]$: Ratio 3

$Cu/[(Ca+Mg+Fe+Mn)^{1/2}+(Al)^{1/3}]$: Ratio 4

DISCUSSION

DISCUSSION

The present study has been carried out to assess the ion interactions in acid saline *Pokkali* soils and to identify the chemical constraints in plant nutrition as well as to identify emerging deficiency or toxicity of nutrients in *Pokkali* soils. For this purpose soil and plant samples were collected from eight *Pokkali* locations of Kottuvally panchayath and RRS, Vyttila. The soil samples were characterized for physical, chemical and biological attributes and the plant samples were analysed for nutrient content and uptake.The yield from each padashekaram was also recorded. The results of the experiments are presented here with evidences from the literature.

5.1. Physical attributes

5.1.1. Soil texture

A wide variation was observed in silt, clay and sand percent of soil samples of different locations. The clay content varied from 15.00 to 60.87 per cent in different locations and RRS, Vyttila (Figure 1). Varghese *et al.*, (1970) reported a clay content of 16 per cent in *Pokkali* soil profile. Higher clay content was recorded in Thathapilli compared to other locations. The silt content showed a range of 6.04 to 19.82 per cent (Figure 2). Varghese *et al.*, (1970) observed silt content of 13.2 per cent in *Pokkali* soils. The lowest and highest silt content was found in RRS, Vyttila and Kalappumpadi respectively. Fine sand content varied between 10.71 per cent and 54.99 per cent in the nine locations. The coarse sand content was very low in Muppathezhukettu padashekaram (0.37 per cent). While studying the physical and chemical characteristics of *Pokkali* soils, Varghese *et al.*, (1970) observed coarse sand and fine sand fraction as 32.3 per cent and 35.1 per cent respectively. Varghese *et al.*, (1970) observed that the soil texture became finer with depth. The predominant fraction in most of the *Pokkali* soils was clay (Padmaja *et al.*, 1994). Joseph (2014) concluded that, the reason for the variation in particle size distribution of *Pokkali* soils was the tidal action throughout the year.

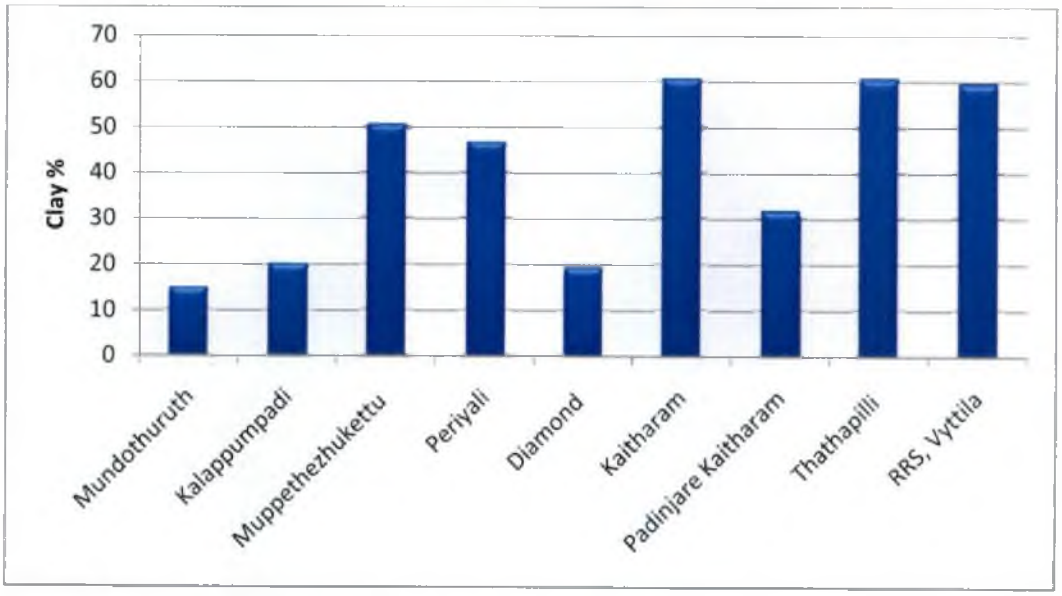

Figure 1: Clay content (%) of soil in different locations

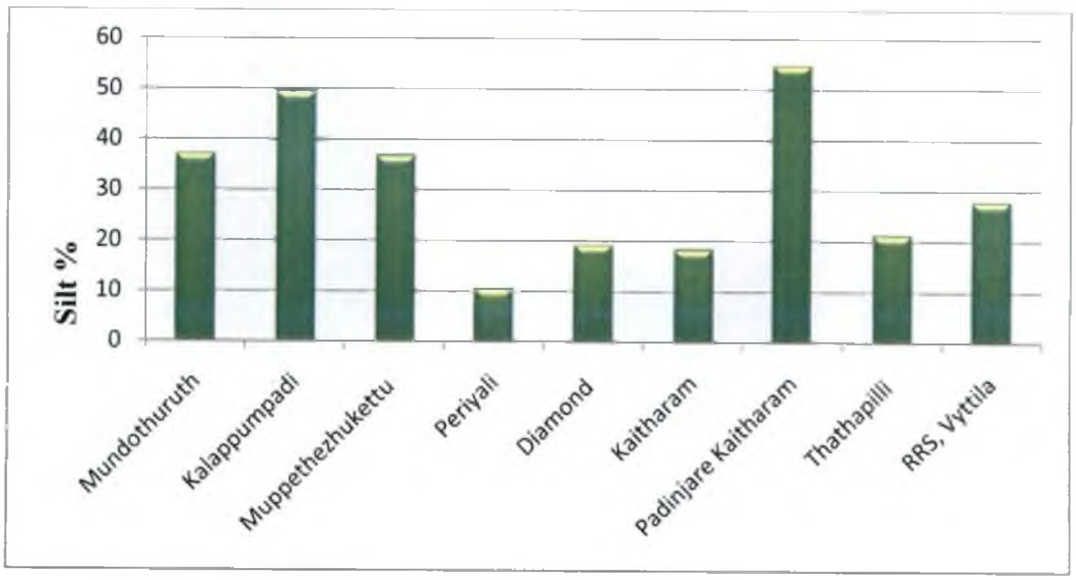

Figure 2: Silt content (%) of soil in different locations

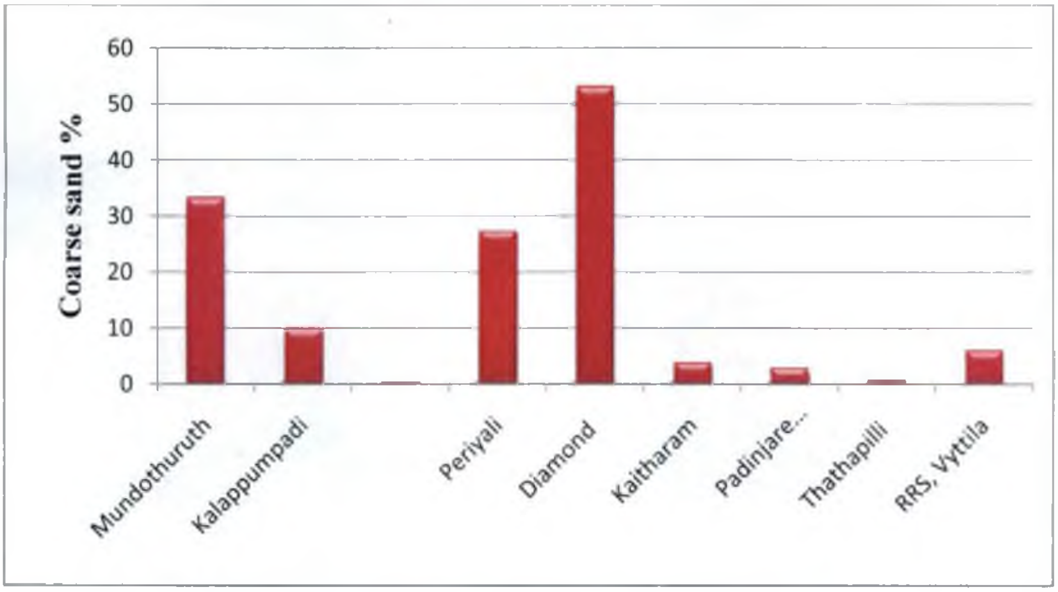

Figure 3: Coarse sand content (%) of soil in different locations

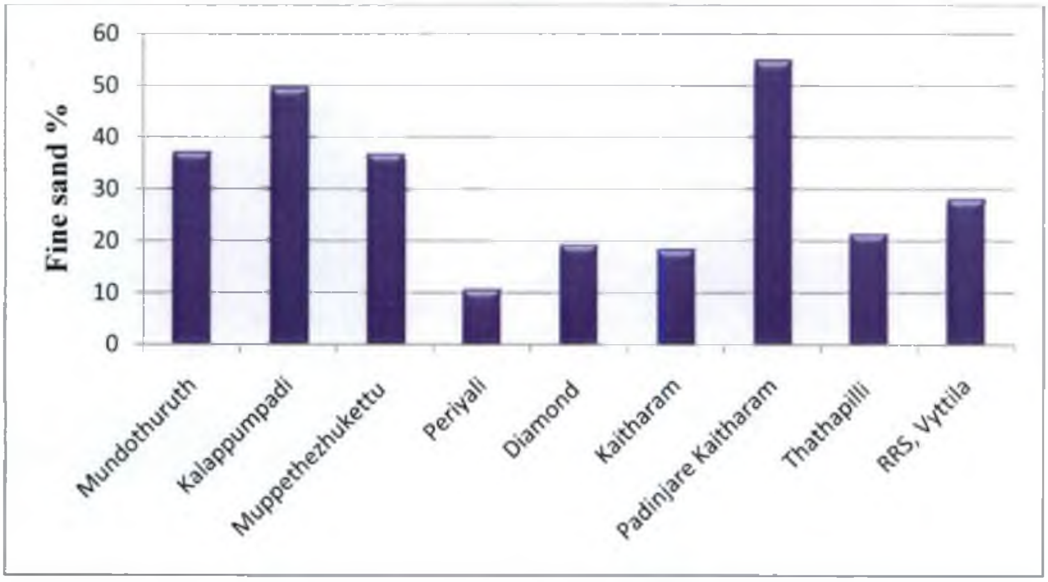

Figure 4: Fine sand content (%) of soil in different locations

5.2. Electrochemical attributes

The soil reaction during the three stages ranged from 3.12 (mound preparation stage) to 5.64 (mound dismantling stage). The pH of the soil ranged from 3.39 (Thathapilli) to 4.75 (Muppathezhukettu) in nine different locations (Figure 5). Most of the soil samples were acidic to neutral. Nair and Money (1972) reported that, the majority of the saline soils of Kerala had acidic pH ranging between 3.0 and 6.8. Since most soils contained more Fe (iii) oxide hydrates, the change in pH is largely due to the reduction of Fe. The inbuilt acidity of *Pokkali* soil becomes more dominant, when the salinity is washed away (Padmaja *et al.,* 1994). Kuruvila (1974) reported that the increase of soil pH will be continued upto 20 days, and then the level was maintained in *Pokkali* fields. Antony *et al.,* (2014) registered a pH of 6.66 in the *Pokkali* fields after the rotational farming. After the harvest of fish and prawn, a pH of 3.9 was reported in *Pokkali* soils (Sasidharan *et al.,* 2012). Decreasing pH with increasing salt concentration has been observed in previous studies in wet land soils and sediments (Khattak *et al.,* 1989; Weston *et al.,* 2006; James *et al.,* 2009).

The electrical conductivity during the three stages ranged from 2.21 (mound dismantling) to 5.61 dS m^{-1} (mound preparation) (Figure 6). Electrical conductivity varied from 1.77 dS m^{-1} to 5 dS m^{-1} in the nine locations. The electrical conductivity was higher during the mound preparation stage due to salts accumulated in the soil during the high saline phase. After that, the rainfall during south west monsoon washes away the salt and electrical conductivity gets reduced in the subsequent stages of cultivation. The EC values ranging from 0.01 to 7.80 dS m^{-1} were observed during low saline phase of *Pokkali* soils (Shylaraj *et al.,* 2013). Most of the rain water and fresh water from rivers removes salinity of the soil partially and soil attains EC, ranging between 6-8 dS m^{-1} (Tomy *et al.* 1984). During January - May, the EC ranges between 12-24 dSm^{-1} (Shylaraj *et al.,* 2013). Salinity tolerant rice varieties are grown when water salinity and soil EC are less than 6 mg g^{-1} and 6 dS m^{-1} respectively (Shylaraj and Sasidharan, 2005). Antony *et al.,* (2014) reported a maximum EC value as 0.19 dS m^{-1} and minimum as 0.02 dS m^{-1} in *Pokkali* soils of Chellanam, after the rotational farming.

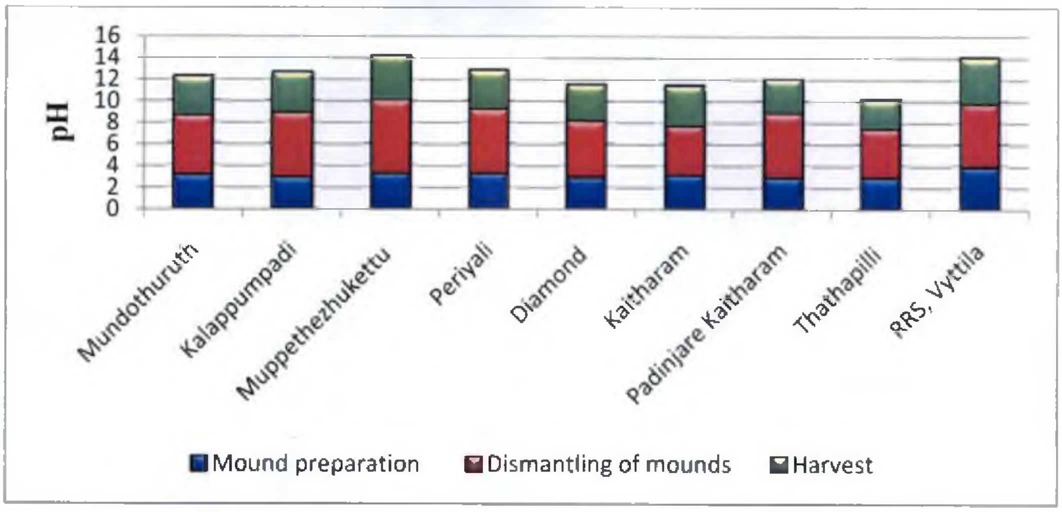

Figure 5: Soil reaction in different locations during three stages of cultivation

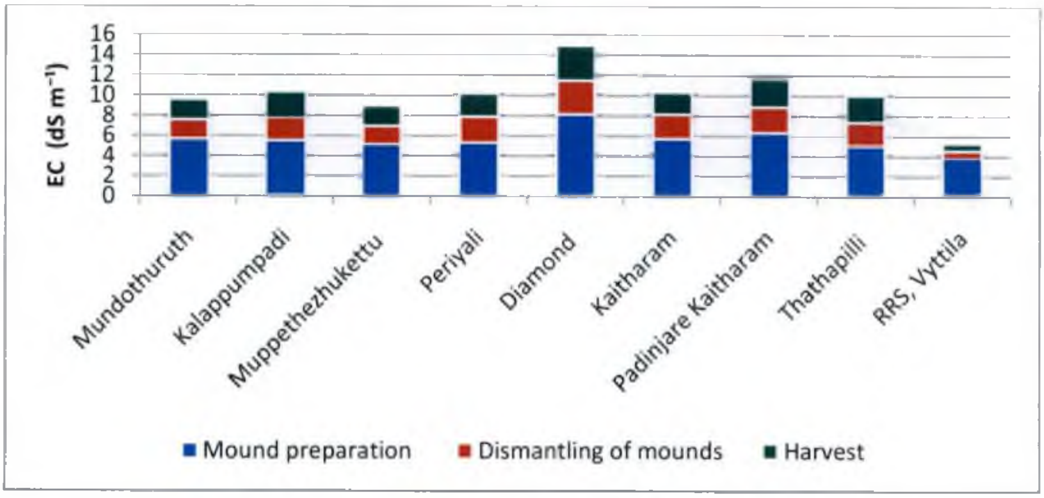

Figure 6: Electrical conductivity of soil in different locations during three stages of cultivation

Among three stages of cultivation, highest redox potential was recorded during harvest stage (358.5 mV) (Figure 7). The redox potential of nine locations varied between 221.66 (Muppathezhukettu) and 278.55 mV (Padinjare Kaitharam). The soil Eh represents an excellent quantifying tool for defining the oxygen status as well as the chemical status in wetland soils (Pezeshki and DeLaune, 2012). In periodically flooded soils, the range of Eh is much wider, between approximately -300 to +700 mV, than either aerated (Eh > +400 mV) or permanently waterlogged (Eh < +350 mV) soils (Pearsall and Mortimer, 1939; Mortimer, 1941; Mitch and Gosselink; 2007). A chain of reactions is initiated upon soil flooding leading to low soil redox potential conditions (Pezeshki and DeLaune, 2012). Redox potential ranging between +400 and -300 mV represents low oxygen conditions. If the Eh of soil is around -300 mV, the soil may be under highly reduced condition (Pezeshki and DeLaune, 2012).

