RHIZOSPHERE CHEMISTRY AND ADAPTATIONS OF NATURAL RUBBER (*HEVEA BRASILIENSIS*) TO ACIDIC SOIL CONDITIONS

Thesis submitted to
MAHATMA GANDHI UNIVERSITY
For the award of the degree of
DOCTOR OF PHILOSOPHY
in
CHEMISTRY
(FACULTY OF SCIENCE)

By
AMBILY K. K.

Under the supervision and guidance of

Dr. MERCYKUTTY JOSEPH

RUBBER RESEARCH INSTITUTE OF INDIA
KOTTAYAM, KERALA, INDIA-686 009

DECEMBER 2019

MAHATMA GANDHI UNIVERSITY

CERTIFICATE ON PLAGIARISM CHECK

1.	Name of the Research Scholar	**AMBILY. K.K**
2.	Title of the Thesis/Dissertation	RHIZOSPHERE CHEMISTRY AND ADAPTATIONS OF NATURAL RUBBER (*HEVEA BRASILIENSIS*) TO ACIDIC SOIL CONDITIONS
3.	Name of the Supervisor	Dr. MERCYKUTTY JOSEPH
4.	Department/Institution/ Research Centre	RUBBER RESEARCH INSTITUTE OF INDIA, KOTTAYAM
5.	Similar Content (%) identified	**1% (One)**
6.	Acceptable Maximum Limit	25%
7.	Software Used	Urkund
8.	Date of Verification	09-12-2019

**Report on plagiarism check, items with % of similarity is attached*

Checked by (with Name, Designation & Signature) : Annu George

9/12/2019

9/12/19

9/12/2019

ANNU GEORGE
Deputy Librarian in-charge
University Library
Mahatma Gandhi University
Kottayam - 686 560

Name & Signature of the Researcher : AMBILY. K.K

Ambily K.K

Ambily.K.K

Name & Signature of the Supervisors : Dr. MERCYKUTTY JOSEPH

Dr. Mercykutty Joseph.

Name & Signature of the HoD/HoI(Chairperson of the Doctoral Committee) :

DR. JAMES JACOB
Director
Rubber Research Institute of India
Rubber Board
Kottayam - 686 009, Kerala, India

RUBBER BOARD
KOTTAYAM 8.

URKUND

Urkund Analysis Result

Analysed Document:	AMBILY-RHIZOSPHERE CHEMISTRY AND ADAPTATIONS OF NATURAL RUBBER (HEVEA BRASILIENSIS) TO ACIDIC SOIL CONDITIONS.pdf (D60585002)
Submitted:	12/9/2019 9:30:00 AM
Submitted By:	library@mgu.ac.in
Significance:	1 %

Sources included in the report:

https://www.researchgate.net/publication/229323148_Alterations_of_microbial_populations_and_composition_in_the_rhizosphere_and_bulk_soil_as_affected_by_residual_acetochlor
https://pure.knaw.nl/portal/files/473668/Miletto,_Bodelier_et_al_complete.pdf
https://www.creaf.uab.es/global-ecology/Pdfs_UEG/2016%20Plant%20Soil.pdf
https://www.jstor.org/stable/24129566
https://www.frontiersin.org/articles/10.3389/fenvs.2018.00140/full
13fd7148-8d77-4088-b7be-2b2b08f76dd3

Instances where selected sources appear:

9

9-12-2019

9.12.19

AnnuGeorge
09-12-2019

ANNU GEORGE
Deputy Librarian in-charge
University Library
Mahatma Gandhi University
Kottayam - 686 560

DECLARATION

I AMBILY K. K. herewith declare that the thesis entitled "RHIZOSPHERE CHEMISTRY AND ADAPTATIONS OF NATURAL RUBBER (*HEVEA BRASILIENSIS*) TO ACIDIC SOIL CONDITIONS" is a bonafied record of the original research work carried out by me under the direct supervision and guidance of Dr. Mercykutty Joseph, Principal Scientist, Rubber Research Institute of India, Kottayam - 686 009 for the award of the degree of DOCTOR OF PHILOSOPHY of Mahatma Gandhi University and further that the present work or any part has not been submitted to any other degree, diploma or fellowship with any other University.

Ambily KK

RRII

Ambily K. K.

Date: 19-12-2019

RUBBER BOARD KOTTAYAM-9.

भारतीय रबड़ गवेषण संस्थान
THE RUBBER RESEARCH INSTITUTE OF INDIA
(वाणिज्य एवं उद्योग मंत्रालय, भारत सरकार)
(Ministry of Commerce & Industry, Government of India)

Phone : 91-481-2353311(10 lines)
Grams : RUBRBOARD
Fax : 91-481-2353327
Email : rrii@vsnl.com; rrii@rubberboard.org.in
Website : http://www.rubberboard.org.in

रबड़ बोर्ड
RUBBER BOARD
कोट्टयम - 9
KOTTAYAM 686 009

CERTIFICATE

This is to certify that the thesis entitled "RHIZOSPHERE CHEMISTRY AND ADAPTATIONS OF NATURAL RUBBER (*HEVEA BRASILIENSIS*) TO ACIDIC SOIL CONDITIONS" is a bonafied record of the original research work carried out by Mrs. Ambily K. K., Scientist, Agronomy / Soils Division, Rubber Research Institute of India, Kottayam - 686 009 under my supervision and guidance for the award of the degree of DOCTOR OF PHILOSOPHY in Chemistry in the Faculty of Science, Mahatma Gandhi University, Kottayam. It is also certified that the present work or any part of this thesis has not been submitted for any degree, diploma in any other university.

RRII

Date: 19-12-2019

Dr. Mercykutty Joseph, M.Sc (Ag).Ph.D.
Principal Scientist, Fertilizer Advisory Group
Rubber Research Institute of India
Kottayam- 686 009, Kerala, India.

RUBBER BOARD
KOTTAYAM - 9.

Dedicated to my father . . .

ACKNOWLEDGEMENT

First and fore most I thank and bow my head before God Almighty for showering me with all his blessings and help during the course of my work for the completion of my Ph.D programme successfully.

I express my sincere thanks and gratitude to my respected guide Dr. Mercykutty Joseph, Principal Scientist, Fertilizer Advisory Group, Rubber Research Institute of India, Kottayam for the whole hearted consent for initiating the present Ph.D programme and all moral support and guidance with valuable suggestions throughout the study. I also am indebted sincerely than anything to her for the belief in me, the keen and most care in the scrutiny of the manuscript of the thesis which only helped in the formation of the thesis in the present form.

I express my very sincere thanks and gratitude to most respected Dr.James Jacob, Director of Research, Rubber Research Institute of India, Kottayam,for the kind permission, support, encouragement and facilities in all times of my Ph.D programme which only throw light in my way to complete this endeavour successfully.

I wish to express my sincere gratitude to Dr. Jessy M. D., Joint Director (Agronomy/ Soils), Rubber Research Institute of India, Kottayam, for her encouragement of my Ph.D programme and favouring me by providing all facilities and support for the completion of the study.

I thankfully and sincerely express my gratitude to Faculty members and Research Guides (Chemical Sciences) for sharing their expertise during the course work and supporting staff for their help during the time of course work at M.G. University, Kottayam for the successful completion of my Ph.D programme.

I express my sincere thanks and gratitude to Dr. Jayasree Gopalakrishnan, Physiology Division, Rubber Research Institute of India, for her sincere efforts and moral support in all the time during the course of the study for the completion of my Ph. D programme successfully.

I sincerely and thankfully express my gratitude with great pleasure to Dr. Smitha. M. Xavier for providing all necessary information and support with patience in all the time during the course of my Ph.D programme that helped me a lot for the successful completion of the work in this format.

I am obliged to Smt. Pheba Joseph, Scientist, Agronomy/Soils Division, Rubber Research Institute of India for her involvement and inspiration for the timely completion of my Ph.D programme successfully.

I sincerely am indebted to my colleagues Dr. Sherin George, Dr. Joshua Abraham, Dr. Prasannakumari. P, Dr. Annie Philip, Dr. P. M. Mathews, Agronomy/Soils division of Rubber Research Institute of India for their valuable suggestions and contributions during discussions to improve my Ph.D programme.

I express my sincere thanks to Smt. Leena K. K, Smt. Sreebindhu. R. S, Smt. Mini J. Palliparambil, Sri. Shaheen M, Smt. Savitha. N. for their help in the analytical work and good wishes for the completion of the study successfully.

I express my sincere thanks to Mr.K.R. Sreekumar, Mr. Babu P, Mr. A.K. Peeusmon and Mr. C.A. Johny, Agronom/Soils division, Rubber Research Institute of India for their help in the field work with all support to full fill the study.

I express my sincere thanks to Dr. Geethakumariamma, Rubber Research Institute of India for the help for the good quality FTIR spectrum for the successful completion of the study.