5.3. Chemical attributes

5.3.1. Available nutrients

The mean value of available N came under low fertility status in eight locations and RRS, Vyttila during different stages of cultivation (Figure 8). Even though the organic carbon content was high, available N status was low. Available N varied from 78.52 (harvest) to 174.22 kg ha^{-1} (mound preparation) during the three stages. A unique feature of submerged soils is the simultaneous formation and loss of NO_3^-, occurring within the adjoining aerobic and anaerobic soil zones (Buresh *et al.,* 2008). The breakdown of soil organic matter and plant residues is typically slower in submerged than aerobic soil (Acharya, 1935; Villegas-Pangga *et al.,* 2000). Hence, a lower gross N mineralization rate would be expected in submerged soils (Buresh *et al.,* 2008).

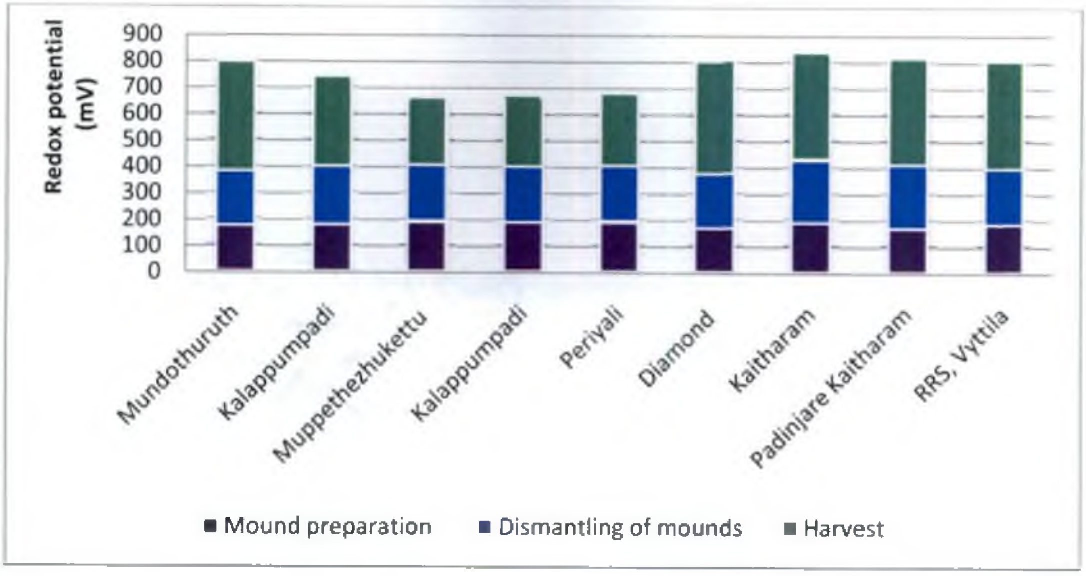

Figure 7: Redox Potential of soil in different locations during three stages of cultivation

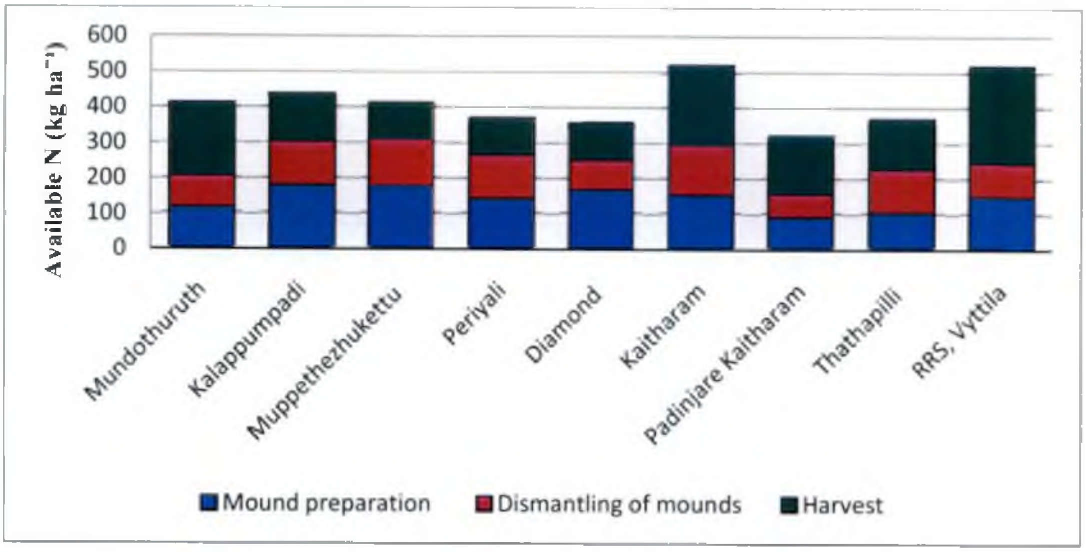

Figure 8: Available nitrogen content of soil in different locations during three stages of cultivation

Available P content in *Pokkali* soil during mound preparation, mound dismantling and harvest stages came under high fertility status (Figure 9). The higher content of available P is observed in all locations, which may be due to the tidal action (Sasidharan, 2004). The availability of phosphorus is more in flooded conditions. This increase is due to reduction of ferric (Fe^{3+}) phosphate to ferrous (Fe^{2+}) phosphate and the release of P from insoluble Fe and Al compounds and some dissolution of Ca phosphates at higher CO_2 levels in the soil solution (Snyder,2002). A decrease in pH favors the solubility of calcium phosphate as well as that of ferrous and manganous phosphate (Stumm and Morgan, 1970).

The three stages recorded high content of available K (Figure 10). Surface soils of *Pokkali* fields were rich in K (Samikutty, 1977). As submergence advanced, the Kcontent of the soil found to be increased (Kuruvila, 1974). This significant increase may be due to the frequent tidal action (Sasidharan, 2004). The available K content of *Pokkali* soils varied between 13 and 1777 kg ha^{-1} (Anilkumar and Annie, 2010).

Available Ca was found to be higher (> 300 mg kg^{-1}) in different locations during three stages of cultivation (Table 10). The calcium content showed a range from 76 to 256 mg kg^{-1} during low saline phase (Anilkumar and Annie, 2010). Nair and Money (1972) reported a total CaO percent of 0.01 per cent in *Pokkali* soils. The observed values of available Mg in *Pokkali* soils showed very low values during mound preparation, mound dismantling and harvest (<120 mg kg^{-1}) (Figure 11). Kuruvila (1974) reported a Mg content of 9.90 cmol (p^+) kg^{-1} in *Pokkali* soils. Aryalekshmi (2016) observed Mg content of 26.17 mg kg^{-1} in *Pokkali* soils. Soil fertility assessment conducted by Kerala state planning board in Ernakulam

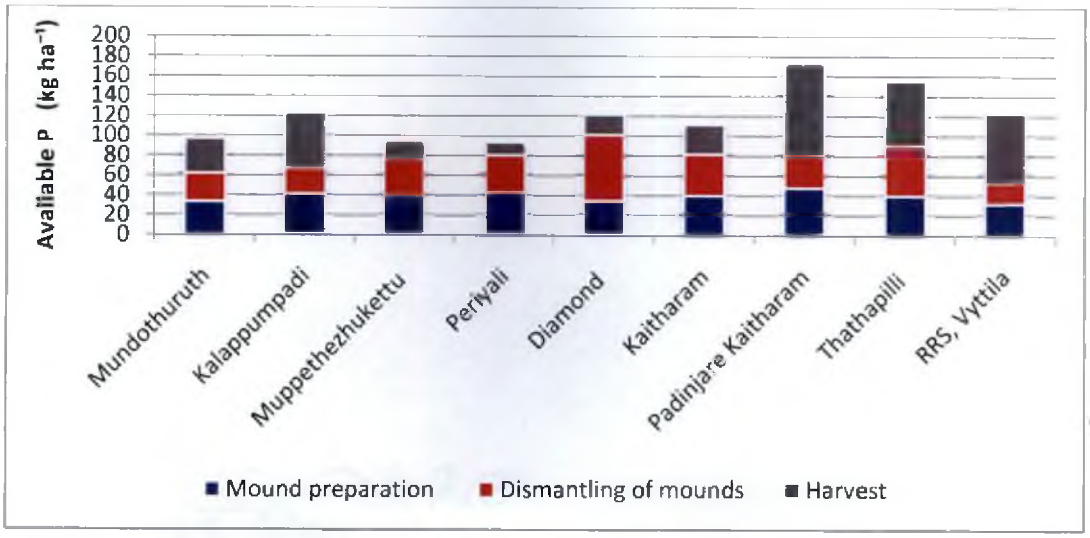

Figure 9: Available phosphorus content of soil in different locations during three stages of cultivation

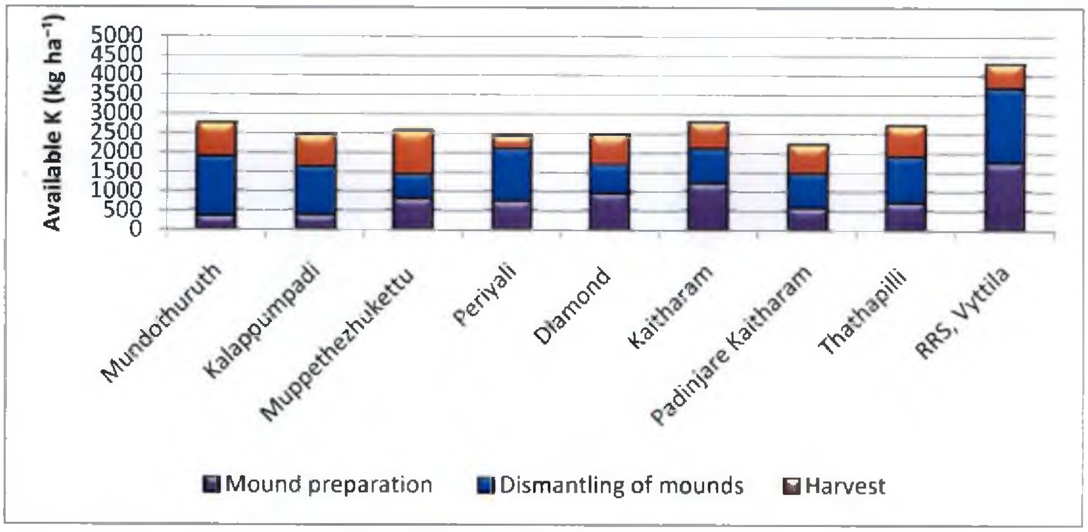

Figure 10: Available potassium content of soil in different locations during three stages of cultivation

district revealed that Mg deficiency was more pronounced in the pokkali lands (85 per cent) (KSPB, 2013). High content of available S was recorded in *Pokkali* soils (Table 12). The high levels of S owes to the high organic matter content. Kuruvila (1974) observed available S content of 242 mg kg^{-1} in *Pokkali* soils. Santhosh (2013) also reported high levels of S in *Pokkali* soils.

Avaialble Fe and Mn were present in toxic levels in *Pokkali* soils (Figure 12 and 13). The Fe toxicity and injurious concentrations of organic acids and sulphide may be present to cause toxicity to lowland rice, especially in soils with high organic matter and impeded drainage (Yoshidha, 1981). The available Fe content in *Pokkali* soils was reported as 171 to 2321 mg kg^{-1} soil (Shylaraj *et al.*, 2013). The availability of Fe and Mn was increased due to submergence (Ponnamperuma, 1972). The Fe is highly soluble in the lowest ranges of pH which are suitable for plant growth (Mahal, 2010). The available Zn was found to be high in *Pokkali* soils (Figure 14). The available Cur was present in a sufficient range during the three stages of cultivation (Figure 15). Anilkumar and Annie (2010) reported that the Cu and Zn content were 2 to 13 mg kg^{-1} and 2 to 173 mg kg^{-1} respectively under low saline phase.

The available B concentration varied between 0.001 and 1.59 mg kg^{-1} soil in different locations (Figure 16). In some locations, it was present in toxic range. Joseph (2014) also reported B content ranged from 1.45 to 4.3 mg kg^{-1} soil in *Pokkali* soils. The available Na content of soil samples showed significant variation among nine locations. It varied between 12.03 and 26.69 meq 100 g^{-1} soil (Figure 17). Kuruvila (1974) observed a range of 0.57 to 2.16% of available Na in *Pokkali* soils. Joseph (2014) also reported high available Na content in *Pokkali* lands. The presence of large content of B and Na may be due to sea water inundation.

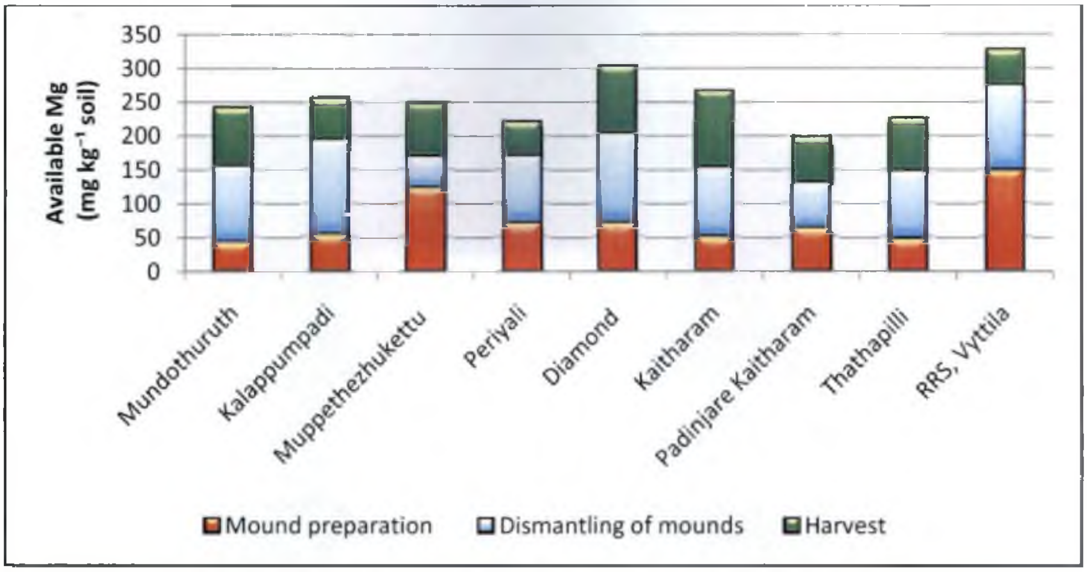

Figure 11: Available magnesium content of soil in different locations during three stages of cultivation

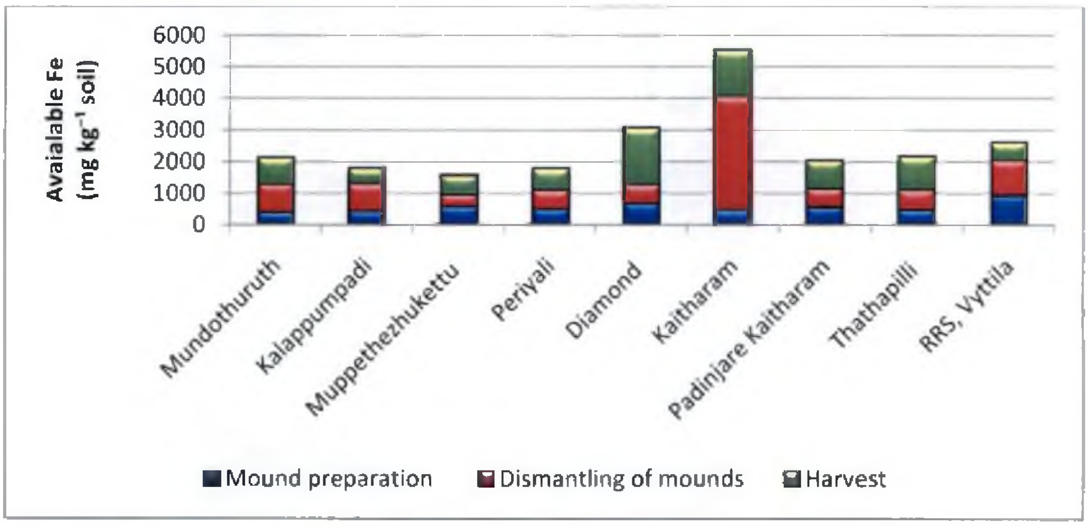

Figure 12: Available iron content of soil in different locations during three stages of cultivation

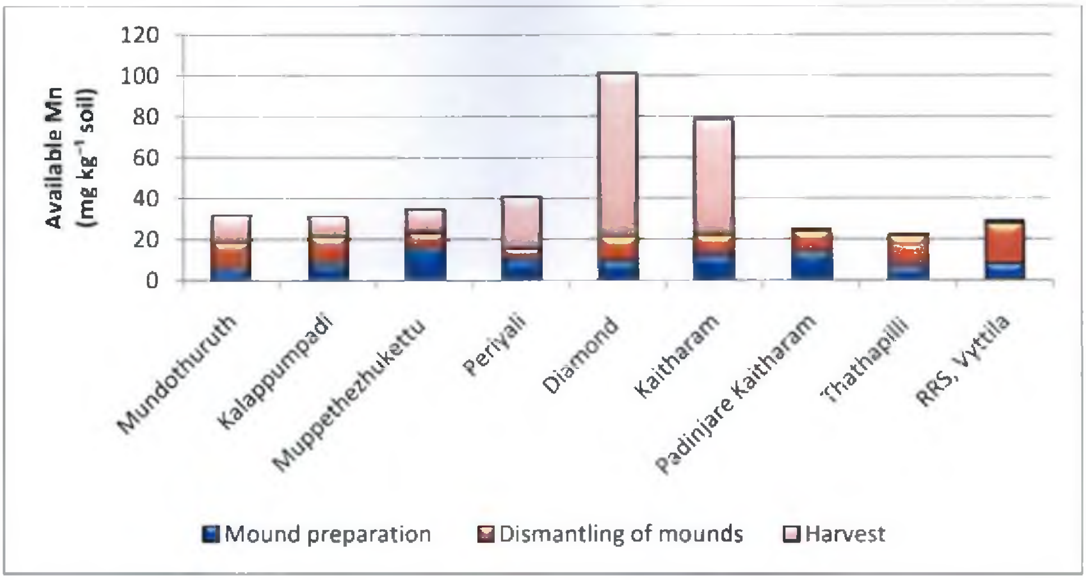

Figure 13: Available manganese content of soil in different locations during three stages of cultivation

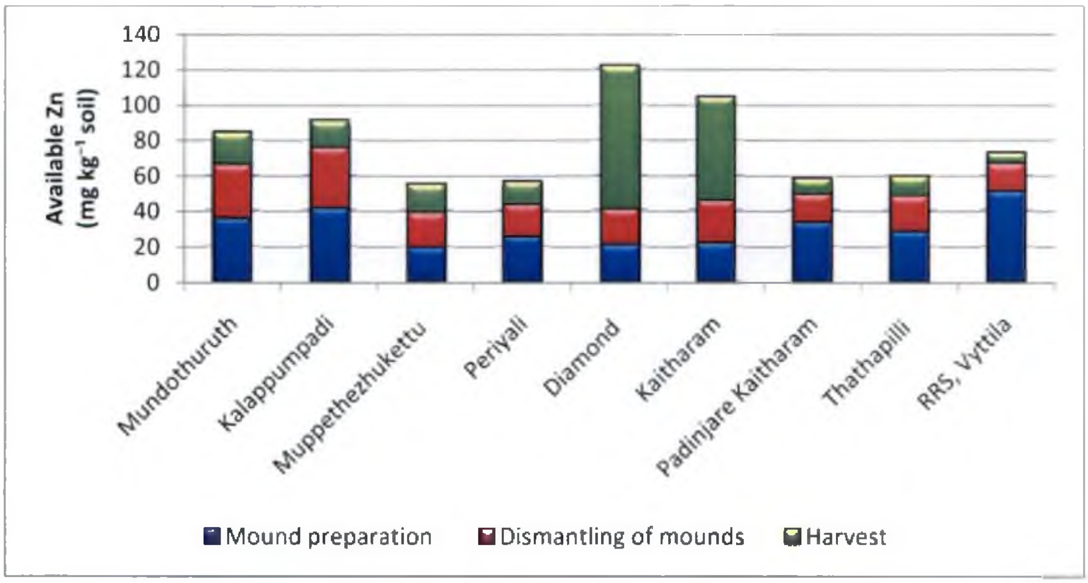

Figure 14: Available zinc content of soil in different locations during three stages of cultivation

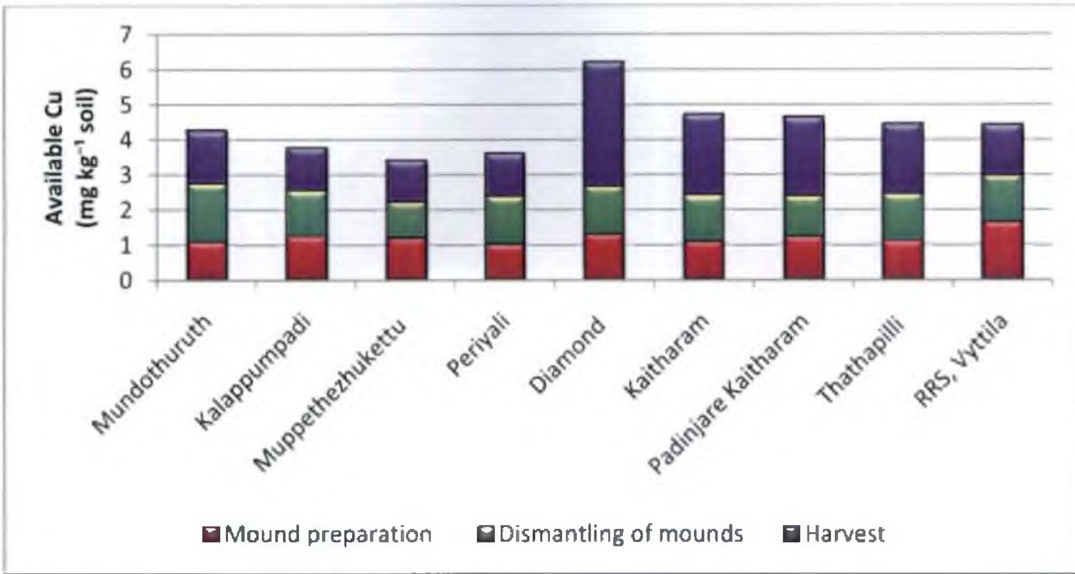

Figure 15: Available copper content of soil in different locations during three stages of cultivation

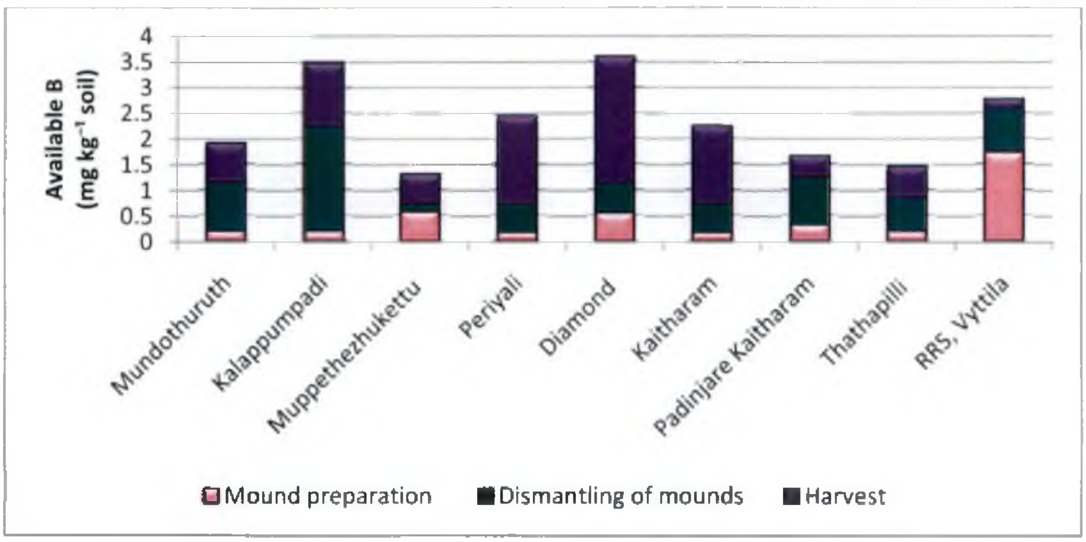

Figure 16: Available boron content of soil in different locations during three stages of cultivation

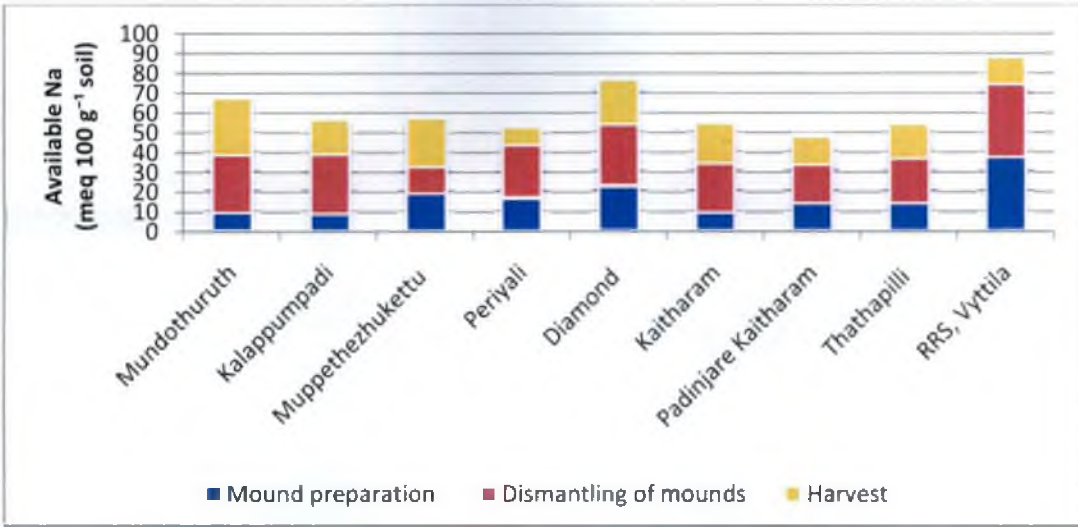

Figure 17: Available sodium content of soil in different locations during three stages of cultivation

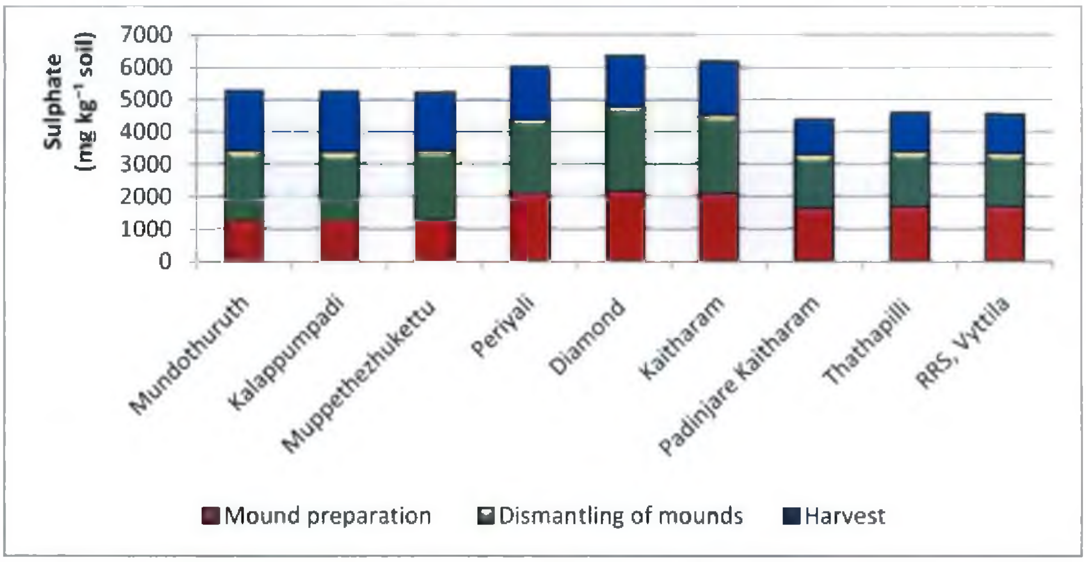

Figure 18: Sulphate content of soil in different locations during three stages of cultivation

The chloride content varied between 0.0086 and 0.026 per cent in soil (Table 20). Nair and Money (1972) reported a chloride content of 0.20 per cent in *Pokkali* lands of Vyttila and 0.68 per cent in *Pokkali* soils of North Paravur. The sulphate content was very high in all the nine soils (Figure 18). Kuruvila (1974) observed a sulphate content of 0.031 per cent in *Pokkali* soils. Nair and Money (1972) observed 0.32 per cent of sulphate in *Pokkali* soils. Flooding caused an increase of sulphate sulphur in *Pokkali* soils during the first ten days of submergence and then decreased (Kuruvila, 1974). The phosphate content was found to be in a range of 17.02 to 28.62 mg kg^{-1} soil (Figure 19). Antony *et al.,* (2014) recorded phosphate content of 32.5 to 157.8 mg kg^{-1} soil in *Pokkali* lands.

5.3.2. Cation exchange capacity and exchangeable cations

The CEC of *Pokkali* soils varied between 9.40 and 24.75 cmol (p^+) kg^{-1} soil among the stages of cultivation (Table 24). Among locations, Diamond registered highest CEC (21.37 c mol (p^+) kg^{-1} soil). According to Varghese *et al.,* (1970), CEC of *Pokkali* soil tends to decrease with depth and CEC was reported as 38.2 cmol (p^+) kg^{-1} soil. Kuruvila (1974) found out a CEC value of 20 cmol (p^+) kg^{-1} in *Pokkali* soils.

Among three stages, mound preparation stage had the highest content of exchangeable Ca (2.14 cmol (P^+) kg^{-1}soil) (Figure 20). The exchangeable Ca content of *Pokkali* soils was reported as 2.20 cmol (P^+) kg^{-1}soil (Varghese *et al.,* 1970). The upper horizon contain higher amount of exchangeable Ca than that of exchangeable Mg (Varghese *et al.,* 1970). Kuruvila (1974) reported an exchangeable Ca content of 5.10 cmol (P^+) kg^{-1}soil.

The content of exchangeable Mg varied between 0.309 cmol (P^+) kg^{-1} soil and 0.376 cmol (P^+) kg^{-1}soil during three stages of cultivation (Figure 21). The content varied between 0.31 cmol (P^+) kg^{-1}soil and 0.34 cmol (P^+) kg^{-1}soil among nine locations. The exchangeable Mg content of *Pokkali* soils was reported as 7.70 cmol (P^{+}) kg^{-1}soil (Varghese *et al.*, 1970). The exchangeable Mg decreases with depth in *Pokkali* soils (Varghese *et al.*, 1970). Kuruvila (1974) reported an exchangeable Mg content of 6.45 cmol (P^{+}) kg^{-1}soil. The low Mg status noticed can be attributed to existence of Mg in the exchangeable complex though it is a dominant exchangeable cation in *Pokkali* soils (Samikutty, 1977; Varghese *et al.*, 1970).