I express my sincere thanks to Dr. K.N.Madhusoodhanan and Mr. P. Aneesh, Rubber Research Institute of India for the preparation of the quality illustrations and all help for the completion of the study successfully.

I express my sincere thanks to Mrs. Latha N., Mrs. Ajitha A. S and Mrs. Sujatha, V.S, Library, Rubber Research Institute of India for their support in the literature collection and all helps for the successful completion of the study.

I express my sincere thanks to Dr. Kala R. G and Dr. P. Kumari Jayasree, Biotechnology Division, Rubber Research Institute of India for their constant inspiration for the successful completion of my Ph.D programme.

I convey my sincere thanks to one and all for all support and help in all my work and that lead to complete my Ph.D programme in time and successfully.

I express my sincere thanks to Minitek Computers for the neat typing and setting of the thesis of the Ph.D programme successfully.

I am greatly indebted for the blessings and wishes of all my famility members for the successful completion of my Ph.D programme.

With great pleasure and satisfaction I express my indebtedness to my children Mr. Gokul Krishnan and Kumari. Anjali Krishna for all their support and care during my Ph.D programme. With their sacrifice and love only my Ph.D programme formed in this present state successfully.

I am fully indebted to my husband Dr. Krishnakumar K. N for all his love, care, support, help, well wishes and all sacrifice with patience in everything that gave me the strength and faith for the completion of this endeavour successfully.

Ambily K.K.

ABSTRACT

Rhizosphere is the important zone of nutrient changes and nutrient activity of plants which governs the nutrient release and uptake for plant growth. Rhizosphere chemical activity is species specific and the changes are in the immediate vicinity of roots. Every plant has its own adaptation to environmental conditions in which it grows to withstand constraints and making a suitable condition for growth and yield. Of which a major portion is rhizosphere oriented in the form of root mediated changes. Different adaptation is operating according to the conditions of the soil. Rubber (*Hevea brasiliensis*), the important source of natural rubber generally growing in acidic conditions is a major crop for economic returns. Rubber cultivation spreads over different soil conditions in traditional areas in Kerala. Recently the rubber cultivation was extended to the high elevation areas in Wyanad where the soil pH and soil nutrients were different from the traditional acidic soils of Kerala. Therefore the rhizosphere chemistry and adaptations of rubber plants in varying pH and base status conditions to make suitable the soil environment congenial for growth is studied. This helps to evolve suitable management practices to improve the growth of rubber plants for the enhancement of productivity of rubber tree.

The rhizosphere, characterized by the small area adjacent to plant roots and the major impact of root activity concentrated in this volume of soil having prime importance to plant nutrition and soil nutrient availability for plant uptake. Plants activities in the rhizosphere were varying in different plants and specific rhizospheric activities were observed thereby plants make alterations, modifications and adaptations of the soil environment during root growth.

Majority of soil reactions was found within a small area in micrometers to millimeter near to the live roots.

Since rubber is a long duration perennial tree crop with fast growth in the initial phase up to seven years of immaturity period before starting of the harvest of latex, growth in the initial years to attain the tappable girth of 50 cm is very important. Hence the evolvement of better management options is an essential component in rubber cultivation especially in the scenario of continuous cultivation along with soil degradation due to many reasons. Since the initial growth (3-4 years) and establishment of rubber plants are most critical, the rhizosphere adaptations in different soils is important for adopting management methods to improve the growth of rubber plants. In view of this, the present study was undertaken to know the rhizosphere chemistry and adaptations by changes in pH and nutrient availability in different soils with extreme pH and base status variations. Study comprises of seven experiments and in the field study the rhizosphere soil (soil adhered to fresh fine roots) samples were collected from the rubber plantations from young plants in different agro-climatic zones of Kerala and the nutrient concentrations were assessed and it was compared with the bulk soils (soils not in contact with roots) of individual trees. Results indicated that rhizosphere soil recorded high available P, exchangeable K, CEC, ECEC and low exchangeable Al indicating specific adaptive strategies to improve the P and K availability and reduce the exchangeable Al status were operating in rhizosphere of rubber plants. The change in CEC observed is also important and has a role in regulating the nutrient changes in the rhizosphere of rubber plants. The rhizosphere changes and adaptations were evident by this study. The mechanisms of the adaptations in detail is to be further studied.

The growth of young rubber plants was studied by two experiments in three different soils including two acidic soils (pH 4.4 and pH 5.5) and a neutral soil (pH 7.4). The growth and establishment of sprouted seeds in extreme soil conditions were studied by a preliminary study in the laboratory condition before conducting the seedling study for eight months period in poly bags in open-air condition. In the laboratory study, the length and biomass of shoot and root were monitored and inferred that establishment and growth up to 30 days in the laboratory condition was not affected by extreme soil conditions. The seedling study for eight months period was to know the growth, plant nutrients and changes in the soil nutrient availability in the rhizosphere in three soil pH *viz.* pH 4.4, pH 5.5 and pH 7.4 with varying base status. Growth measurements at the 45th day indicated no difference between plants grown in three soils with extreme difference in pH and base nutrients. This again indicated that the initial growth and establishment for about a period upto 45 days was not affected even by extreme soil conditions. However, at the third month (90th day) and eighth month (240th day) significantly lower growth was recorded by plants grown in extremely acidic pH (pH 4.4). Highest growth was recorded by plants grown at 7.4 pH. The shoot and root biomass also recorded similar trend. Growth of plants were reduced at extremely acidic pH which may be due to the combined effect of extreme acidity coupled with high aluminium and hydrogen content with the low availability of nutrients warranting soil acidity management and specific nutrient management for maintaining soil productivity and good growth of rubber plants. The observations on changes in the rhizosphere of rubber plants indicated that the extremely acidic pH (pH 4.4) is adjusted to a pH around 4.84 and the neutral pH (pH 7.4) was adjusted towards pH 6.2. The pH 5.5 soil not showed any significant change. Soil organic carbon, the major soil health index was maintained in the medium range as in the initial status in all three soils. The Ca and Mg content of the extremely acidic and strongly acidic pH were improved whereas the very high status of neutral soil was decreased significantly. Adjustments in the availability of other nutrients were also observed. This indicated that specific adaptations are operating in the rhizosphere in natural rubber plants to adjust the pH and nutrient availability.

The response of young plants to liming on growth, plant nutrients and the rhizosphere nutrient availability in extremely acidic pH (pH 4.4) and strongly acidic pH (pH 5.5) was studied through an incubation experiment. Incubating the soil with lime improved the exchange properties of the soil and availability of P, K and Ca. However the Mg availability was reduced. Exchangeable Al content and exchange acidity of the soil were reduced with lime application in both soils. The effect was more pronounced in soil having the pH of 4.4. Liming had no effect in strongly acidic (pH 5.5) soil except Ca enrichment indicated that a rhizosphere pH near 5.5 is desirable to rubber plants. From seedling response study in extremely acidic soil, it was inferred that the lime incorporation enhanced the diameter and height of the rubber plants than the no-lime treatment. Increase in the rhizosphere pH from 4.4 to pH 5.5 after eight months of plant growth is also an indication that the desirable pH for rubber plants is near to pH 5.5. Reduced concentration and uptake of Mg observed after lime incorporation indicated strong negative effect of Ca on Mg availability.

Fourier transform infrared spectroscopy (FTIR) spectrum identification of changes in soil organic carbon due to growth of rubber plants was also conducted. This was reported as having many applications in soil studies.

The fertilizer urea and rock phosphate used in rubber plantations were incubated in the three soils to know the variations in transformation of urea and release of P from rock phosphate in comparison with superphosphate in three soils. Variations in the availability of N forms and P availability in different pH soils were observed. Based on this, field study is to be conducted to know the plant response and suitability of fertilizers.

Key words: Rhizosphere, *Hevea brasiliensis*, Adaptation, Natural rubber plants, Soil pH, Soil acidity, Soil base status.

PREFACE

The study is an investigation of rhizosphere chemistry and the adaptations of natural rubber (*Hevea brasiliensis*) plants to acidic soils. The study helps to know the changes occurred in the rhizosphere of rubber plants and based on this we have to study the various mechanisms and plant functions further and to evolve management methods for increased growth and productivity. In this study, the rhizosphere changes in the young plants in the main field and detailed study of performance of young rubber plants in extreme soil variation in pH and base status were included. As a soil acidity management, the effect of lime in rhizospere of rubber plants also carried out to explore the possibility of rhizosphere management. The fertilizer reactions in the same soil were also assessed which gave the primary information on transformation of urea and rock phosphate in the three soils and to be further confirmed through field experiments. The FTIR confirmation of changes in soil organic carbon due to growth of rubber plants was also performed.

The present research programme was conducted by seven experiments under four major objectives. The data of the study and the conclusions formed have been presented in five chapters. Introduction of the topic and the description of major objectives are given in the first chapter. In the second chapter a review of the related literature of the study with various sub titles is presented. The details of the materials and methodology followed in different experiments conducted are explained in the third chapter. The results of the study and the discussions of various results are included in the fourth chapter. The summary of the study and conclusions arrived are given in fifth chapter. The bibliography of the references cited and the publications from the study are presented towards the end of the thesis.