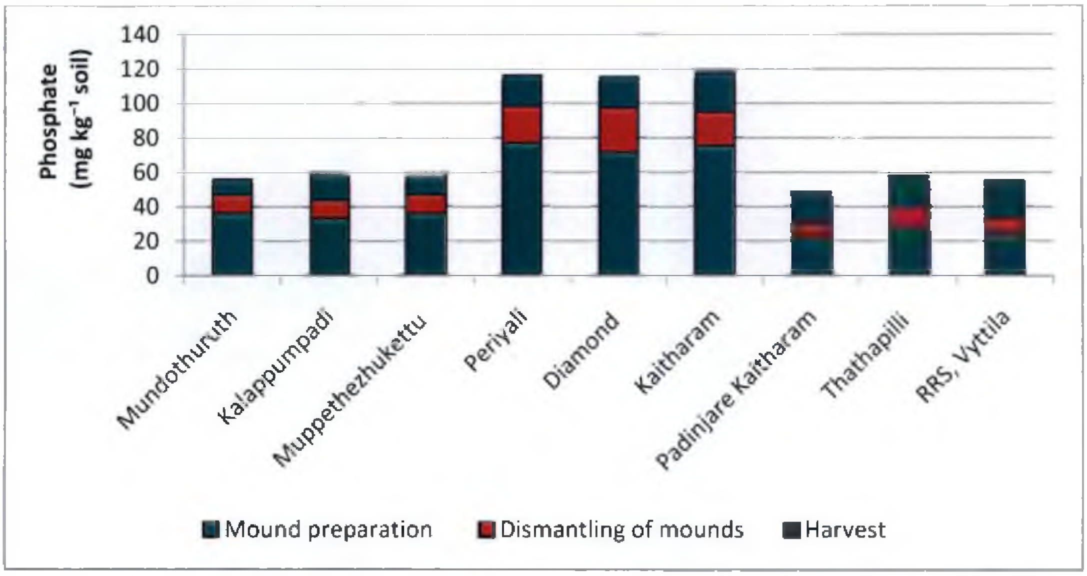

Figure 19: Phosphate content of soil in different locations during three stages of cultivation

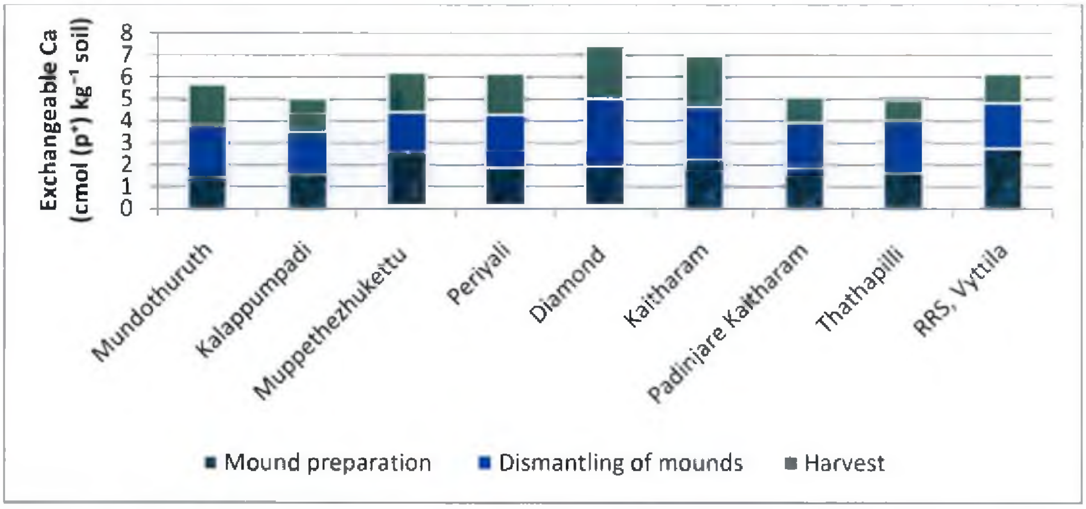

Figure 20: Exchangeable calcium content of soil in different locations during three stages of cultivation

The exchangeable Na content showed an increasing trend from mound preparation to harvest stage (Figure 22). This increase can be attributed to the sea water inundation. Santhosh (2013) reported a higher quantity of exchangeable Na in *Pokkali* soils. The exchangeable K content showed a range of 0.03 to 0.96 cmol (P^+) kg^{-1} soil during three stages among nine locations (Figure 23). Soil samples collected during harvest stage had the highest K content (0.655 cmol (P^+) kg^{-1} soil). The exchangeable K content of *Pokkali* soils was reported as 1.10 cmol (P^+) kg^{-1} soil (Varghese *et al.*, 1970). Kuruvila (1974) reported an exchangeable K content of 0.64 cmol (P^+) kg^{-1} soil.

The exchangeable Al content ranged from 0.04 to 4.27 cmol (P^+) kg^{-1} soil among locations, during three stages of cultivation (Figure 24). Kuruvila (1974) reported an exchangeable Al content of 2.95cmol (P^+) kg^{-1} soil in *Pokkali* soil. Among three stages, the exchangeable Fe content ranged between 0.15 to 0.68 cmol (P^+) kg^{-1} soil (Figure 25). Kuruvila (1974) reported an exchangeable Fe content of 0.09 cmol (P^+) kg^{-1} soil. The order of dominance of exchangeable cations in

Pokkali soils was reported by Aryalekshmi (2016), which as Ca = Na> Al> Mg>K > Fe.

5.3.3. Exchangeable sodium percentage, sodium adsorption ratio and percentage cation saturation

The ESP of soil did not vary significantly among three stages of cultivation. It varied between 59.35 and 69.17 per cent among eight locations and RRS, Vyttila (Figure 26). The ESP of the *Pokkali* soils ranged between 13.7 and 83.3 (Samikutty, 1977). The SAR showed a range of 1.48 to 11.45 (Figure 27). Samikutty (1977) reported a SAR range of 11.7 to 34.8 in *Pokkali* soils.

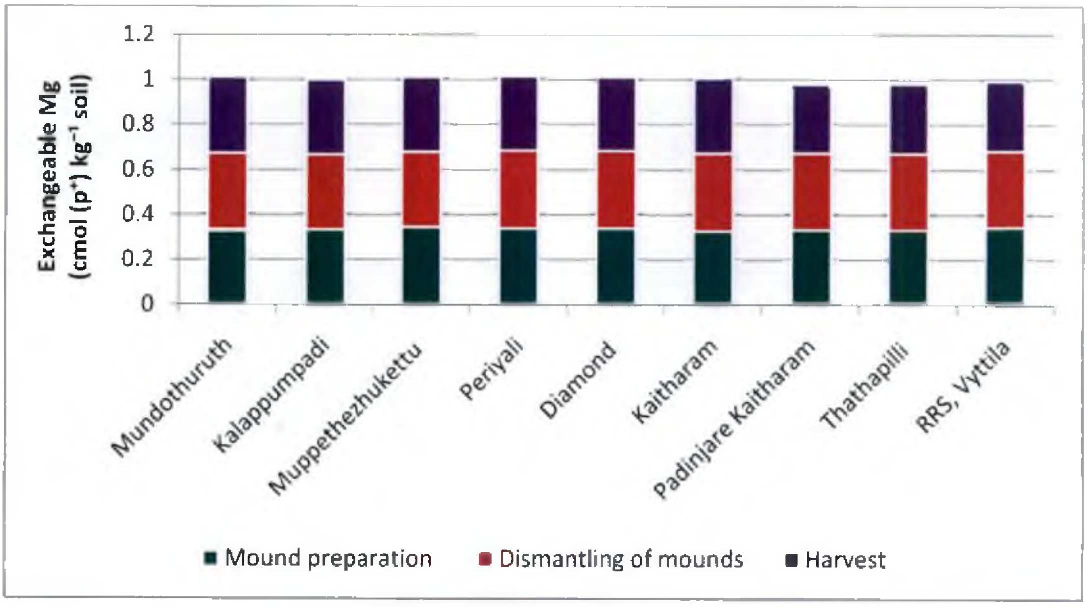

Figure 21: Exchangeable Magnesium content of soil in different locations during three stages of cultivation

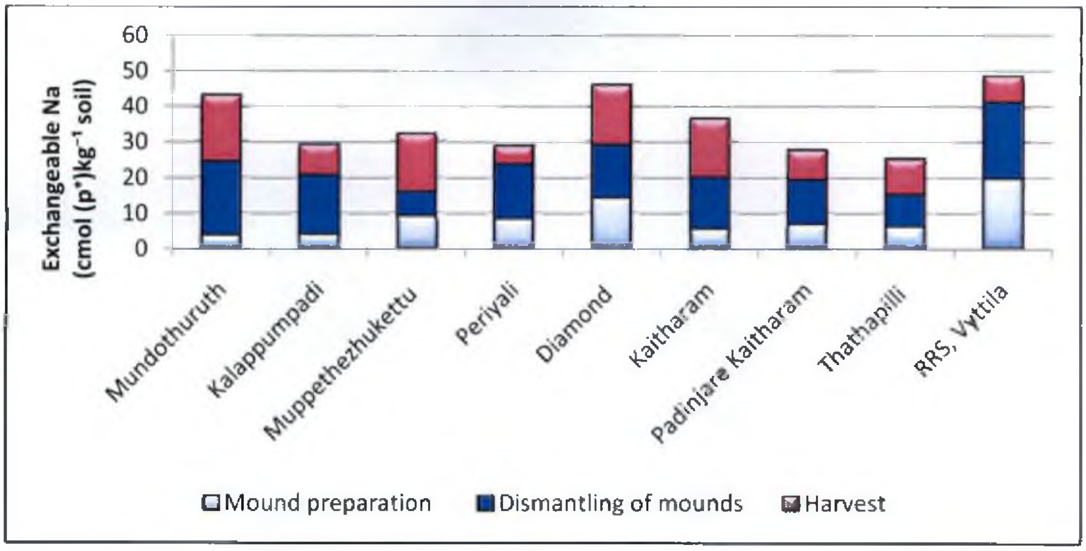

Figure 22: Exchangeable sodium content of soil in different locations during three stages of cultivation

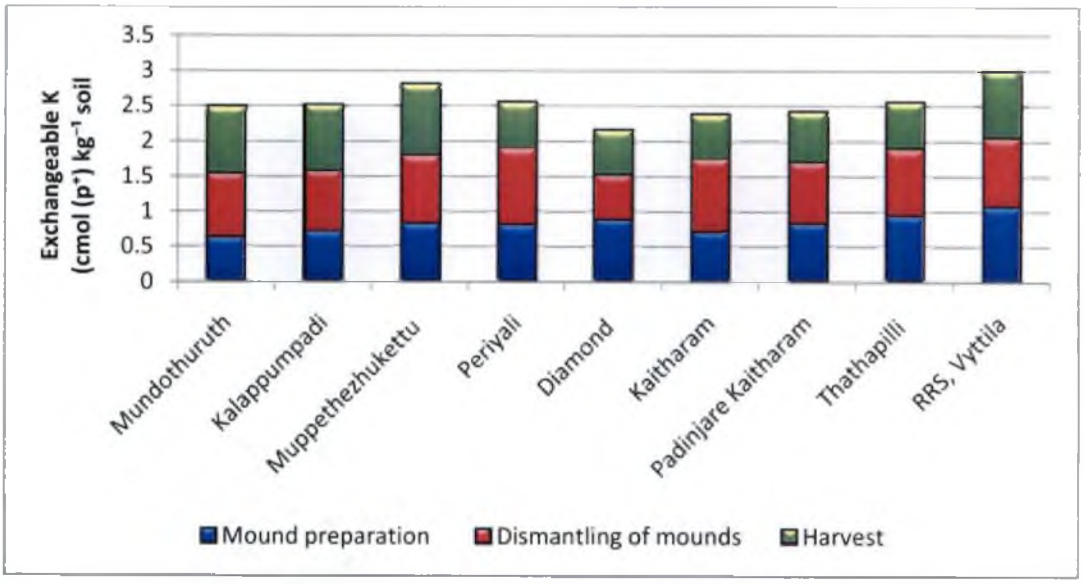

Figure 23: Exchangeable potassium content of soil in different locations during three stages of cultivation

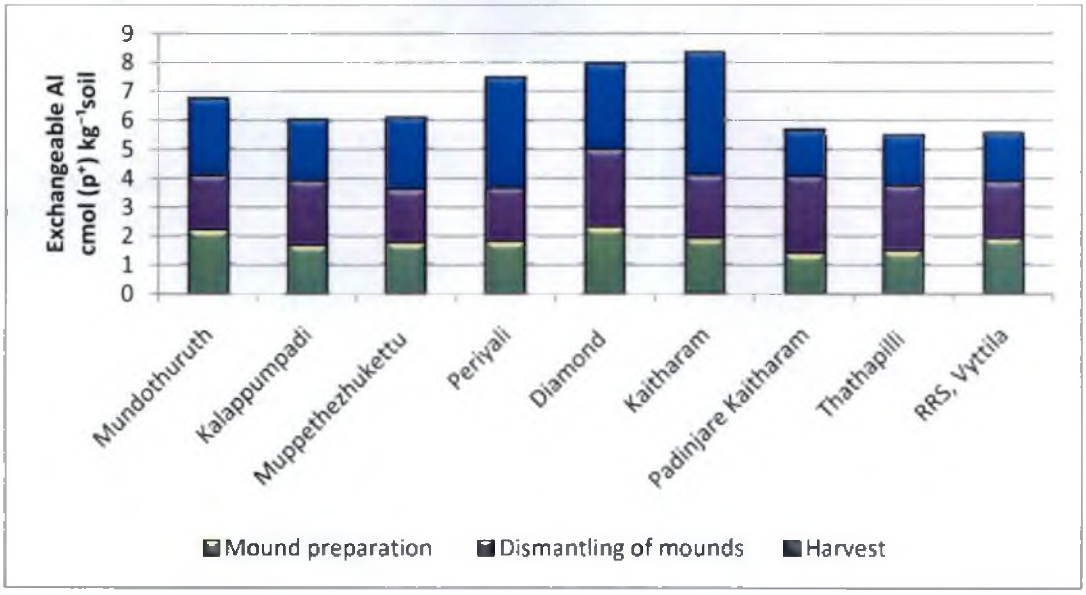

Figure 24: Exchangeable aluminium content of soil in different locations during three stages of cultivation

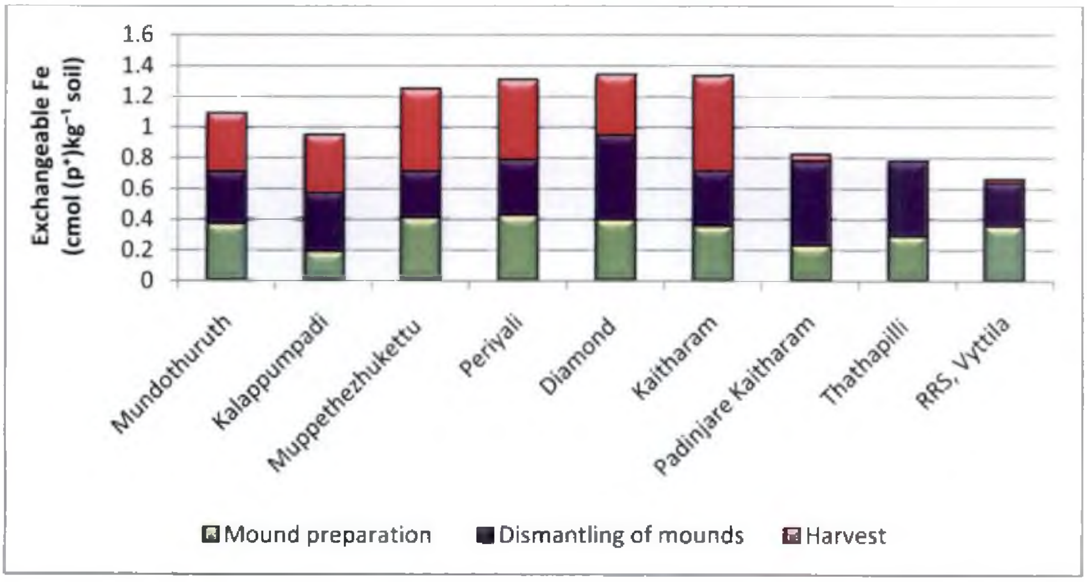

Figure 25: Exchangeable iron content of soil at different locations during three stages of cultivation

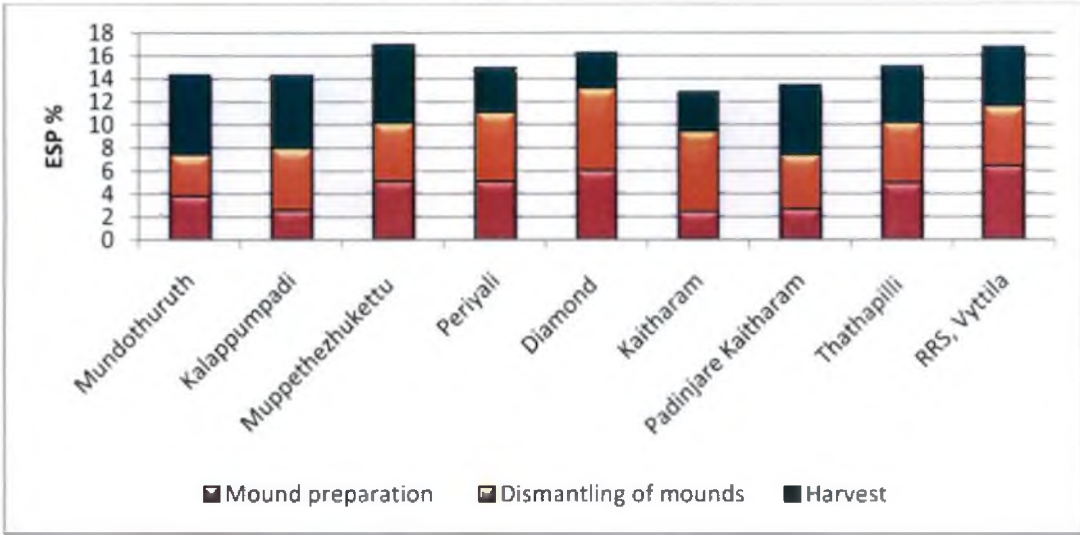

Figure 26: Exchangeable sodium percentage of soil at different locations during three stages of cultivation

The percent saturation of cations such as Ca, Mg, Na, K, Fe and Al were found to be significant during three stages of cultivation. Among the different locations, the percent Mg saturation was found to be in the range of 1.185 to 5.240 per cent (Table 37 and figure 30). The percent saturation of Ca was in a range of 6.7 to 29.4 during three stages (Table 36 and figure 29). The percent saturation of K (Table 39 and figure31) and Fe varied significantly during mound preparation, mound dismantling and harvest stages (Figure 28). The per cent K saturation varied between 2.46 and 4.44 among nine locations during three stages. The ideal percent saturation ranges for soils are 60–80, 10–25 and 3–5 for Ca, Mg and K, respectively (Bear and Toth, 1948; Graham, 1959; Eckert, 1987). In *Pokkali* soil, the percent Ca saturation and percent Mg saturation of soil samples was found to be very low compared to the ideal percentage. The percent K saturation during mound preparation and harvest stages represented the perfect percentage.

5.3.4. Per cent base saturation

Significant difference was observed in percent base saturation of three stages of cultivation as well as nine locations (Table 45). Among the stages, Mound dismantling recorded the least (76.02 per cent) and mound preparation recorded the highest (91.45 per cent).The higher percent base saturation may be due to the presence of large quantity of sodium and calcium in *Pokkali* soil.

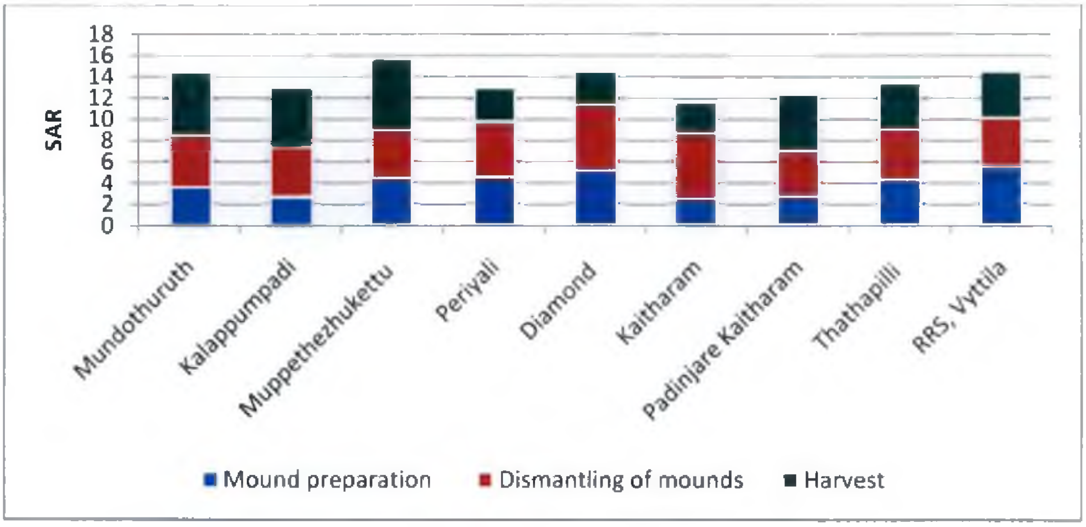

Figure 27: Sodium adsorption ratio of soil in different locations during three stages of cultivation

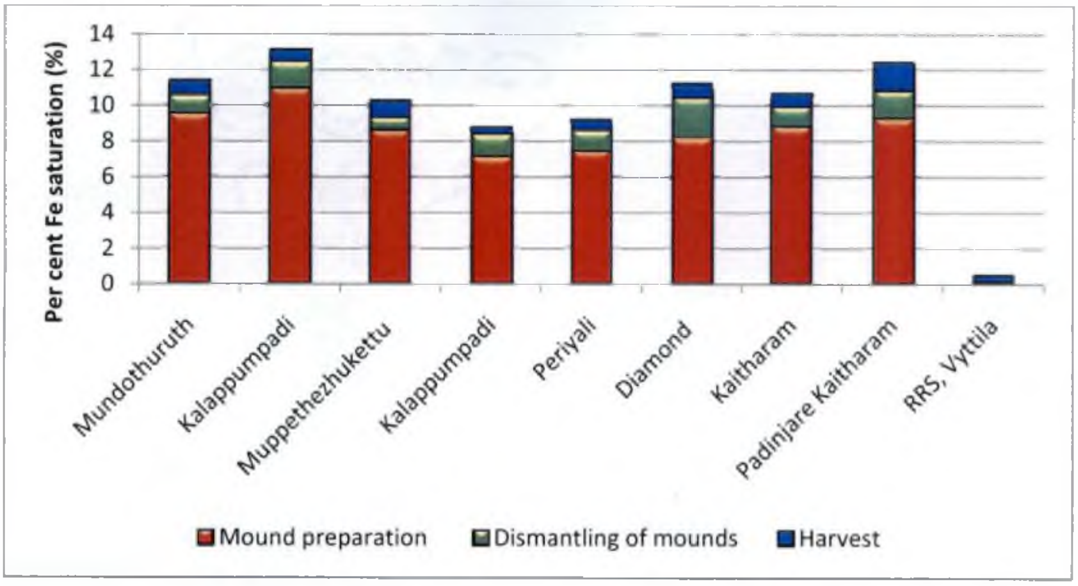

Figure 28: Percent iron saturation of soil in different locations during three stages of cultivation

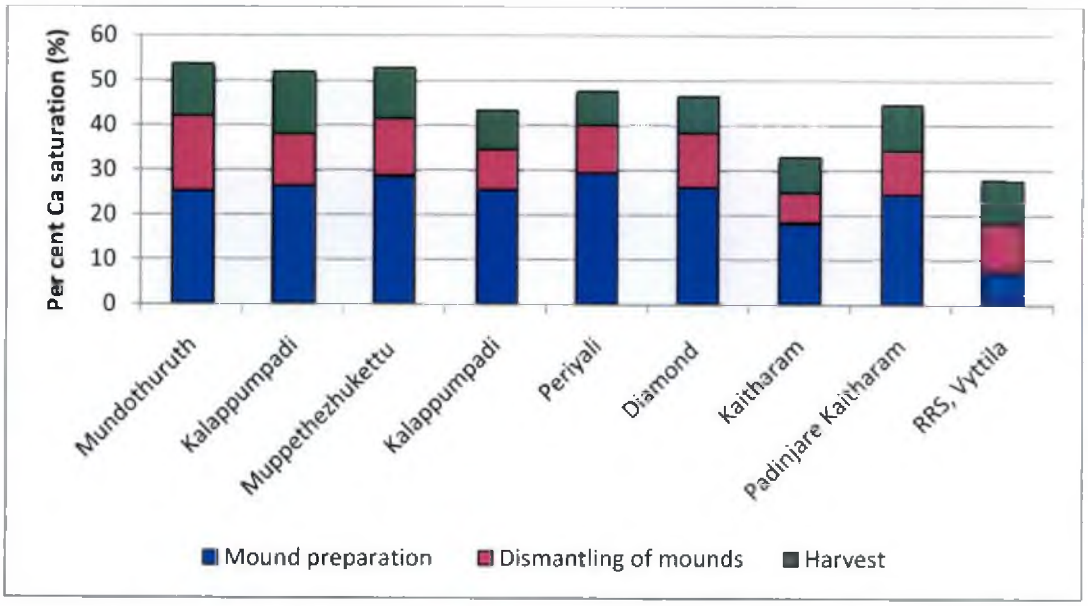

Figure 29: Percent calcium saturation of soil in different locations during three stages of cultivation

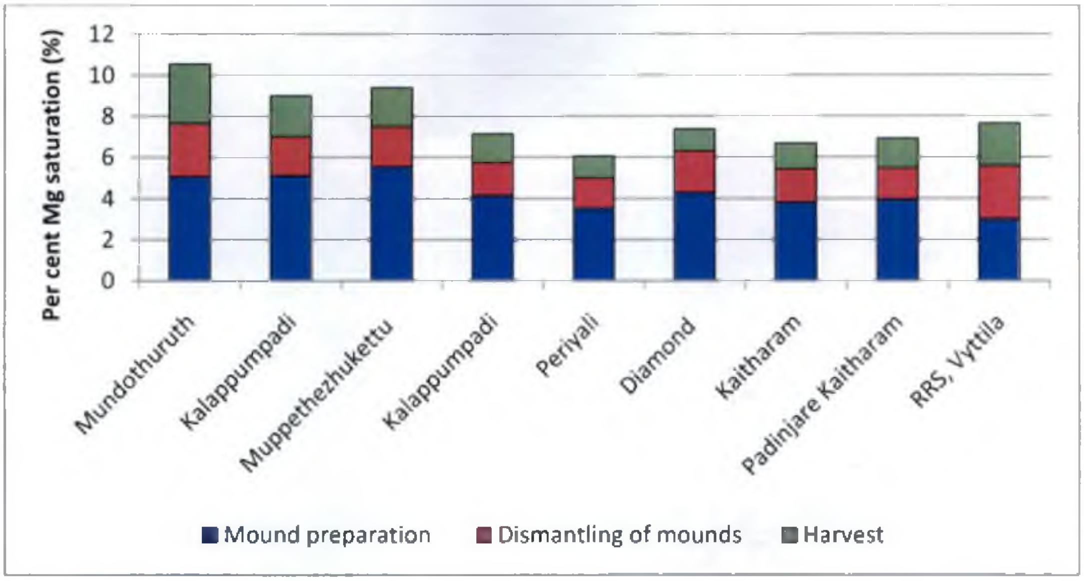

Figure 30: Percent magnesium saturation of soil in different locations during three stages of cultivation

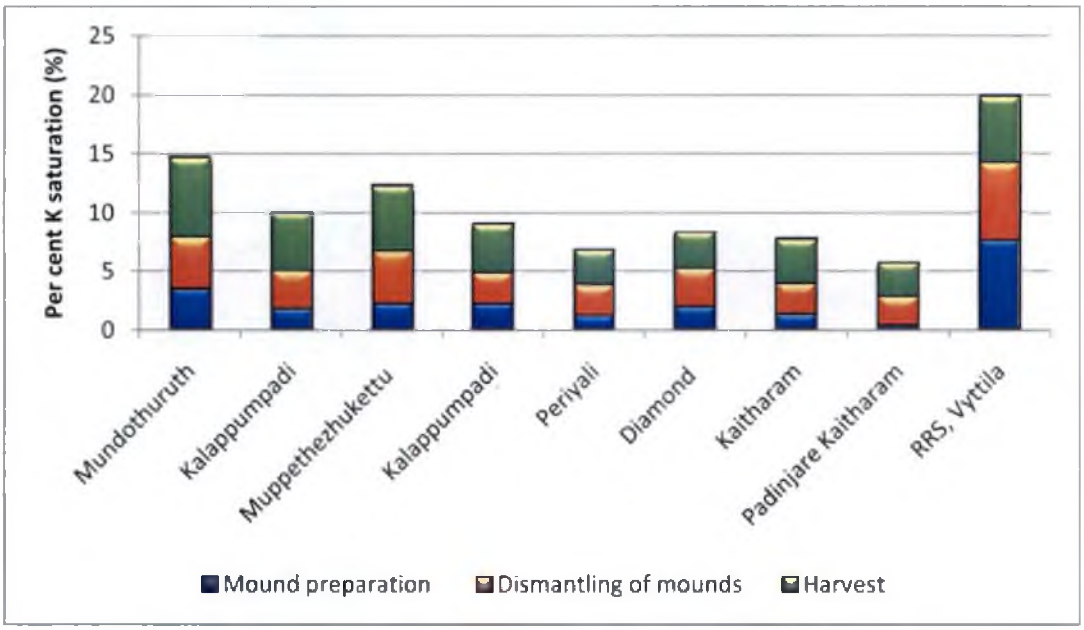

Figure 31: Percent potassium saturation of soil in different locations during three stages of cultivation

5.4. Biological properties of soil

Organic carbon status ranged from 1.2 to 2.1 per cent, which comes under high organic carbon status (> 0.75 per cent) (Figure 32). Kuruvila (1974) reported upto 3.45 per cent of organic carbon in *Pokkali* soils. Joseph (2014) recorded 0.79 to 2.09 percent organic carbon in *Pokkali* tracts. The observed range of total organic carbon was from 0.0325 per cent to 1.05 per cent after rotational farming (Antony *et al.,* 2014). According to Annie *et al.,* (2014), the *Pokkali* soil maintains medium to high organic carbon. Soils with moderate to high content of organic matter can help in adjusting the soil pH to the neutral range, which benefits the wetland rice crop by favoring the nutrient uptake (Sahrawat, 2008).

The MBC content of different locations was not significantly different during the three different stages of cultivation (Figure 33). The microbial biomass is reduced under saturated conditions of soil, due to the shift from aerobic to anaerobic respiration (Inglett *et al.,* 2005). The DHA activity differed among different locations at different stages of cultivation (Figure 34). Flooding cause a significant increase in the DHA activity of soils (Chendrayan *et al.,* 1980; Tate, 1979). Gu *et al.,* (2009) observed higher DHA level (even by 90 per cent) in flooded soil, rather than in non flooded conditions. The DHA activity is positively correlated with organic matter content.

5.5. Soil fertility status

The decisive cations in soil exchange complex were K, Mg, Cu and Na (Table 76). Concentrations of ions namely P, Fe, Mn, Zn, Al, B and sulphate were high in *Pokkali* soils, compared to the sufficiency range (Annexure II). At pH values less than 5.0, Al, Fe, and Mn become soluble and present in toxic concentrations, affecting

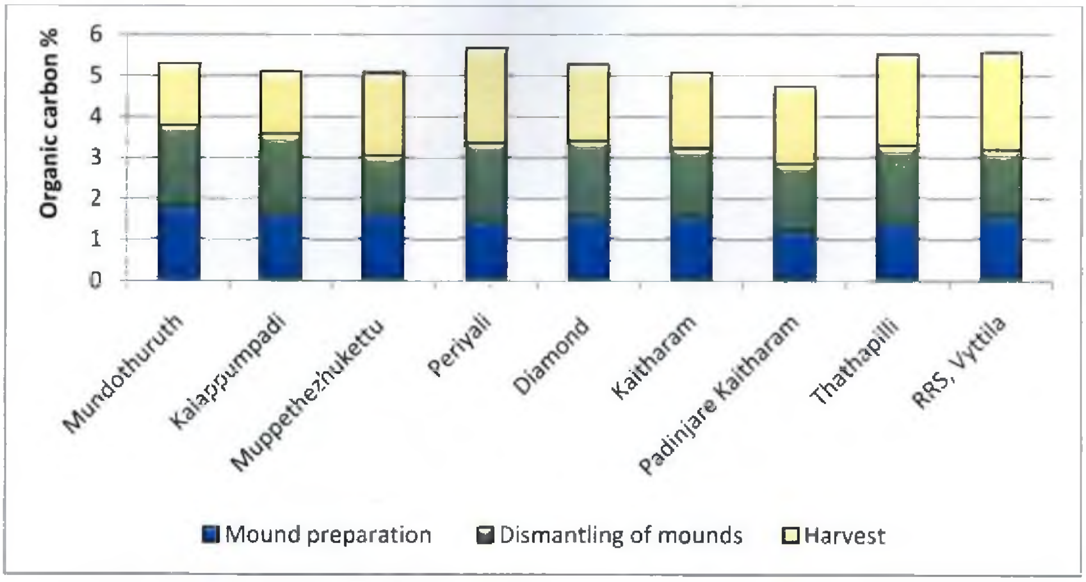

Figure 32: Organic carbon content of soil in different locations during three stages of cultivation

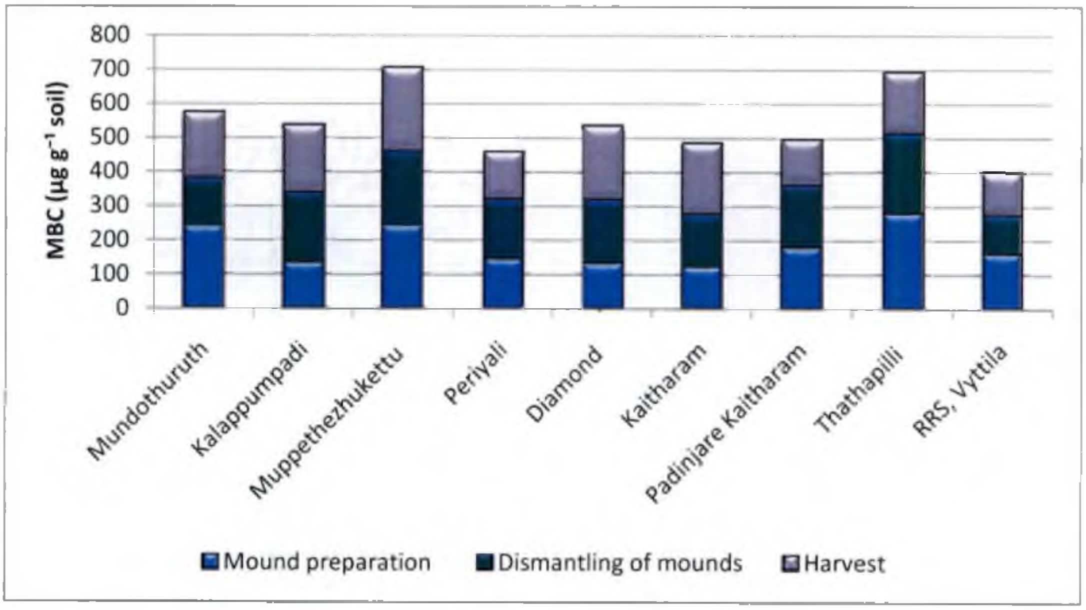

Figure 33: Microbial biomass carbon of soil in different locations during three stages of cultivation