Fig. 1. Rubber Plantation

CONTENTS

)-119

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

pH	Measure of acidity, alkalinity and neutrality
CEC	Cation exchange capacity
ECEC	Effective cation exchange capacity
ANOVA	Analysis of variance
cmol (+) kg^{-1}	Centimol per kilogram
CD	Critical difference
FTIR	Fourier transform infrared
g	Gram
g kg-1	Gram per kilograme
HCl	Hydrochloric acid
Kg	Kilogram
Kg ha^{-1}	Kilogram per hectare
mM	Milli molar
NS	Non significant
SOC	Soil organic carbon
H	Hydrogen
ha^{-1}	Per hectare
R	Rhizosphere soil
B	Bulk soil
mg kg^{-1}	Milligram per kilogram
VAM	Vessicular arbascular mycorrhiza
XRD	X- ray diffraction

Saloid-P - Saloid phosphorus
Al-P - Aluminium phosphorus
Fe-P - Iron phosphorus
Ca-P - Calcium phosphorus
Total-P - Total phosphorus
WS-K - Water soluble potassium
Ex-K - Exchangeable potassium
Fixed-K - Fixed potassium
Total-N - Total nitrogen
N-fractions - Nitrogen fractions
mg plant^{-1} - Milligram per plant
IR - Infra red
cm^{-1} - Per centimetre
OH - Hydroxide
C-H - Carbon hydrogen
SOM - Soil organic matter
+Lime - With lime
T stat - Statistical t-test
NH_4^+ - Ammonium ion
NO_3^- - Nitrate ion
meq100g^{-1} - Milli equivalent per hundred gram

CHAPTER - I

I. INTRODUCTION

Soil is the precious natural resource and primary requirement for plant growth and existence of mankind. The vegetation existing are influencing the soil properties and plants have specific nutrient chemistry and adaptations to make suitable the soil in the immediate surroundings of roots for growth and development which is of having more importance in diverse soil environments.

PLANT RHIZOSPHERE

The plant rhizosphere, the immediate vicinity of root is the important area of plant activities which regulates the plant functions and metabolism for growth and productivity. The rhizosphere chemistry is the chemical reactions of various elements and compounds in the soil due to plant functions depending on the specific requirement of each species. Every plant have its own specificity to make the soil environment conducive for its existence and development and this means that plants exert changes in the immediate surroundings by chemical reactions.

The rhizosphere, characterized by the small area adjacent to plant roots and the major impact of root activity concentrated in this volume of soil having prime importance to plant nutrition and soil nutrient availability for plant uptake (Dessaux *et al.*, 2009; Hinsinger *et al.,* 2006). The term rhizosphere which comes from 'rhiza', a Greek origin means root was presented first time by Hiltner (1904) and after that in the studies conducted by Darrah, (1993) Hinsinger, (1998) and

Hartmann *et al.* (2008). It was reported that the plants activities in the rhizosphere were varying in different plants and specific rhizospheric activities were observed and there by the plants make alterations, modifications and adaptations of the soil physical, chemical and biological environment during root growth (Zak *et al.*, 2003; Bird *et al.*, 2011).

NATURAL RUBBER

Natural rubber (*Hevea brasiliensis*) tree is the primary source of natural rubber and 99 per cent of the world natural rubber requirement is met from this crop (George and Panikkar, 2000). It is a forest tree species belonging to the plant family *Euphorbiacea* and was identified from the river basin of Amazone forest, Brazil (George and Jacob, 2000). The economic produce of rubber tree is latex harvested from the trunk bark of the tree. Rubber tree is fast growing in the initial years and normally achieved 50 cm girth within seven years which is the pre-requisite to open the trees for yield. The effective life span is 25-30 years and growth in the short period (7 years) in the initial years and necessary management is very important. Natural rubber is one of the major commodity crop in the economy of India because of its huge industrial application of which the important ones are the tyre manufacturing and export of value added products (Jacob *et al.*, 2018).

SOIL pH

Soil pH is the most important variable because most of the chemical functions are mediated through the pH of the soil and plays major role in nutrient availability and plant adaptations to make a suitable environment for growth and productivity (Marshner, 1991). Plant species are sensitive to specific soil pH and in general, the soil pH effect was most pronounced when pH conditions reach extreme values (Pattanayak and Sarkar, 2016). In acidic soils the pH is the deciding factor for available nutrients (Malavolta, 2006). Within the acidic soil, the extreme acidity is in the range of 3.5-4.4, and strong acidity is in the range 5.1-5.5 and 6.6-7.3 is neutral soil (Soil Survey Manual, 1993, Hamza *et al.,* 2013). Available nutrients were high in the pH 5.8 to 7.0 and pH decreased to below 5.5 toxic concentration of Al will be increased and simultaneously the availability of K, Ca and Mg will be decreased. When pH further decreased lower than 5, dissolution of Al will takes place and increases the free Al ion content. At pH 4.5 ionic status of Al was thousand fold higher than in pH 5.5 and this becomes reason of impaired growth of roots and plants due to lack of nutritional elements (Sarkar *et a*l., 2007). There were specific pH requirement for each plant species and impairment of plant growth and productivity is resulted in the case of beyond the tolerable limit especially in soil pH and mineral nutrients (Pattanayak and Sarkar, 2016). Usually plants existed in acidic soils possess adaptive mechanisms either to withstand or inhibit adverse conditions/ constraints (Marschner, 1991). The changes were included the influence of plant roots in the immediate surroundings to make available the nutrients. Different species have specific responses to nature of the soil and reactions of each vegetation are essential to manage the soil resources.

RHIZOSPHERE CHEMISTRY

Rhizosphere soil chemistry thereby the nutrients in the soil surrounding root (Rhizosphere) for absorption to plants is different from that of the soil not in contact with roots (Bulk soil) (Marshner *et al.*, 2003). Also the process of dissolution of ions for plant uptake is an associated phenomenon of peculiarity of soil and the existed vegetation and speciality of microbe in the rhizosphere (Jones *et al.*, 2003). In the rhizosphere, plants make the nutrients for absorption to cells of the root and the important reactions included the changes in soil pH in the root zone and nutrient availability, solubilisation of phosphate and rhizosphere priming effect of carbon (Marschner, 1995).

Performances of rubber was different in different locations with variation in pH and base nutrients. Rubber is a species which can withstand a wide range of pH (3.8- 8.0) (Karthikakuttyamma *et al.*, 2000; Syamala and Joseph, 2012; Joseph, 2012) with variations in growth and yield and low pH affecting more to young seedlings than mature trees. Enhanced growth and yield in extreme conditions especially in high and low pH and base status is essential for the sustainability of rubber production.

Based on the hypothesis that rhizosphere chemistry and associated adaptations/modifications of nutrient elements are operating in the rhizosphere of rubber plants which influence the growth of the rubber plants and the scenario of different soil conditions of rubber growing areas and variation in growth performance of rubber trees observed in the field, the present study was conducted with the following objectives to know the rhizosphere chemistry and adaptations of natural rubber plants to acidic soil conditions and to evolve further management options to improve growth.

2. OBJECTIVES

1. To study the rhizosphere chemistry and adaptations at the rhizosphere of young rubber plants grown in acidic soils in the main field.
2. To study the growth and rhizosphere chemistry of young rubber plants grown in soils with varying pH, exchangeable Al and base status.
3. To study the effect of acidity management through liming on the availability of nutrients and growth of young rubber plants.
4. To study the effect of varying pH and base status on the transformation of fertilizer nitrogen and phosphorous in soil.

CHAPTER II

II. REVIEW OF LITERATURE

Review of literature related to the research programme comprised of seven experiments is presented in various sub titles.

NATURAL RUBBER

Natural rubber (*Hevea brasiliensis*) is the major source of natural rubber in the world. It is a perennial deciduous tree species observed in rain forests conditions in tropical area of Central and Southern America. Cultivation of *Hevea* is now spreads in 25° North in high elevations of Yunnan, China and 21° South in the areas in Brazil. It is also spread in Malaysia, Indonesia, Thailand, Sri Lanka, South India, Combodia, Vietnam, Phillipines, Papua-New Guinea and Southern China. Plantations are present in the central and West Africa (Cengo, Cameroon, Ivory Coast, Liberia) and small areas in the tropical America (Verhege, 2010). In India, total rubber cultivated area is around eight lakhs hectares including the traditional rubber growing area covering Kanyakumari district of Tamil Nadu state, Kerala and southern districts of Karnataka and the non- traditional regions including North eastern states, Konkan region of Maharshtra and small areas in the state of Odisha.