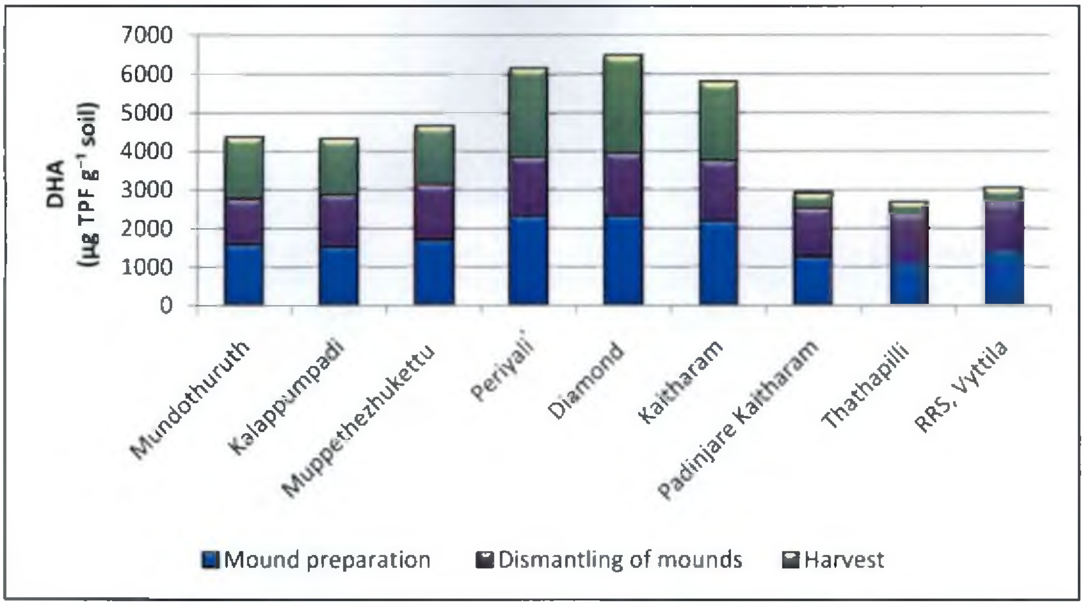

Figure 34: Dehydrogenase activity of soil in different locations during three stages of cultivation

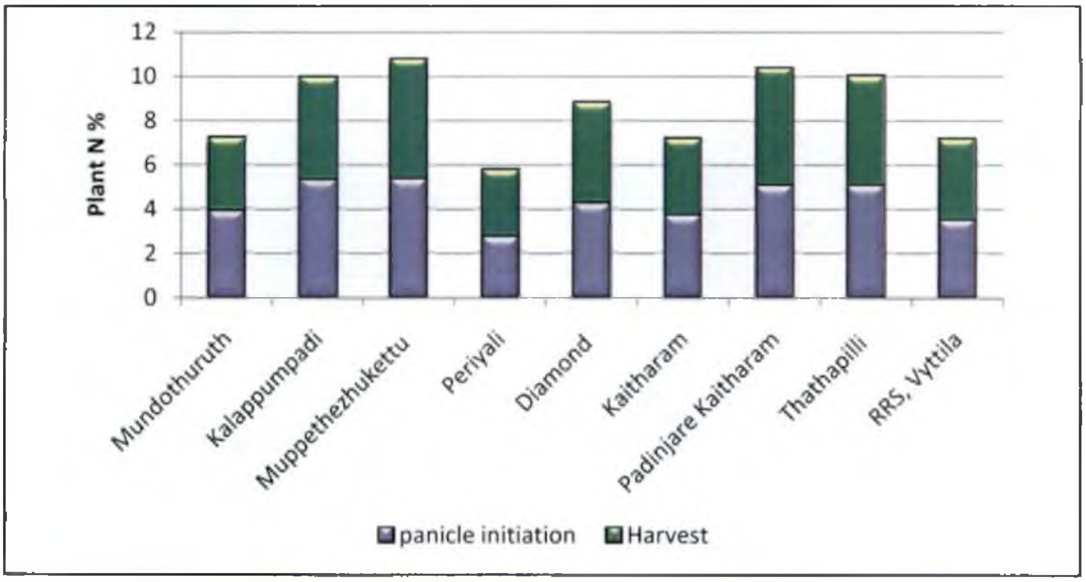

Figure 35: Nitrogen percent of plant samples

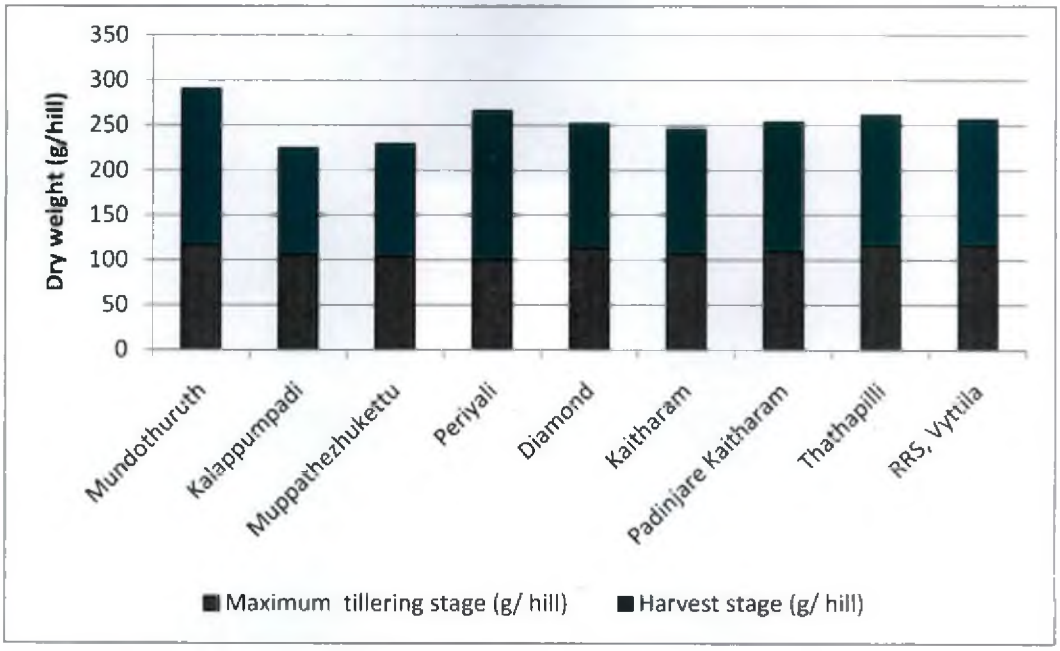

Figure 36: Dry weight of plant samples at two growth stages

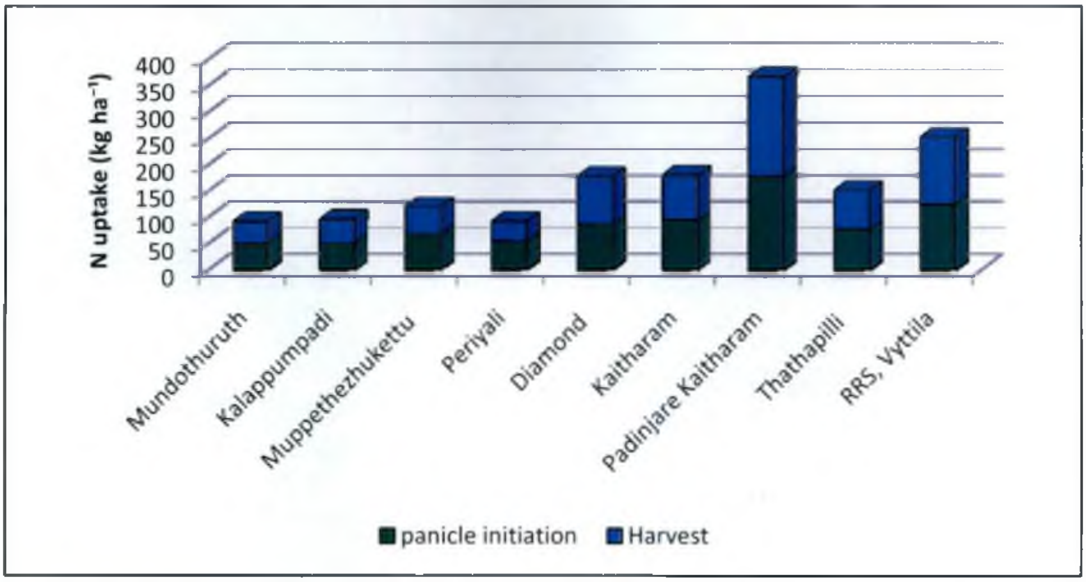

Figure 37: Plant nitrogen uptake

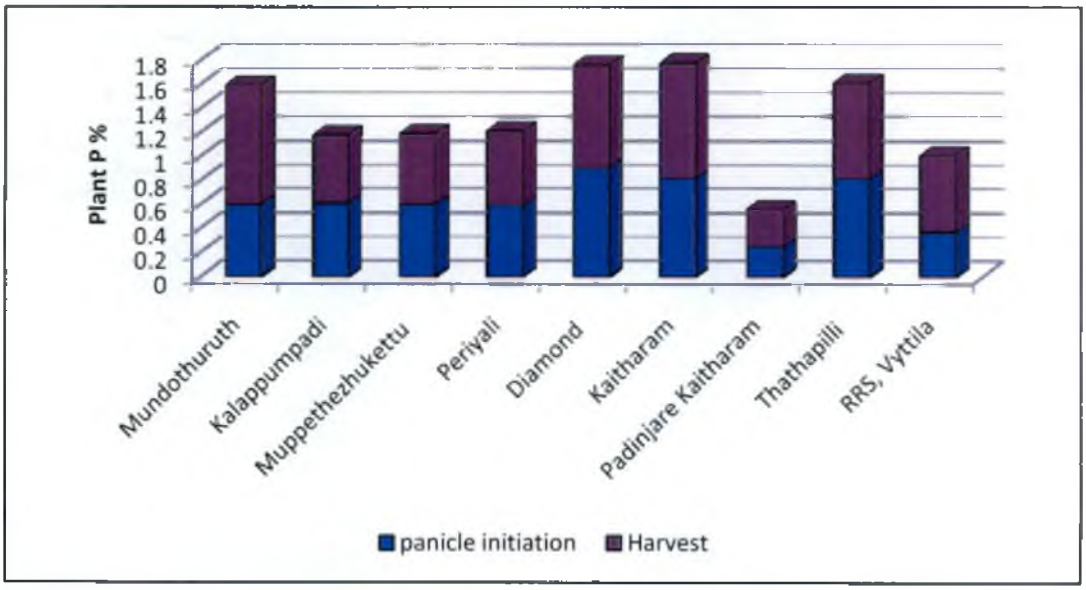

Figure 38: Phosphorus content in plant samples

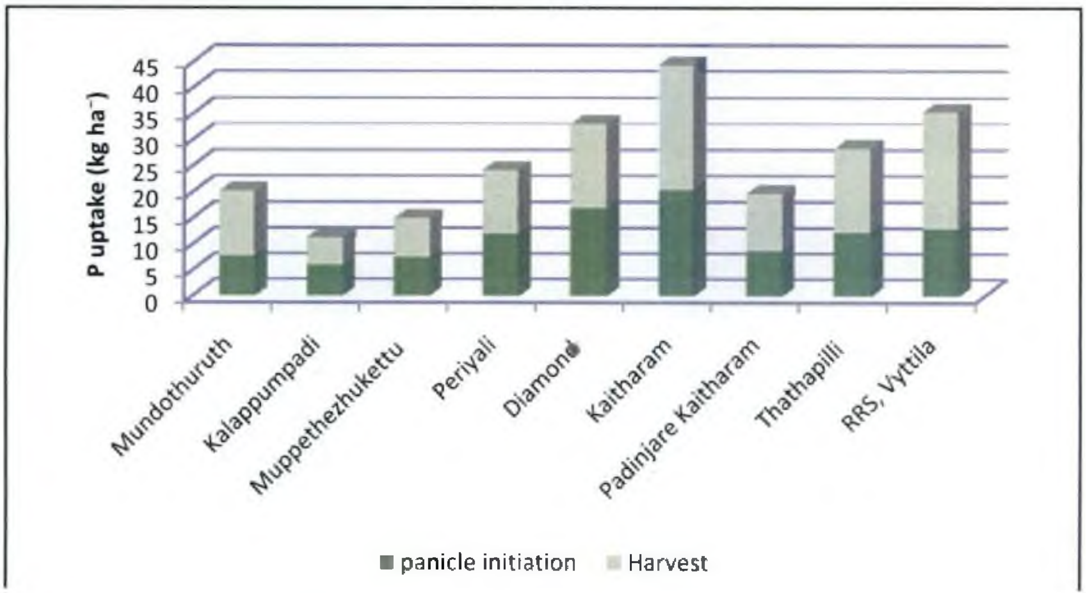

Figure 39: Plant phosphorus uptake

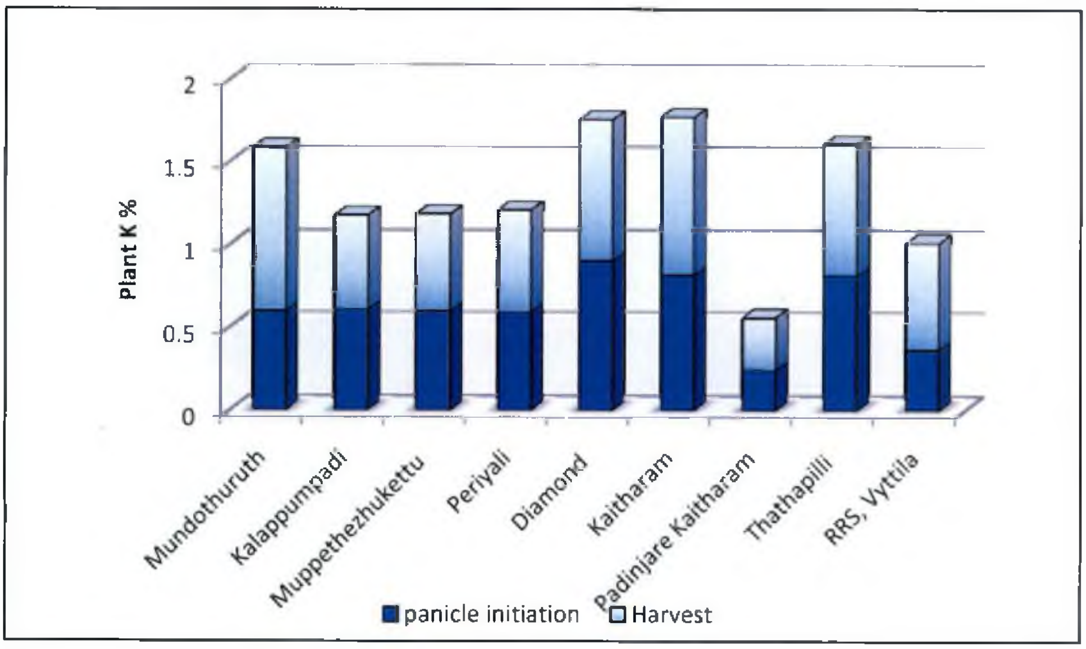

Figure 40: Potassium content of plant samples

growth of some plants. The Al toxicity limits plant growth in most strongly acid soils. Below a pH of 5.3, Al solubilizes from silicate clays and aluminium hydroxides, increasing the activity of exchangeable Al. The Mg was found to be deficient in soil. The availability of Mg in soils depends on soil pH, texture and clay content. Leaching of Mg from coarse textured soils with low pH usually results in its deficiency. Because of increased solubility due to changes in pH and redox potential associated with waterlogged soils, element toxicities during water logging include Mn, Fe, Na, Al and B (Setter *et al.*, 2004).

The anions like bicarbonate and chloride were present in limited quantities in the soil. *Pokkali* soils recorded the absence of carbonate ions. Sulphate and phosphate were the predominant anions existing in the soil (Table 78). Kuruvila (1974) reported mean sulphate content of 1819 mg kg^{-1} in *Pokkali* soils. Anions are not attracted to the predominantly negative charge of soil colloids. Therefore, they are more susceptible for leaching. An exception to this behavior is phosphate anions. These anions do not leach easily through the soil profile, for their specific complexing reactions with soil components (Mortimer, 1941).

5.6. Plant Nutrition

The N content observed in plant samples was in the range 3.413 to 5.060 per cent, which was sufficient for paddy crop (Figure 35). Aryalekshmi (2016) reported 1.07 to 1.42 per cent of N content in rice crop. Padmam (1992) reported 1.58 per cent and 2.21 per cent of N content in rice, in panicle initiation and harvest stages respectively. Higher content of P was seen in plant samples (Figure 37). The P uptake was recorded as 6.34 to 18.59 kg ha^{-1} in *Pokkali* soils (Figure 38). Zhang and Wang (2005) reported 33.0 to 59.8 kg ha^{-1} of N uptake and 8.4- 18.1 kg ha^{-1} of P uptake in rice. The K uptake and Ca uptake was reported as 9.951 to 136.161 kg ha^{-1} and 3.012 to 19.859 kg ha^{-1} respectively. The uptake of N, P and K were reported as 52 kg ha^{-1}, 27.5 kg ha^{-1} and 83 kg ha^{-1} in rice (De Datta, 1987). Zhang and

Wang (2005) observed K uptake 49.1 to 82.7 kg ha^{-1} in rice. Padmam (1992) reported Ca uptake of 10.47 to 24.65 kg ha^{-1} and 18.21 to 24.41 kg ha^{-1} in panicle initiation and harvest stages respectively.

The nutrients, Ca, Fe, Mn and Cu were present in sufficient quantities in plant samples (Annexure IV). Extractable Ca and Mg were slightly higher than water-soluble Ca and Mg after flooding. The S content was deficient in plant samples though soil recorded a higher concentration. It was found to be decreasing from panicle initiation to harvest stage (Annexure IV). The percentage of S decreases with growth. Micronutrients such as Fe, Mn and Cu were present in adequate quantities (Annexure IV). Toxic concentrations of Zn, B and Al were recorded in plant samples. At pH 4.5, the rice plants absorbs significantly high concentrations of Zn, Mg, and Al under reducing conditions (Patrick *et al.*, 1987) and this lead to toxic concentrations in rice. Patrick *et al.*, (1987) reported that, the content of Al in the rice plants ranged from 709 mg kg^{-1} at pH 4.5 to 655 mg kg^{-1} at pH 7.5 and both were above the critical level of Al toxicity of 300 mg kg^{-1}. Wagatsuma (1984) found direct relationship between Al-uptake and Al in the medium. Rice genotypes differ greatly in Zn use efficiency and grain Zn contents and this aspect has been investigated by various researchers (Graham *et al.*, 1999; Nagarathna *et al.*, 2010; Neue, *et al.*, 1988; Refuerzo *et al.*, 2009; Wissuwa *et al.*, 2006; Wissuwa *et al.*, 2008; Yang *et al.*, 1998). Another study revealed that native soil Zn status is the predominant factor to determine grain Zn concentrations followed by genotype (Wissuwa *et al.*, 2006; Wissuwa *et al.*, 2008). A high concentration of sodium was observed in plant samples (Annexure IV).

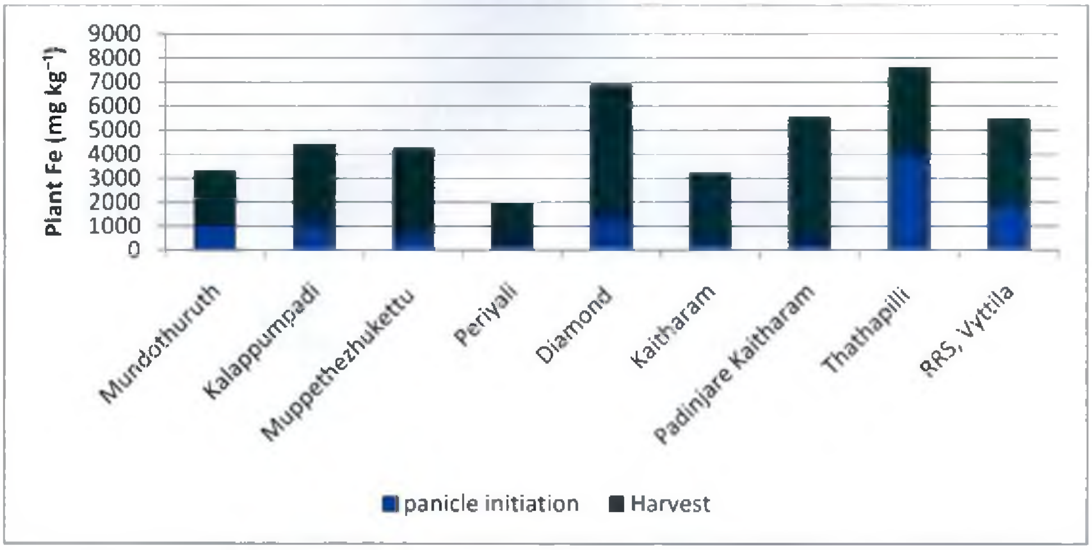

Figure 41: Iron content of plant samples

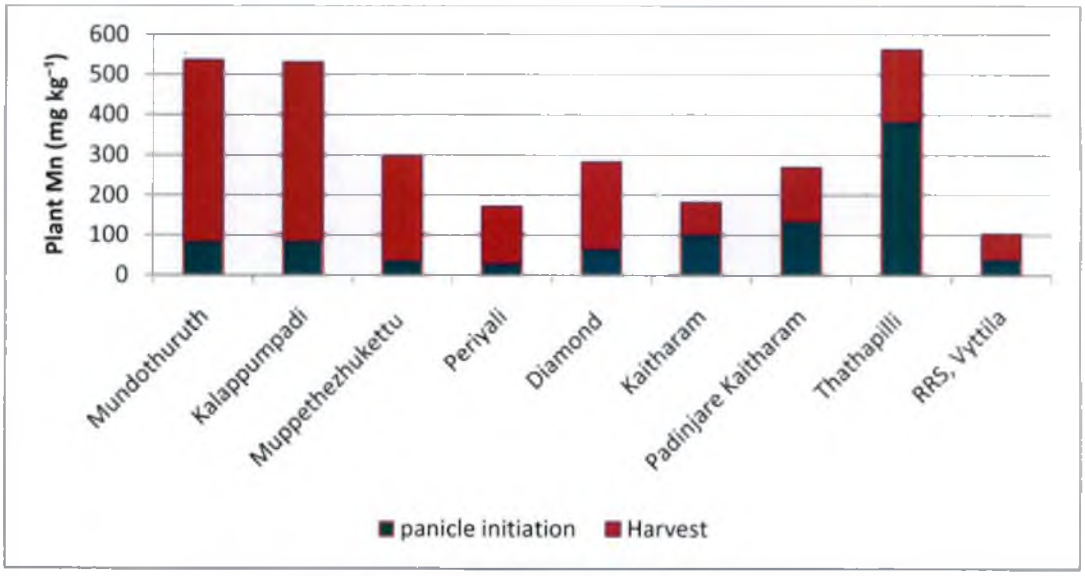

Figure 42: Manganese content of plant samples

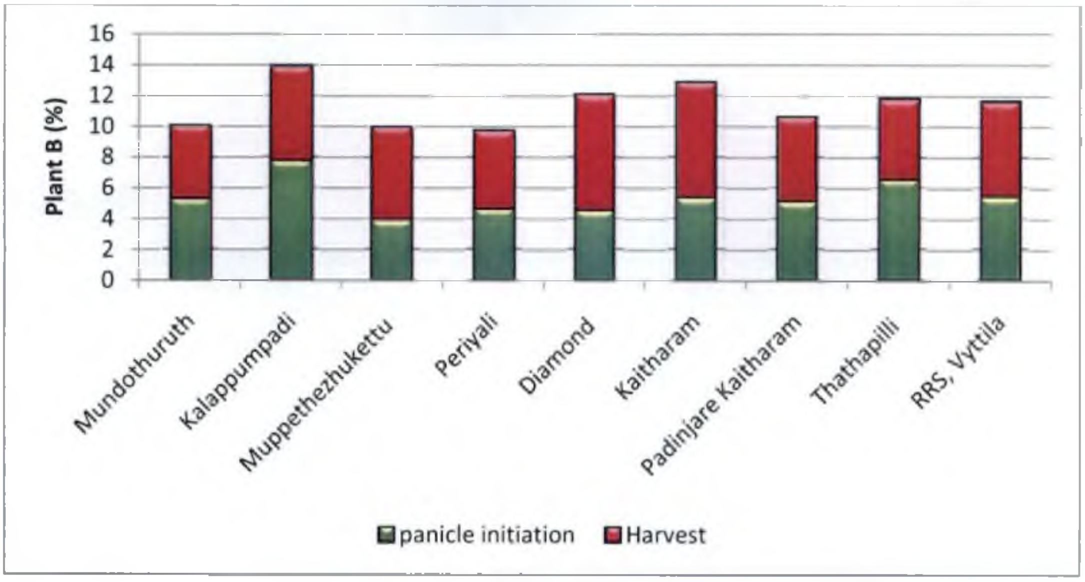

Figure 43: Boron content of plant sample

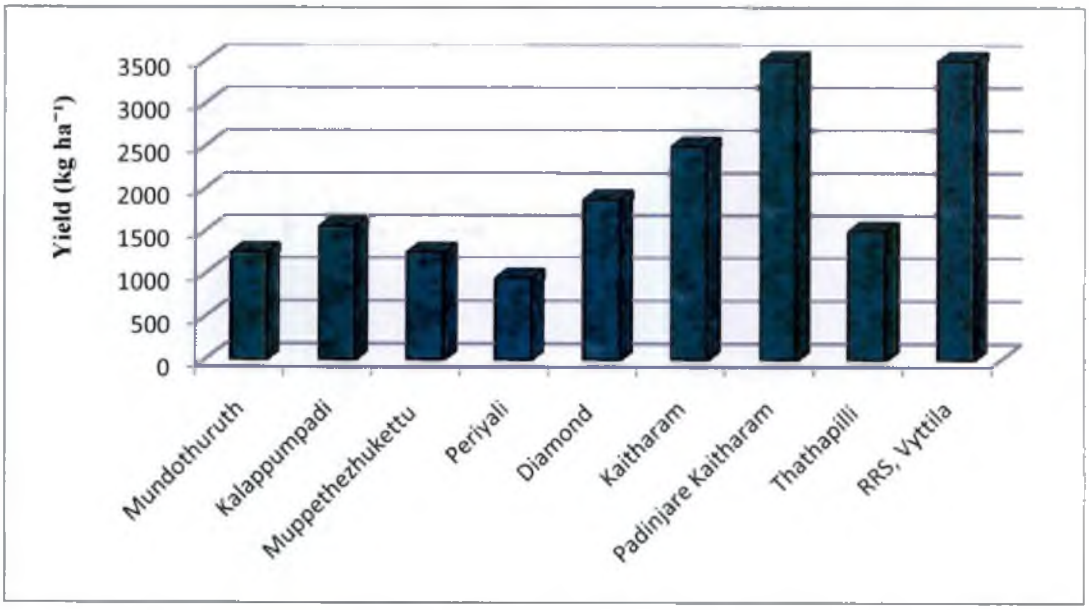

Figure 44: Rice yield of different locations

5.7. Yield of *Pokkali* rice

The rice yield ranged from 950 to 3500 kg ha^{-1} in different locations (Figure 43). Highest yield was recorded in Padinjare Kaitharam and RRS, Vyttila. Average yield of *Pokkali* rice was reported as 1500 to 2000 kg ha^{-1} (Shylaraj *et al.,* 2013). Sebastian (1977) found a rice yield of 1.967 to 3.400 t ha^{-1} in saline soils.

The rice yield was significantly correlated with available K, Ca, Zn and Cu content of soil at the harvest stage. Except K, the other three nutrients showed a strong negative correlation. The variation in yield (45 per cent) can be mainly accounted for K, Ca, Zn and Cu content in soil (Equation 1). At the mound dismantling stage, the yield was found to be positively correlated with available P content and negatively correlated with available Zn content in the soil. Yoshida (1981) found an increase in grain yields of about 70 per cent when the amount of P_2O_5 was increased from 6 kg ha^{-1} to 20.25 kg ha^{-1} in a rice crop grown on a volcanic ash soil. The rice yield showed a significant negative correlation with plant P and Mg content during the maximum tillering stage of the rice (Equation 6). The yield showed significant correlations with Mg, Cu, Mn and Fe content of plant at harvest stage. It was positively correlated to Mg, Cu and Fe content (Equation 8).

Recently, the unsustainable monoculture of prawn takes over the *Pokkali* lands from the rotational rice- prawn cultivation because of the immediate and higher returns. But, it is not sustainable in the long run. The labour intensiveness of rice cultivation also added to the pace of this shift. The shift to monoculture challenges the conservation of indigenous rice varieties and cultivation practices (Vijesh, 2006).

5.8. Toxic nutrients in *Pokkali* rice

The nutrients N, K, Ca, Fe, Mn and Cu were found in adequate amounts in plant samples, where as P and Mg were present in higher concentrations. The content of Zn, Na, B and Al were in sufficient concentrations to cause toxicity in crop

(Annexure IV). Patrick *et al.,* (1987) reported that, the rice plant absorbs significantly high concentrations of Zn, Fe, Mn, Ca, Mg, and Al under reducing conditions at pH 4.5. The amounts of Na^{+}, K^{+} and Mg^{2+} of shoot and root tissues increased at high salt levels. Zinc interaction with B has been reported and it reduces the toxic effects of excessive boron in crop plants (Graham *et al.,* 1987).

5.9. Ion interactions in soil

The Net Ionic Equilibrium ratios of ions namely K^{+} , Mg^{2+} , Na^{+} and Cu^{2+} to divalent ions (Ca^{2+} , Mg^{2+} , Fe^{2+} and Mn^{2+}) and trivalent Al were calculated separately for the soil samples in accordance with ratio law and the ratios were correlated with various soil parameters (Annexure VII). This law was proposed by Schofield (1947) governing the distribution of soil cations. The ratio law has subsequently been interpreted rather differently. It has been found out that for a number of ion pairs and a variety of soils activity ratios and products remain approximately constant while solution concentrations vary up to 0.02 mol dm^{-3} (Beckett,1964).The availability of ions to plants is directly related to the relative activity of the ions in exchange- solution equilibria (Schofield, 1947). The intensity factor of potassium and sodium is expressed as $K/(Ca+Mg)^{1/2}$ and $Na/(Ca+Mg)^{1/2}$ respectively. This relationship implies that, the ability of soil system to maintain a certain concentration of a cation in solution is determined by the total amount of the cation present in readily available forms and the intensity by which it is released to the soil solution. Seena (2007) reported that, by considering Al, Mn and Fe in acid soils as multivalent ions, much clearer picture of exchange- solution equilibria was obtained.

The NIE ratios $K/[(Ca+Mg+Fe+Mn)^{1/2}+(Al)^{1/3}]$ and $Mg/[(Ca+Mg+Fe+Mn)^{1/2}+(Al)^{1/3}]$ were found to be in negative correlation with pH (Table 80). The nutrients K and Mg are generally not as available for plant uptake in acid soils since they may have been partially leached out of the soil profile. Priya (2003) observed a positive correlation of the ratio K/ [(Ca+ Mg+ Fe+ Mn) $^{1/2}$ + (Al) $^{1/3}$] with potassium and sodium. The NIE ratios of K and Na showed negative correlation with each other. The potassium ion, in comparison with sodium, is more strongly adsorbed since it has a smaller hydrated radius and hence is more strongly adsorbed to the site of the negative charge. Variable charged soils saturated with hydrogen and aluminium tends to adsorb K preferentially to Na (Li and Ji, 1992). The distribution of Na in two phases namely soil solution and soil surface depends on K adsorption ratio of the solution (Levy and Feigenbaum, 1996).The ratio Mg/ [(Ca+ Mg+ Fe+ Mn) + (Al) $^{2/3}$] showed a negative correlation with calcium and positive correlation with phosphate. Magnesium availability was disturbed by calcium. Excess calcium causes magnesium deficiency. Sposito *et al.,* (1986) reported that, the soil adsorption of calcium was preferred more than that of magnesium.

The ratio Mg/ [(Ca+ Mg+ Fe+ Mn) + (Al) $^{2/3}$] showed negative correlations with exchangeable Mg (Table 80). This may be due to the increased chance or tendency for that cation to be adsorbed, if the concentration of a cation in soil solution is high. The ratio Na/ [(Ca+ Mg+ Fe+ Mn) $^{1/2}$ + (Al) $^{1/3}$] was found to have a positive correlation with exchangeable Na. It may be due to the higher content of sodium in exchange complex.

The NIE ratio Cu/ [(Ca+ Mg+ Fe+ Mn) $^{1/2}$ + (Al) $^{1/3}$] was positively correlated to iron and manganese (Table 76). McBride (1994) concluded that, the manganese oxides had high selectivity for Cu. McLaren and Crawford (1973) stated that, manganese oxides were the dominant mineral constituents in the specific adsorption of Cu by the soil. But, for more weathered soils, the iron oxides became more important for Cu adsorption for their higher concentrations in the soil.

5.10. Interaction between soil and plant nutrients

Interaction between nutrients in crop plants occurs when the supply of one nutrient affects the absorption and utilization of other nutrients. Organic carbon content was significantly correlated with plant Cu and Al content (Annexure VI). It is reported that Cu is more strongly complexed by soluble organic matter (Hodgson *et al.,* 1966). The interaction of Al^{3+} with organic matter may be of considerable importance in controlling soil solution levels of Al^{3+} in acid soils.