RUBBER GROWING SOILS

The suitability of rubber cultivation was reported as well drained soil with a pH below 6.5 (Karthikakuttyamma *et al.,* 2000). Generally the rubber growing soils in the traditional areas in India are acidic within the pH range of 4.5-6.0 and mostly laterites and lateritic in nature in the form of weathered conditions (Joseph, 2016). Other soil forms include the red and alluvial soils. Sixty two soil series were identified in the traditional belt of cultivation with majority (51) coming under ultisols followed by inceptisols and entisols (NBSS and LUP, 1999). According to Verhege (2010) an optimum pH between 4.5 to 6.0 is congenial for rubber cultivation even though a higher pH can also be tolerated by rubber plants. Stevanus *et al.* (2017) in a study of growth of rubber in pyrite constraint tidal swampy area with low pH (2.87-3.05) found that rubber can be grown in these areas but the growth was retarded as compared to the dry land area. According to Rodrigo *et al.* (2011) in two soil types in Menaragala district in Sri Lanka where the soil pH is higher than the optimum range are suitable for rubber cultivation.

PLANT RHIZOSPHERE

The rhizosphere, defined as the volume of soil adjacent to and influenced by the plant roots is of great importance to plant health and soil fertility. Rhizosphere is characterized like a gradient of combined chemical, biological and physical properties along the root. Rhizosphere is depicted by three zones: the endorhizosphere - being the part of cortex and endodermis where microorganisms and minerals were existing; the rhizoplane - the middle zone and the ectorhizosphere - outer end zone and these were extended out towards the bulk soil (Mc Near Jr, 2013). Dessaux *et al.* (2016) described the rhizosphere as immediate vicinity of root where soil components and plant roots were in contact to make a suitable environment for plant growth. Prashar *et al.* (2018) identified the rhizosphere as a region of higher nutrients and a hot spot of chemical and biological reactions. The nutrient concentration was higher in the rhizosphere due to root mediated changes (Neumann and Romeheld, 2002).

De-Graaff *et al.* (2010) and Orwin *et al.* (2010) reported that the stoichiometric relationship among plant, microbial and soil components within the root zone directly influenced by the plant roots, is known as the rhizosphere. Therefore plants are different in their activities in the rhizosphere and the rhizospheric activities are species specific as the plants are influencing the activities through the alterations or adaptations of the physical environment during root growth (Bird *et al.*, 2011).

The spatial distribution of the rhizosphere in different crops varied between each other. With the help of Scanning Electron Microscopy (SEM) and Electron Microbeam Analysis (EMA) rhizosphere extension in peanut and soybean was estimated as 0.2 mm thick. In the case of oat (*Avena sativa*) crop, it lies within 0.1 mm of a root and for the Italian ryegrass (*Lolium multiflorum*) sward, it was 0.3 mm (Curl and Truelove, 1986). Dotaniya and Meena (2015) reported rhizosphere as a vital region of plant ecosystem; ~ 2 mm from the root surface. Root induced changes are different depending on soil texture and structure. According to Jones *et al.* (2003) soil properties induced by plant roots were generally observed up to a distance of a few micrometers to about seven millimetre from the surface of an active root segment or a root mat.

RHIZOSPHERE SOIL

Even though the rhizosphere contributes 1-2 per cent of the total volume of the soil (Calvaruso *et al.*, 2011; Gobran and Clegg, 1996), it is having a major role for functioning of soil-plant system. Rhizosphere soil strongly influences the organic and inorganic nutrient availability thereby nutrition of plants (Dessaux *et al.*, 2009; Hinsinger *et al.*, 2006). According to Yanai *et al.* (2003) rhizosphere soil is the soil adhered to root after gentle shaking of the root-soil segment. Pandey and Palni (2007) collected the rhizosphere soil as the soil adhered to plant roots collected from the top 5-10 cm layer. Zhao *et al.* (2010) collected the rhizosphere soil of tree crops as the soil adhering to live fine roots (<1mm) after gentle shaking. Gracia *et al.* (2005) considered the soil strongly attached to roots as the rhizosphere soil. Wang and Zabowski (1998) collected the roots from the soil carefully without disturbances and gently shaken and soil tightly adhered to roots were collected as rhizosphere soil. Collingnon *et al.* (2011) collected the rhizosphere soil as the adherent soil aggregates less than one cm of the roots of spruce (*Picea abies krast*) and peech (*Fagus sylvatica L*) stands. Seguin *et al.* (2004) collected the soil adhered to roots by hand shaking to obtain the rhizosphere soil from Populus (Populus deltoids) plants.

RHIZOSPHERE pH

The rhizosphere pH are formed due to different reasons such as the imbalances between adsorption of cations and anions, generation of CO_2 by rhizosphere respiration and secretion of organic acids, H^+ and other chemical compounds (Soong *et al.*, 2014). Hinsinger (1998) explained that the rhizosphere pH changes can be considered as the strategic way of adaptations of plants making the nutrients to be available for absorption by roots. The rhizosphere pH was influenced by the activities of roots by release of H^+ and OH^- for the balance of cation-anion uptake at the soil root interface, the rhizosphere (Riley and Barber, 1971). Recently, many authors reported that depending on the environmental constraints, pH changes occurred in the rhizosphere as a response of plants.

Because of various environmental stresses, there will be release of H^+ ions as in the case of scarcity of Fe or P and toxicity of Al and other metals (Haynes, 1990; Hinsinger, 1998, 2001a, b; Marschner, 1995, 1995a). Buffering capacity of soil is also having a major role in the rhizosphere pH activities (Youssef and Chino, 1989). Roots are acquiring most of the minerals required in the form of ions and thus in order to compensate the imbalances between cation and anion uptake, roots excreting ions into the soil to prevent the changes in the electro neutrality of the root tissue (Darrah, 1993; Calvaruso *et al.*, 2006).

Imbalances of cationic - anionic absorption are the reason for increase or decrease of rhizosphere pH (Soong, 2014; Haynes, 1980). The differential absorption of cations or anions by the roots resulted in the excretion of H^+. This differential uptake is due to the systolic pH maintenance and plant requirement of anions or cations. To compensate the electric charge to maintain the electro neutrality of the cation - anion balance is operating in the rhizosphere. Hinsinger *et al.* (2003) reviewed the origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints. Riley and Barber (1971) reported that the rhizosphere changes were evident by the release of H^+ or OH^- to compensate the unbalanced cation-anion uptake of the rhizosphere. Bernal and McGrath (1994) reported that there will be an enhanced H^+ efflux rate generally resulted due to imbalances between inorganic anion or cation absorption by the roots.

The alterations in the rhizosphere due to the activity of plant roots are a function of nutritional requirement / status of the plant. Because of the differences of nutrients, roots exerts changes in the rhizosphere and the rhizosphere acidification and alkalization depends on many factors including buffering capacity of soil, moisture status, soil aeration, soil respiration, microorganisms, root exudates, genotypic differences of the plants *etc.* (Neumann and Romheld, 2000).

Dicots acidification is most general due to P deficiency as seen in many plants(Kirk and Leven Du, 1997; Le Bot *et al.*, 1990; Neumann and Romheld, 2000). The plant available form of N exists in both cationic (NH_4^+) and anionic (NO_3^-) form. Also this comprises of 80 per cent of the ion uptake as a whole, the N concentration has a major role in changes in cation/anion uptake thereby acidification or alkalinization (Marschner, 1995). Gahoonia and Nilson, (1992) and Jungk *et al.* (1993) reported that in acid soil in order to enhance P availability, rhizosphere alkalinization in response to NO_3^- fertilization is observed. Rhizosphere alkalinization in acidic soil also alleviates the Al-toxicity by the increased availability of Ca^{2+} and Mg^{2+} (Marschner, 1998, Bagayoko *et al.*, 2000). Alkalinization/acidification due to Al concentration in Al-sensitive and Al-resistant genotypes was reported in acid soils (Calba and Jaillard, 1997; Haynes, 1990, Rufty *et al.*, 1995; Degenhardt *et al.*, 1998, Foy, 1988). Environmental stresses also cause this type of release of H^+ ions due to enhanced organic anions (Ohwaki and sugahara, 1997). Because of excess K^+, an increase of negatively charged exudates (carboxylates) is increased (Ryan *et al.*, 1995).

RHIZOSPHERE CHEMISTRY AND NUTRIENT AVAILABILITY

The chemical changes in the rhizosphere are different compared to the bulk soil because of the changes in nutrient elements, nutrient uptake, root exudates and microbial activities (Marschner, 1995). Availability of nutrient is a factor of output fluxes and input fluxes of elements (Hinsinger *et al.*, 2009) and the release of organic substance from the root is the major process involved (Grayston *et al.*, 1997; Lambers *et al.*, 2009). Marcet *et al.* (2006) suggested that the rhizosphere nutrient element changes were due to the dynamic interactions of root processes and soil characteristics along with microbial activities in the rhizosphere. The solubility of nutrients and its uptake by plants and microorganisms against their release by decomposition and its balance have the influence on the ambient concentration of soluble nutrients in the rhizosphere (Toberman *et al.,* 2011; Priha and Smolander, 2003).

The rhizosphere chemistry and nutrient availability in the rhizosphere is species specific and different plants showed different patterns of chemical reactions and nutrient availability in the rhizosphere. The production of root exudates helps plants by adaptations of nutrient changes to increase the availability of necessary nutrients in each species. Due to the presence of exudates, the availability of nutrients enhanced by dissolution of insoluble minerals and desorption from clay minerals or organic matter. These were liberated to soil solution for plant uptake. Massaccesi *et al.* (2015) described that the rhizosphere reactions have profound influence on the nutrient availability and cycling of nutrients along with the microbial communities.

Bagayoko *et al.* (2000) reported that the Bray-P levels were two to four fold in rhizophere than bulk soil. Soil mineral N, Ca and Mg were also higher in the rhizosphere than bulk soil. In the Douglas fir (*Pseudotsuga menziesii*) trees, the K, Ca, and Mg were higher in the rhizosphere than bulk soil (Wang and Zaboswski, 1998). Rhizosphere is usually represented as the zone of higher nutrient availability as this was not true for all metals (Youssef and Chino, 1989). It was reported that Zn in water extract was higher in rhizosphere than bulk soil. Yanai *et al.* (2003) viewed universal accumulation of K in the rhizosphere. Also Ca, Mg and Na was accumulated in the rhizosphere. Higher soil available P in the rhizosphere was observed by Fang *et al.* (2017).

Collingnon *et al* (2011) observed that the K, Ca and Mg concentration was higher in the rhizosphere in Norway spruce and beech stands. Plants have the ability to increase the recalcitrant P by the rhizosphere changes (Gahoonia and Nilson 1992; Zoysa *et al.*, 1998). Dieffenbach and Matzner (2000) and Braun (2001) found a higher K^+ content in the rhizosphere solution in mature Norway spruce. Kirlew and Bouldin (1987) reported less Ca content in the rhizosphere in corn seedlings. Schottelndreier and Grerup (1999) reported difference in the Ca^{2+} Mg^{2+} and K^+ availability between rhizosphere and bulk soil. Philips and Fahey (2006) reported that tree roots can influence the nutrient release in the rhizosphere with particular effects on C, N and P cycling. Trace elements present in the soil is undergoing various changes especially in the root rhizosphere which resulted in the increase or decrease of their mobility, availability and toxicity (Lombi *et al.*, 2001). Fenn and Assadian (1999) reported mobilization of Cu and Mn in the rhizosphere in the plant Bermuda grass (*Cynoden dactylen Pers.*) and accumulate them in the leaves.

Doyle and Otte (1997) observed the excess concentration of Zn in the rhizosphere of aquatic plants. There is a difference in the Mn content between rhizosphere and bulk soil as reported in wheat (*Triticum aestivum*), maize (Zea mays) and sugar beet (Bela vulgaris L.) (Hinsinger, 2001b). Increased availability of Fe and Mn in rice (*Oriza sativa*) was also reported (Lindsay, 1979; Flessa and Fischer 1992; Begg *et al.*, 1994). Mobilization of Fe, Mn or Zn was reported (Gardner *et al.*, 1982;

Dinkeleker *et al.*, 1989; Gerke *et al.*, 1994). Availability of Zn, Mn and Cu contents were higher in the rhizosphere of *Garuga pinnata* and *Gliricidia. sepium* whereas, Fe content was higher in the rhizosphere of *Erytrhina variegata* and *Ailanthus triphysa* (Dinesh *et al.,* 2010). Elevated concentration of Fe and Mn and depletion of Zn and Cu in the rhizosphere as compared to bulk soil was reported (Calvaruso *et al.,* 2014).

In a study on the N-fractions in the rhizosphere of three tree species (18 year old) *viz.* Siberian elm (*Ulmas pumila*), Simon poplar (*Populus simonii*) and Mongolian pine (*Pinus sylverstris var.mongolica*) plantation on a nutrient poor sandy soil in Northern China, Zhao *et al.* (2010) found an increased N-mineralisation and nitrification in the rhizosphere in all the three plantations than the bulk soil. There were species difference in this observation that a higher NH_4^+N and NO_3^-N was recorded in the Mongolian pine plantation and lowest in the Simon poplar plantation. Nitrate$^-$ N showed a decrease whereas NH_4^+N have an increased value in the Siberian elm and Simon poplar plantation in the rhizosphere than bulk soil. However, the NH_4^+ N had no variation between rhizosphere and bulk soils in the Mongolian pine plantation. Liu *et al.* (2014) reported a study of N transformations in the rhizosphere of different trees in a seasonally flooded soil. He observed that a net increase of NH_4^+N and NO_3^-N concentration in the rhizosphere than bulk soil in all the tree species studied. But the NO_3^-N showed depletion in the rhizosphere soil and attributed as the differences of uptake of nutrients and microbial activities. In this study also, there was species difference in the NH_4^+N and NO_3^-N fractions, clearly indicating the different pattern of N- transformation ability of trees. Hermann *et al.* (2006) observed that there was a ten times increase in the N-mineralisation in the rhizosphere soil than bulk soil for the annual grass (*Avena barbata* (Slender wild oats) in California oak woodland-Savannas. He also found that the bacterial count was higher in the rhizosphere as compared to bulk soil and location-wise_differences were also there for this observations.

Jungk *et al.* (1993) studied the mobilization of different phosphate fractions in the rhizosphere. Because of the presence of very small quantity of P in soil solution the fractions of P attached to soil solid phase is important in which the apatitic P like sorbed P and Ca-P are mostly absorbed by plants. Cabeza *et al.* (2017) reported the P fractions depletion in the rhizosphere of young and adult maize and oilseed rape plants on acid sandy soil and neutral loamy soil. He observed that the inorganic P-fractions were depleted in the rhizosphere in both soil for both species. George *et al.*, (1996) and George *et al.*, (2002) reported various P-fractions under the agroforestry and crop species. Among the P-fractions variations observed under different plants and there was species differences also_for the individual fractions of P in the rhizosphere (Neumann and Massonneau, 2000; Neumann *et al.*, 1999).

Niebes *et al.* (1993) studied the non-exchangeable K in the rhizosphere of rape (*Brassica napus cv Drakker*) and was observed that the fine clay had less nonexchangeable K than coarser fractions. Again Kuchenbusch and Jungk (1982) reported that the exchangeable K was also less in the rhizosphere. This was explained that it was related to the sink concentration due to the liberation of the fixed - K in the rhizosphere. The decreased concentration of K in the rhizosphere and the availability of non-exchangeable K were reported also by Hinsinger and Jaillard (1993).

Cocco *et al.* (2013) observed rhizosphere and bulk soil difference in the exchangeable Ca, Mg, Na and K and its distribution with soil depth in the profile of the tree Heather (*Erika arborea L.*) plants. A higher CEC and base cation concentration were observed in the rhizosphere of Norway Spruce (*Picea abies*) stand in a nutrient poor condition in Southwest Sweden (Gobran and Clegg, 1996).

RHIZOSPHERE ADAPTATIONS

Soil acidity and interaction of various factors associated with this is usually a major limitation for plant growth in acidic soils. The adaptations of species and genotypes are different to these conditions and each plant respond differently (Marshner, 1991) and H^+, Al^{3+} and Mn^{2+} Ca^{2+}, Mg^{2+}, K^+ deficiency, stress adaptations are important in acidic soils (Bromfield, 1983). When wild plants are adapted to acidic soil infertility constraints, the usual visual symptoms of deficiencies were not seen instead there will be an increased shoot concentration of elements such as P, Ca or Mg as adaptive mechanisms (Marschner, 1991). In the rhizosphere, in order to compensate the depletion of K, the release of K from non exchangeable or organically bound from is undertaking as an adaptation (Jungk and Claassen, 1986). Another important adaptation in the rhizosphere is the absorbance of NH_4^+ and NO_3^- and associated acidification or alkalinization as mentioned earlier. The other important adaptation is in the form of changes of initial pH when plants starts to grow to make a convenient pH by either decreasing or increasing the initial pH. Jilliang *et al.* (2018) illustrated the rhizosphere activities and N-availability and its relation to organic substances and emphasized on the importance of soil-plant interaction especially in the rhizosphere. Anderson *et al.* (2017) in his study mainly focused on the understanding of the rhizosphere changes after the application of CuO nanoparticles (to enhance root hair increase) and ZnO nanoparticle (to improve lateral root production) and how to make a precise quantity of nanoparticles for the rhizosphere level in different crops.