Avaialble K was negatively correlated with plant P, Ca and Mg content (Annexure VI). Fageria (1983) studied potassium interaction with P, Ca, and Mg in rice plants grown in nutrient solution. Significant decrease in the uptake of P and Ca was observed with increasing K concentration in the solution culture. But Mg uptake decreased only at the higher concentration of K. Higher absorption of P and Ca in the lower concentrations of K may be due to high mobility of K (Fageria, 2001). The decrease in Ca uptake with increasing K concentrations may be related to competition between K and Ca due to physiological properties of these ions (Johnson *et al.,* 1968).

Plant Ca was found to have significant negative correlation with available Mg content of soil (Annexure VI). Magnesium significantly decreased the uptake of K and Ca in the rice plants grown in nutrient solution (Fageria, 2001).This depressive effect may be due to the competition for metabolically produced binding compounds (Fageria, 1983). Plant Mn content was negatively correlated to soil Ca, but which was not significant. Increased Ca levels in the growth medium often decrease Mn uptake and Mn toxicity (Heenan and Carter, 1976). Available Zn in soil was found to have negative correlation with plant Mn. Excess zinc decreases manganese uptake.

Available Mn content was positively correlated to plant Na, Al, Cu, P and Mg. Plant Ca, S, Mn, Zn and B were negatively correlated with available Mn

(Annexure VI). Lidon (1999) observed a general synergistic effect of increasing Mn concentrations in nutrient solution, on Ca, Mg, Na, P, and Cu net uptake and antagonistic action of Mn on K and Zn in rice plants.

SUMMARY

SUMMARY

The present study entitled "Ion interactions and rice nutrition in acid saline *Pokkali* soils" has been carried out to assess ion interactions in acid saline *Pokkali* soils and to identify the chemical constraints in plant nutrition as well as to study the emerging deficiencies and toxicities of nutrients in *Pokkali* soils. For this purpose, eighty one soil samples and fifty five plant samples were collected from eight *Pokkali* locations of Kottuvally panchayath and one sample from RRS, Vyttila. The soil samples were characterized for physical (soil texture), chemical (pH, EC, CEC, exchangeable cations and anions, ESP, SAR, cation saturation, available N,P,K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, Al and Na) and biological attributes (MBC, DHA and organic carbon) and the plant samples were analyzed for nutrient contents and uptake. The samples were collected with the aid of GPS. Soil samples were collected during three stages of cultivation namely mound preparation, mound dismantling and harvest stages. Plant samples were collected during two stages of growth namely panicle initiation and harvest. The main findings were summarized below.

- In the nine locations, soil texture varied from sandy loam to clay
- Acidic pH range was observed in *Pokkali* soils during all the three cultivation stages
- Electrical conductivity was highest during mound preparation stage
- The available P, K, Ca, S, Fe, Mn, Zn, Cu, Al and B were very much higher in the soil samples
- Organic carbon in *Pokkali* soils showed a very high status
- Available Mg was low (< 120 mg kg^{-1})
- Dehydrogenase activity was highest during harvest stage
- The decisive cations identified in exchange complex of *Pokkali* soils were K, Mg, Cu and Na

- Sulphate and phosphate were the predominant anions found in these soils
- *Pokkali* soils recorded the absence of carbonate ions
- Stepdown regression identified K having predictive ability towards the presence of sulphate ion
- The plant nutrients namely P, K, Ca, Mg, Fe, Mn, Cu, Zn, B and Na were significantly varying among three stages of cultivation
- The nutrients N, K, Ca, Fe, Mn and Cu in plant samples were found to be sufficient
- Toxic concentrations of Zn,B and Al were recorded in plant samples
- The NIE ratios $K/ [(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ and $Na/ [(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ showed significant positive correlations only with CEC and sodium and phosphate showed a strong negative correlation with both the ratios
- The other NIE ratio $Mg/ [(Ca+ Mg+ Fe+ Mn) + (Al)^{2/3}]$ showed significant negative correlation with pH and phosphate
- The ratio $Cu/ [(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ showed a negative correlation with electrical conductivity, Na and K
- The availability of cations namely K, Mg, Cu and Na was significantly influenced by various soil parameters like soil pH, CEC and phosphate content
- The content of K, Ca and Zn in *Pokkali* soils at the mound preparation stage can predict 47 per cent of variation in rice yield
- The P and Zn content during the mound dismantling stage can predict 45 per cent of variation in rice yield
- The rice yield mainly depended on available K, Ca, Zn, P and Zn contents in soil
- The plant P and Mg content at maximum tillering stage can predict 25 per cent of yield variation.

ANNEXURE

ANNEXURE- I

Correlation coefficients of yield with available nutrient content at three stages of cultivation

Available nutrient content	Correlation coefficients		
	Mound preparation	Mound dismantling	Harvest
OC	0.14	0.009	0.35
N	0.10	0.19	0.27
P	-0.21	0.64**	0.45*
K	0.49**	-0.08	0.03
Ca	-0.50**	-0.17	0.06
Mg	-0.25	0.10	0.08
S	-0.27	0.006	-0.03
Fe	-0.24	0.16	-0.17
Mn	-0.34	-0.2	-0.24
Zn	-0.54**	-0.44*	0.11
Cu	-0.42*	0.28	-0.17
B	-0.17	0.02	0.01
Al	-0.15	-0.02	0.03
Na	0.30	-0.18	0.35
*- Significance at 5% level; **- Significance at 1% level			

ANNEXURE- II

Correlation coefficients of yield with plant nutrient content at two stages of growth

Plant nutrient content	Correlation coefficients	
	Maximum tillering	Harvest
N	-0.005	0.13
P	-0.51**	-0.30
K	-0.31	-0.22
Ca	0.25	-0.26
Mg	-0.46*	0.55**
S	-0.33	-0.34
Cu	0.02	0.65**
Mn	-0.03	-0.56**
Fe	-0.06	0.40*
Zn	0.12	0.02
Al	-0.09	0.30
B	-0.002	0.26
Na	-0.16	-0.16

*- Significance at 5% level; **- Significance at 1% level

ANNEXURE- III

Canonical analysis

Canonical R: 0 .44307 $Chi^2 (18) = 29.095$

Correlation	K	Ca	Mg	Fe	Mn	Cu	Zn	Al	Na
Sulphate	0.2717	0.1988	0.1397	0.0158	0.0392	-0.1013	-0.1034	0.1619	0.0738
phosphate	-0.2022	-0.1122	0.3711	-0.0840	-0.0273	0.0189	-0.0595	-0.1420	-0.1873

Cations	Root 1	Root 2
Potassium	-0.6095	-0.4870
Calcium	-0.0308	-0.5577
Magnesium	0.5618	-0.6880
Iron	0.0643	0.1132
Manganese	-0.3768	-0.6031
Copper	0.3792	0.2969
Zinc	0.1313	0.5413
Aluminium	0.0196	-0.0233
Sodium	-0.2417	0.3907

Anions	Root 1	Root 2
Sulphate	-0.5106	-0.8693
Phosphate	0.9274	-0.3954

ANNEXURE- IV

Soil nutrient status

Nutrients	Standard value		Observed value		t value		Status
	Minimum	Maximum	Mean	Standard deviation	In comparison with minimum	In comparison with maximum	
OC (%)	0.50	0.75	1.75	0.64	17.35	13.89	**High**
N (kg ha^{-1})	280.00	560	137.99	78.52	-16.27	-	**Low**
P(kg ha^{-1})	10	25.00	40.40	27.43	-	5.38	**High**
K(kg ha^{-1})	110.00	280.00	918.23	838.89	8.56	6.84	**High**
Ca (mg kg^{-1})	300.00	-	1219.70	846.44	10.81	-	**High**
Mg (mg kg^{-1})	120.00	-	101.05	77.03	-2.44	-	**Low**
S (mg kg^{-1})	2.00	5.00	181.02	141.95	12.33	-	**High**
Fe (mg kg^{-1})	2.00	5.00	720.19	1082.03	6.57	-	**High**
Mn (mg kg^{-1})	1.00	3.00	43.84	77.90	5.47	-	**High**
Cu (mg kg^{-1})	0.50	1.00	33.07	79.61	4.00	-	**High**
Zn(mg kg^{-1})	0.50	1.00	53.30	74.44	6.99	-	**High**
Al(mg kg^{-1})	1.00	10.00	581.09	668.92	8.62	8.49	**High**

ANNEXURE- V

Plant nutrient status

Nutrients	Standard value		Observed value		t value		Status
	Minimum	Maximum	Mean	Standard deviation	In comparison with minimum	In comparison with maximum	
N (%)	1.00	5.00	4.30	0.97	24.96	-5.29	**Sufficient**
P (%)	0.10	0.40	0.65	0.23	17.37	8.02	**High**
K (%)	1.00	5.00	2.74	2.08	6.15	-7.91	**Sufficient**
Ca (%)	0.20	1.00	0.29	0.21	3.40	-24.29	**Sufficient**
Mg (%)	0.10	0.40	0.09	0.02	14.02	11.65	**High**
S (%)	0.10	0.40	0.04	0.01	-21.92	-148.88	**Low**
Fe (mg kg^{-1})	50.00	500.00	236.52	1748.20	9.73	7.84	**Sufficient**
Mn (mg kg^{-1})	25.00	300.00	163.46	136.13	7.74	-7.37	**Sufficient**
Cu (mg kg^{-1})	5.00	100.00	25.88	11.65	13.17	-46.73	**Sufficient**
Zn (mg kg^{-1})	20.00	100.00	911.99	1568.05	4.18	3.80	**Toxic**
B (mg kg^{-1})	10.00	50.00	57223.00	11461.02	36.68	36.65	**Toxic**
Al (mg kg^{-1})	10.00	100.00	709.79	983.30	-	4.55	**Toxic**

ANNEXURE- VI

Correlation coefficients of plant nutrients with soil available nutrients

Available nutrient content	Plant P	Plant Ca	Plant Mg	Plant S	Plant Cu	Plant Mn	Plant Zn	Plant Al	Plant B	Plant Na
OC	-0.259	-0.048	0.284	-0.091	0.416*	-0.159	0.154	0.547**	0.126	0.029
N	-0.032	0.004	0.208	-0.029	0.378	-0.296	-0.017	0.063	-0.226	0.273
P	0.043	0.474*	0.360	-0.235	0.571**	-0.343	0.309	0.075	0.420*	0.045
K	-0.039	-0.350	-0.067	0.272	-0.015	-0.138	-0.317	-0.079	0.344	-0.193
Ca	-0.062	-0.545**	0.133	0.043	-0.037	-0.32	-0.254	0.041	0.235	-0.082
Mg	0.105	-0.507**	0.195	0.071	0.062	-0.378	-0.235	0.119	0.051	0.132
S	0.229	-0.340	0.225	0.054	-0.04	-0.159	0.00	0.153	0.078	0.298
Fe	0.399*	-0.229	0.386*	0.573**	0.167	-0.142	0.448*	0.162	0.287	0.264
Mn	0.271	-0.380	0.239	-0.009	0.031	-0.118	-0.041	0.220	-0.207	0.557**
Zn	0.121	-0.290	-0.043	-0.045	-0.147	-0.013	-0.133	0.010	-0.221	0.276
Cu	0.155	-0.241	0.211	-0.074	0.214	-0.264	-0.091	0.092	-0.177	0.428*
B	0.038	-0.331	-0.093	0.106	-0.089	-0.239	-0.191	-0.051	-0.055	-0.061
Al	0.088	-0.431*	0.272	0.035	0.098	-0.314	-0.116	0.182	-0.007	0.304
Na	0.043	-0.433*	0.107	0.145	-0.012	-0.386*	-0.26	0.036	0.298	-0.030

*- Significance at 5% level; **- Significance at 1% level

ANNEXURE- VII

Correlation coefficients of Net Ionic Equilibrium ratios with various soil parameters

Particulars	(Ratio 1)	(Ratio 2)	(Ratio 3)	(Ratio 4)
Ratio 1	1	_	_	_
Ratio 2	0.998**	1	_	_
Ratio 3	-0.609**	-0.625**	1	_
Ratio 4	0.029	0.023	0.163	1
pH	-0.169	-0.165	0.221*	0.276*
EC	0.074	0.074	-0.098	0.168
CEC	0.264*	0.252*	-0.112	-0.345**
Ca	0.161	0.144	-0.051	0.022
Mg	-0.006	-0.006	-0.042	0.328**
Na	0.238*	0.228*	-0.093	-0.368**
K	0.065	0.062	0.027	-0.449**
Al	0.188	0.181	-0.101	-0.056
Fe	0.068	0.065	-0.075	0.266*
Mn	0.138	0.132	-0.065	0.323**
Cu	-0.116	-0.120	0.134	-0.070
Zn	-0.171	-0.171	0.153	0.114
Cl^-	0.079	0.092	-0.175	-0.136
HCO_3^-	0.153	0.158	-0.011	-0.129
SO_4^{2-}	0.134	0.131	-0.080	-0.038
PO_4^{3-}	-0.384**	-0.394**	0.426**	0.235*

*- Significance at 5% level; **- Significance at 1% level

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ION INTERACTIONS AND RICE NUTRITION IN ACID SALINE POKKALI SOILS

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ABSTRACT OF THE THESIS

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ABSTRACT

The present study entitled 'Ion interactions and rice nutrition in acid saline *Pokkali* soils' has been carried out to assess the ion interactions in acid saline *Pokkali* soil, to identify the chemical constraints in plant nutrition and emerging deficiencies or toxicities of nutrients in *Pokkali* soils. For this purpose, soil samples and plant samples were collected from eight *Pokkali* locations of Kottuvally panchayath and one from RRS, Vyttila. The eight locations included Mundothuruth, Kalappumpadi, Muppathezhukettu, Periyali, Diamond, Kaitharam, Padinjare Kaitharam and Thathapilli. The soil samples were collected during three stages of cultivation namely mound preparation, mound dismantling and harvest. Two growth stages namely maximum tillering and harvest were selected for the collection of plant samples.

The soil samples were characterized for physical (soil texture), chemical (pH, EC, CEC, exchangeable cations, ESP, SAR, percent cation saturation, anions, available N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, Al and Na) and biological attributes (MBC, DHA and organic carbon) and the plant samples were analyzed for nutrient contents and uptake. The measured attributes were analysed by two- way analysis of variance using statistical package operational statistics. Canonical analysis was done to find out the decisive ions in *Pokkali* soils. The t-test was carried out to identify the toxicity and deficiency of nutrients in *Pokkali* soils and rice. The correlation of Net Ionic Equilibrium (NIE) ratios of K, Mg, Cu and Na with various soil parameters were carried out to identify ion interactions in soil.

Analysis of variance revealed that, among various measured attributes, pH, EC, redox potential, available nutrients (N, P, K, Ca, Mg, S, Al and Na), anions (chloride, bicarbonate, sulphate and phosphate), exchangeable cations (Mg, Na, K, Al, Fe and Mn), percent cation saturation (Ca, Mg, Na and K) and dehydrogenase activity varied significantly among the three stages of cultivation. The decisive

cations identified in the exchange complex of *Pokkali* soils were potassium and magnesium, copper and sodium. Sulphate and phosphate were the predominant anions existing in the soil. Step down regression identified 'potassium' having predictive ability towards the presence of sulphate ion. Higher concentrations of P, K, Ca, S, Fe, Mn, Zn, Cu, Al and SO_4^{2-} were observed in the soil. Magnesium was found to be deficient in the available pool of *Pokkali* soils. . The plant nutrients namely P, K, Ca, Mg, Fe, Mn, Cu, Zn, B and Na were significantly varying among three stages of cultivation. Magnesium was present in higher concentration in plant despite the deficient concentration of magnesium in soil. The variation in *Pokkali* rice yield (45 per cent) can be mainly accounted for potassium, calcium, zinc and copper content in soil at the mound preparation stage. During the harvest stage, yield was correlated only with available P. Zinc, boron and aluminium were present in toxic concentrations in plant.

The NIE ratios K/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ and Na/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ showed significant positive correlations only with CEC and sodium. Phosphate showed a strong negative correlation with both the ratios. The other NIE ratio Mg/ $[(Ca+ Mg+ Fe+ Mn) + (Al)^{2/3}]$ showed significant negative correlation with pH and phosphate. The ratio Cu/ $[(Ca+ Mg+ Fe+ Mn)^{1/2} + (Al)^{1/3}]$ showed a negative correlation with electrical conductivity, Na and K. The availability of cations namely K, Mg, Cu and Na was significantly influenced by various soil parameters.

The present investigation identified high concentrations of micronutrients, Al and B in *Pokkali* soils, toxic concentrations of Zinc, boron and aluminium in plant and influence of different soil parameters on availability of K, Mg, Cu and Na. The rice yield mainly depended on available K, Ca, Zn, P and Zn contents in soil.