The study was conducted in Wheat (*Triticium aestivum*) and this was an important step in the growing prescription for sustainable cultivation. Rahmanian *et al.* (2016) reported that the alterations of nutrients in the rhizosphere is very important and in this work the changes in various fractions of Zn by the application of chelators in rhizosphere and bulk soils and its role in the uptake of Zn by maize plant was described. Song *et al.* (2016) studied and reported the specificity of grafted watermelon rhizosphere chemistry, microbe's reactions and the diversity in nature of reactions performs both biologically and chemically.

FOURIER TRANSFORM INFRARED SPECTROSCOPY (FTIR)

Identification of soil components and soil organic matter characterization by functional group differentiation are the important applications of Infrared spectroscopy (IR) in which Fourier transform infrared spectroscopy (FTIR) is important. Functional group present in the organic substances and the mineral particle associated groups contained in the soil can be identified using FTIR (Dick *et al.,* 2003; Du and Zhou, 2009))

MANAGEMENT OF LOW pH SOIL

Borja and Nilson (2009) studied the long term effect of liming on the tree growth and nutrient concentration in old Scot pine (*Pinus sylvestrin. L*) needle increased and the Mn, Al and Fe in needles decreased after long periods of lime application. Liming had no effect on tree growth, but increased Ca content after lime application was observed by Bakker *et al.* (1999,2000) and Kreutzer (1995). A negative effect of lime application on tree growth was reported in Finland and Sweden for the Scot pine (*Picea abies*) stand after a period of 30 years of liming (Anderson *et al.*, 2017) but the effect was positive in the more productive sites (Staaf *et al.*, 1996). An increase of total root length after liming was reported (Bakker *et al.*, 1999, 2000). Apart from the pH changes after liming, the effect on availability of N and P was reported (Haynes, 1990). Increase of fine root growth was reported by Nowotny *et al.* (1998) also, but the liming was ineffective on fine root biomass in low productive area of Pine stands (Borja and Nielson, 2009). Maier *et al.* (2002) found that in a glasshouse experiment lime incorporation increased the plant height but the number of leaves or stems was not increased.

INFLUENCE OF pH AND BASE STATUS ON N TRANSFORMATION

Curtin *et al.* (1998) studied the effect of pH on N mineralization and reported that when pH increase by lime application resulted in the increased mineralization of N and C. Urea mineralization and soil pH variations are directly related (Basri *et al.* 2013). Cabrera *et al.* (1991) and Chen *et al.* (2010) reported that in high pH soil, urea is undergoing volatilization by the process of hydrolysis and enzyme activity. Thangarajan *et al.* (2015) reported the N transformation from different sources including inorganic fertilizer urea in Australian soils with varying pH *viz.* 4.3, 7.09 and 9.15. It was observed that the nitrification was higher in neutral soil and alkaline soil than acid soils. Irshad *et al.* (2005) studied the N mineralisation in saline soils after urea application in an incubation experiment. A significantly higher NH^+ N release was observed in the 4th week after application. The release pattern of NH^+ N and NO_3^- N was different.

INFLUENCE OF pH AND BASE STATUS ON PHOSPHOROUS RELEASE FROM FERTILIZER

Phosphorous deficiency due to P-fixation is a limitation in acid soils. The adsorption of P is pH dependant and Saunders (1958) studied the release of P from superphosphate, double superphosphate, potassium dihydrogen phosphate and diammonium phosphate in soil of yellow-brown loam group formed from andesitic volcanic ash and high P retention capacity. In the high P and low P soils the reactions of different sources of P is different. While ammonium phosphate increased the pH after incorporation, the super phosphate decreased the pH. Huang *et al.* (2005) studied the P release in response to pH variations in the lake sediments and pH has profound influence on release of P. Borovec (2000) observed that the release of P in the lake sediment is more dependent on pH rather than oxygen depletion. Devau *et al.* (2010) studied the changes in the rhizosphere and its influence on P availability and described the pH dependant changes also. In this study a pH range of 4- 8.5 was investigated and found that when pH was less than 6, P availability was decreased and when pH increased above 7, the P availability was increased.

CHAPTER III

III. MATERIALS AND METHODS

The methodology of the experiments and the procedure for the chemical analysis of samples of the seven experiments undertaken in the present investigation is presented in this chapter.

III-1. Rhizosphere chemistry (Young plants in the main field)

In this experiment, the chemistry and availability of major nutrients in the rhizosphere of young rubber plants grown in different locations in Kerala were studied.

III.1.1. Identification of location

The study was conducted in the most popular clone RRII 105 occupying 85 per cent of the total cultivated area in India. Age of the plantation selected was 3rd and 4th year. A total of 26 locations in large estate plantations in the agro-climatic zones comprises of Palakkad, Thrissur, Kottayam, Pathanamthitta and Kollam in the traditional rubber growing areas of Kerala (Fig. 2a) were included for the study. All the plantations selected were followed uniform management practices as per the recommended practices by the Rubber Board. Leguminous cover crops were maintained in all the selected fields as one of the important soil management practices followed in systematic rubber cultivation. Details of the locations are given in Table 1.

Table 1. Locations of young rubber plantations selected for rhizosphere and bulk soil sample collection

Sl.No	Locations
1	Mannarkad-1
2	Mannarkad-2
3	Vaniampara-1
4	Vaniampara-2
5	Chimony
6	Mooply-1
7	Mooply-2
8	Kundai-1
9	Kundai-2
10	Palapilly
11	Puthukkd
12	Adirapally
13	Kallala
14	Mundakayam
15	Konney
16	Kumbazha
17	Kodumon
18	Chandanapally
19	Ayiranalloor-1
20	Ayiranalloor-2
21	Kulathupuzha
22	Bee-bee estate
23	Shaliacary-1
24	Shaliacary-2
25	Rajagiri-1
26	Rajagiri-2

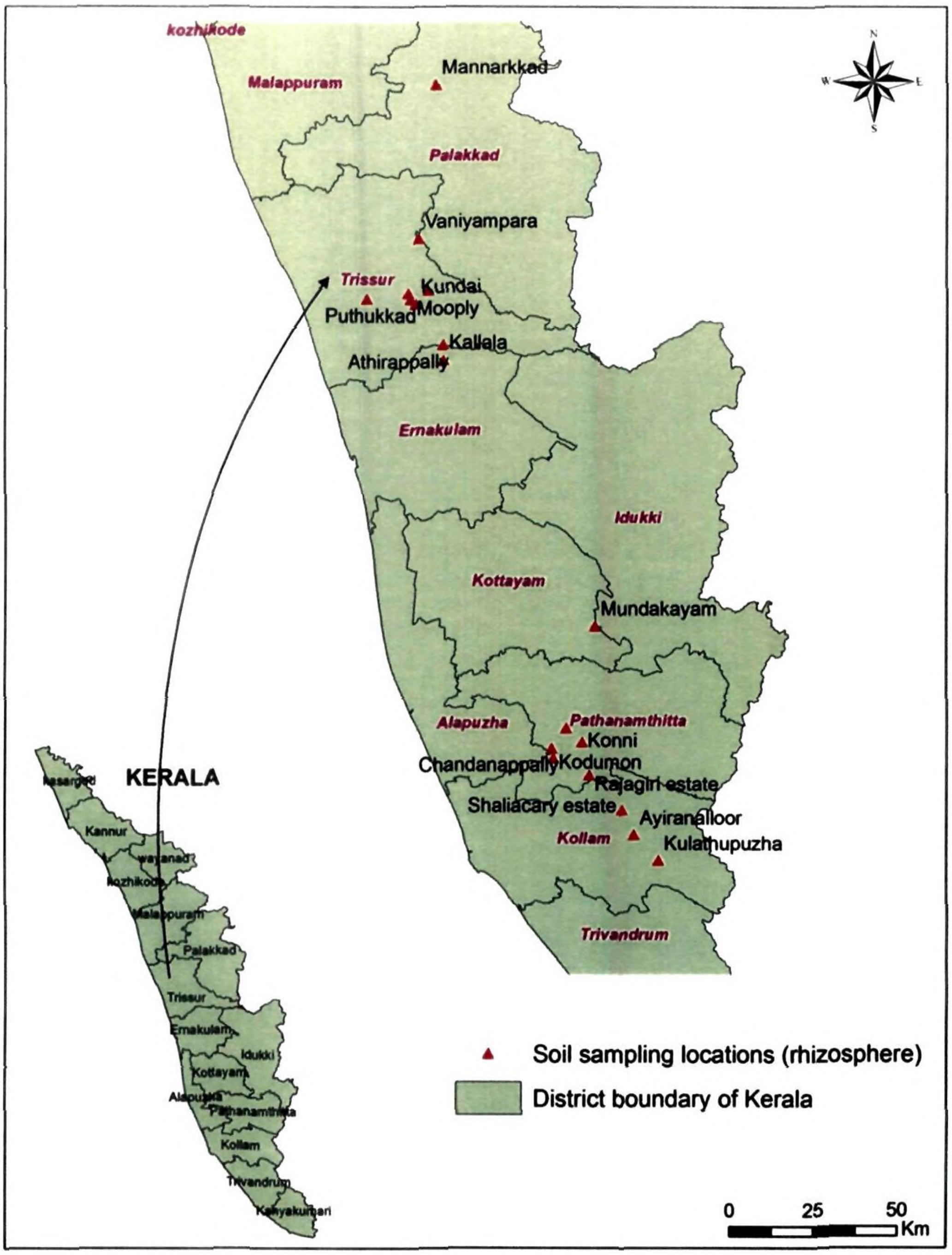

Fig 2(a). **Sampling locations of the young rubber plantations for rhizosphere vs bulk soils in Kerala.**

III.1.2. Soil sample collection

Rhizosphere soil (soil adhered to fresh fine roots) samples were collected from fresh fine roots at a radial distance of 45-50 cm from the tree base (stem of the tree) at the vertical depth of 10-15 cm at three points around the plant to obtain sufficient quantity of samples for processing and analysis. After collection of rhizosphere soil, the soil not in contact with roots were collected as bulk soil. From each location, separate rhizosphere and bulk samples from five adjacent trees were collected. The samples were taken in polythene bags and brought to the laboratory on the same day and air- dried in shade, sieved through 2 mm sieve and stored for the chemical analysis. The sampling period was during September end through October to November just starts during 2014 with uniform soil moisture conditions and this was the period for routine soil and leaf sample collection for fertilizer recommendation to rubber plants. The rhizosphere and bulk soils were analysed for chemical properties as per standard proceedures and the data were compared using t-test (Snedecor and Cochran, 1967).

III. 1.3. Chemical properties

III. 1.3.1. Soil reaction (pH) (Black, 1965)

A known quantity (10 g) of soil with measured quantity (25 ml) of distilled water (1:2.5 soil: water ratio), stirred at regular intervals and equilibrated for 30 min. The pH of the suspension was recorded on a direct reading pH meter with combined calomel-glass electrode unit standardised with different buffer solutions with known pH.

III. 1.3.2. Soil organic carbon (SOC) (Walkley and Black, 1934)

Soil organic matter in the accurately weighed (0.5 g 0.2 mm sieved) finely powered soil was oxidised under standard conditions with 10 ml 1N potassium dichromate ($K_2Cr_2O_7$) and add 20 ml sulphuric acid , gently rotated to mix the solution and kept for 30 min on an asbestoes sheet. The excess $K_2Cr_2O_7$ was back titrated with Ferrous Ammonium Sulphate with 1, 10 phenanthrolin indicator. A blank was kept without soil. The per cent organic carbon was estimated using the blank value.

III. 1.3.3. Available nitrogen (Subbiah and Asija, 1956)

Available N was estimated by the distillation of a known weight (20g) of soil with 2.5 per cent alkaline (100 ml NaOH) and 0.32 per cent potassium permanganate (100 ml) by steam distillation to liberate ammonia. The ammonia thus formed was absorbed in 25 ml boric acid with mixed indicator and this was titrated against standard acid and expressed as $kgha^{-1}$.

III. 1.3.4. Available phosphorous (Bray and Kurtz, 1945)

A known weight (2.5 g) of soil (2 mm sieved) was extracted with 25 ml Bray-II reagent (0.03 N NH_4F in 0.1 N HCl) by shaking in a mechanical shaker for five minute and the available P in the extract was determined using colorimetric procedure in a Spectrophotometer at 660 nm by ascorbic acid method.

III. 1.3.5. Available potassium (Jackson, 1958)

A known weight (5 g) of soil (2 mm sieved) was extracted with 25 ml neutral normal ammonium acetate by shaking for five minutes in a mechanical shaker and available K in the extract was determined by direct reading using Flame Photometer.

III. 1.3.6. Available calcium and magnesium (Jackson, 1958)

From the 1N neutral ammonium acetate extract, 2.5 ml was taken and 2.5 ml strontium chloride was added and made up to 50 ml and the available Ca and Mg were determined by direct reading using Atomic Absorption Spectrophotometer.

III. 1.3.7. Available micronutrients (Wear and Sommer, 1948; Whitney, 1988)

Available micronutrients (Zn, Mn, Fe and Cu) were extracted from three gm soil with 30 ml 0.1N HCL by shaking in a mechanical shaker for one hour and the concentration of each element was measured by direct reading using Atomic Absorption Spectrophotometer.

III. 1.3.8. Cation exchange capacity (Black, 1965)

A known quantity (10 g) of soil was saturated with 250 ml neutral normal ammonium acetate and leached continuously to displace the cations. The excess ammonium acetate was removed with 60 per cent alcohol until the solution became chloride free using silver nitrate solution. Absorbed ammonium ions were determined by steam distillation using MgO and liberated ammonium is absorbed in 50 ml boric acid with mixed indicator (methyl red and bromocresol green). This solution was then titrated with 0.01 N HCl to estimate the cation exchange capacity as cmol (+)kg^{-1}soil.

III. 1.3.9. Exchangeable calcium and magnesium (Jackson, 1958)

From the ammonium acetate leachate of the CEC determination, 45 ml was taken and 2.5 ml strontium chloride were added and made up to 50 ml and exchangeable Ca and Mg (cmol (+) kg^{-1}) were determined by Atomic Absorption Spectrophotometer.

III. 1.3.10. Exchangeable potassium (Jackson, 1958)

Exchangeable K was determined from the ammonium acetate leachate of the CEC estimation by direct reading using potassium chloride as standard solution by Flame photometer and expressed as cmol (+) kg $^{-1}$.

III. 1.3.11. Exchangeable aluminium and exchangeable acidity (McLean, 1965).

Weighed 10 g air-dry soil into a 250 ml beaker and added 50 ml KCl, mixed thoroughly and kept for 30 min. Filtered the solution through the Whatman No. 1 filter paper into 100 ml volumetric flask and leached the soil with KCl solution till the volume reached the mark. After this the solution was transferred to 500 ml conical flask and titrated against 0.05 N NaOH by adding 6-8 drops of phenolphthalein until the pink colour persist for 30 minutes to obtain the exchangeable acidity values. To determine the exchangeable Al, added one drop of sulphuric acid and 10 ml potassium fluoride solution and mixed well. Titrated against 0.05 N sulphuric acid till pink colour disappeared. Kept for 10 minutes and again titrated to a lasting colourless end point. Exchangeable Al and exchangeable acidity was expressed as cmol(+)kg^{-1}soil.

III. 1.3.12. Base saturation (Jackson, 1958)

Base saturation was calculated from the value of cation exchange capacity and total exchangeable bases measured from the leachate for the determination of cation exchange capacity and expressed as percentage.

$$\text{Base saturation (\%)} = \frac{\text{Total exchangeable bases (cmol (+) kg}^{-1}\text{ soil)}}{\text{Cation exchange capacity (cmol (+) kg}^{-1}\text{ soil)}} \times 100$$

III. 1.3.13. Total Nitrogen - Modified Kjeldhal Method (Piper, 1966)

Total N in the soil was determined by modified Microkjeldhal distillation method Combined N in soil organic matter is converted to ammoniacal form by digestion of (0.5 g ground and passed 100 mesh sieve soil) with 4 ml Con. H_2SO_4 in the presence of selenium-potassium sulphate catalyst mixture along with 5 per cent salicylic acid and 0.3 g sodium thiosulphate to trap nitrate N as nitro salicylic acid. The digest was made alkaline with NaOH and the ammonia liberated was determined by titration against standard acid by Kjeldahl distillation unit.

III. 1.3.14. Total phosphorous (Jackson, 1958)

Total P present in soil (2 g) was digested using 1:1 concentrated sulphuric acid- perchloric acid (60 per cent) mixture at high heat for two hours. Cooled and added 25 ml distilled water and boil for one hour, filtered to a 100 ml standard flask until the solution became chloride free. The P in the extract was determined using spectrophotometer by ascorbic acid method.

III. 1.3.15. Total potassium (Jackson, 1958)

Total K in the soil is determined from the perchloric acid extract of total P using Flame Photometer.

III. 1.3.16. Ammoniacal nitrogen (NH_4+N) and Nitrate nitrogen (NO_3-N) (Page *et al*, 1982)

A known quantity (10g) of fresh soil was extracted with 50 ml 2 M KCL by shaking in a mechanical shaker for one hour and filtered through Whatman No. 1 filter paper. From this 20 ml was distilled with magnesium oxide powder to determine ammoniacal N and titrated against 4 per cent boric acid containing mixed indicator (Methyl orange and Bromocresol green) by auto Kjeldhal distillation unit. From the same solution nitrate N was distilled off with Devardas alloy.

III. 1.3.17. Fractions of phosphorous (Chang and Jackson, 1957)

III. 1.3.17.1. Saloid bound phosphorous (Saloid-P)

Saloid bound P (mg kg^{-1}) was extracted by shaking 0.5 gm of the soil (0.2 mm sieve) with 25 ml of 1 N NH_4Cl for 30 minutes and estimated by ascorbic acid method using spectrophotometer at 660 nm.

III. 1.3.17.2. Aluminium bound phosphorous (Al-P)

The soil kept after the above extraction of saloid bound-P was shaken with 25 ml of NH_4F (pH 8.2) for one hour and centrifuged. The aluminium bound P (Al-P- mg kg^{-1}) in the extract was estimated by ascorbic acid method using spectrophotometer at 660 nm.

III. 1.3.17.3. Iron bound phosphorous (Fe-P)

The soil left after the extraction of Al.P was washed twice with 12.5 ml of NaCl solution, centrifuged and decanted. The soil was shaken with 25 ml of 0.1 N NaOH for four hours and centrifuged and after flocculation of organic matter in the extract with con. H_2SO_4 and centrifuged. The iron bound P (Fe-P - mg kg^{-1}) was determined by the ascorbic acid method with spectrophotometer at 660 nm.

III. 1.3.17.4. Calcium bound P (Ca-P)

The residue left after iron -P in the centrifuge was washed twice with 12.5 ml of saturated NaCl solution. The washed residue was shaken for one hour with 25 ml 0.5 N H_2SO4 and centrifuged and the extract read for the Ca bound P (Ca-P- mg kg^{-1}) using ascorbic acid by Spectrophotometer at 660 nm.

III. 1.3.18. Organic phosphorus (Saunders and Williams, 1955)

Organic- P in soil (2 g air-dried processed through 0.5 mm sieve) was extracted with dilute acid (50 ml, 0.5 M H_2SO_4 in a centrifuge tube) after oxidation of organic matter by ignition at 550 ^{0} C for one hour in muffle furnace. Phosphorous was determined by ascorbic acid method. The difference between the ignited and unignited sample gave the measure of organic P (mg kg^{-1}).

III. 1.3.19. Fractions of potassium

III. 1.3.19.1. Water soluble potassium (Black, 1965)

Weighed 5 gm soil in a centrifuge tube and added 25 ml distilled water and shaken well for one hour and centrifuged at 5000 rpm and filtered through whatman no 1 filter paper and read the K (mg kg^{-1}) content using flame photometer.

III. 1.3.19.2. Exchangeable potassium (Black, 1965)

To the residue left over in the above estimation in the centrifuge tube, added 50 ml ammonium acetate (neutral) and shaken well for 30 minutes at 130 oscillation and centrifuged and repeated the extraction until 100 ml filtrate was collected. The extract was read for K (mg kg^{-1}) content.

III. 1.3.19.3. Fixed potassium/Non-exchangeable potassium (Black, 1965)

To the residue of the above extract added 50 ml of 1 N HNO_3 and transferred to 250 ml conical flask and placed on a boiling water bath for half an hour. After this filtered through whatman No. 1 filter paper and collected 100 ml extract and the K (mg kg^{-1}) content was read in in Flame Photometer.

III.1.3.20. Soil moisture (%) (Gravimetric method)

A known weight of air-dried soil is dried at 105 °C until constant weight is obtained and the loss in weight after oven dried is expressed as percentage moisture content.

III. 1.3.21. Gravel content (%)

A known weight of soil was weighed in a top loading weighing balance. After this the soil was sieved through the 2 mm sieve and the coarser gravel content obtained was again weighed. The gravel per cent was calculated as the difference in weight to the total weight of soil and multiplied by 100.

III. 1.3.22. Field capacity (%)

Pressure plate of the pressure plate apparatus is placed in a tray of water and soaked overnight. After this the circular disc width of 1 cm with internal empty space placed on the pressure plate and filled with the soil and remained undisturbed for a day to get saturated. Transferred the soil to the filtering funnel and kept for completely draining of water. Transferred the drained soil to an initially weighed moisture can and again weighed the soil with can and then kept it in the oven at 105 ^{0}C for constant weight and per cent field capacity is calculated from weight difference of soil multiplied by 100.

III. 1.3.23. Soil mechanical separates (Robinson, 1922)

Mechanical separates *viz.*, coarse sand, fine sand, silt and clay were determined by international pipette method with the sedimentation principle and decantation method based on the Stock's law and expressed as per cent content.

III. 2. Compariosn of growth of rubber seedlings under three distinct soil pH having different base status

The experiment was conducted by growing rubber seedlings in three distinctly different soil pH *viz.*, i). Extremely acidic (pH 4.4), ii). Strongly acidic (pH 5.5) and iii) Neutral to slightly alkaline soil (pH 7.4). The two acidic soils and the neutral to slightly alkaline soil were extremely different in base status. Bulk quantity of these soils were brought from rubber plantations from three different locations *viz.*, Malankara estate, Thodupuzha (soil pH 4.4), Mundakayam estate, Mundakayam (soil pH 5.5) and a large plantation in Wyanad (soil pH 7.4) respectively in Kerala.

III. 2.1. Initial study

Before initiating the study in the polybag, a preliminary study was conducted for close observation of the growth of rubber seedlings in three soils. 500 gm of soil was taken in four plastic trays of each pH and sprouted seeds were planted in all the trays and watered uniformly. After 30 days of growth, 15 seedlings of similar growth from each pH was selected and uprooted for the initial growth measurements *viz*, shoot length, root length, number of roots, fresh weight and dry weight of shoot (leaf+ stem+ petiole) and root. Shoot and root length (cm) were measured by meter scale. Tap root, small roots and fine roots were numbered physically and fresh and dry weight (g) of shoot and root were recorded separately to estimate dry biomass and expressed in g plant^{-1}.

III. 2.2. Experiment in poly bags

Using the bulk soil collected from three different locations, experiment was conducted for longer period of 240 days (8 months) by raising seedlings in the polythene bags in three soils to closely monitor the growth, rhizosphere chemistry and adaptations of rubber seedlings in different pH and base status. The experiment was carried out in Rubber Research Institute of India, Puthuppally, Kottayam, the central part of Kerala. A seedling study in polybag in the open-air condition was conducted. Seeds collected from the approved seed gardens were germinated on a specially made germination bed as per the recommendation of Rubber Board. Seeds sprouted within seven days were carefully transplanted to polythene bag (55 cm length and 25 cm width) and 400 gauge (100 micron) thickness with 10 kg soil (top soil -0-30 cm) collected in bulk quantity from rubber plantations at three different locations. The poly bags filled with the soil were placed in trenches taken with 30 cm depth. Three trenches for three different soils were taken and in each trench 50 plants were maintained. Regular watering and manual weeding were conducted and partial shading also provided uniformly when required. No fertilizer was added for any of the soils.

The growth of the plants were monitored in three different interval at 45, 90 and 240 days from the sprouted seeds stage in three soils. To study the growth parameters, 12 plants with uniform growth from three soils were uprooted and separated into shoot (leaf+ stem+ petiole) and root. The plant parameters *viz.* shoot length, root length, number of roots, fresh weight and dry weight of shoot (leaf+ stem+ petiole) and root were determined. The shoot and root length (cm) were measured by meter scale. Tap root, small roots and fine roots were numbered physically and fresh and dry weight (g) of shoot and root were recorded separately to estimate dry biomass and expressed in g plant^{-1}.

The rhizosphere soil was collected from the top surface of the polybag to a depth of 10 cm where maximum feeder roots with fresh fine roots were concentrated (Fig.12) from three soils at 90 (3 months) and 240 (8 months) days along with the uprooting of plants for growth parameters. The soil samples were brought to the laboratory, air-dried in shade and kept for chemical analysis.

The soil pH, soil organic carbon, available nutrients, fractions, exchangeable nutrients and total nutrients were done by the standard methods described in earlier session. The data were statistically analysed by ANOVA (Snedecor and Cohran, 1967).

To study the plant nutrient content, the uprooted plants at 90 and 240 days were separated into shoot (leaf+ stem+ petiole) and root and analysed for major (N, P, K), secondary (Ca, Mg) and micro (Zn, Fe, Mn, Cu) nutrients. The nutrient uptake (g plant^{-1}) of each nutrients by shoot, root and the total uptake were calculated from the nutrient concentration multiplied with dry biomass.

III. 2.2.1. Nitrogen (Microkjeldhal method) (Piper, 1966)

A known quantity (50 mg) of plant samples (after powdered and dried at 105^{0} C for six hours and dessicated) weighed into Kjeldhal digestion tube and digested with 2.4 ml con. H_2SO_4 in the presence of potassium sulphate and mercuric oxide at 420^{0} C until clear solution reached. This solution was distilled with 10 ml NaOH in Kjeltech nitrogen analyser and expressed as per cent content.

III. 2.2.2. Phosphorous and potassium (Piper, 1966)

0.5 g of plant samples (powdered and dried at 105^0 C for six hours) in a silica dish were ashed in the muffle furnace at 550^0C for half an hour, cooled and carefully moisten the ash with distilled water. Added 5 ml 1:1 HCl and digested in a water bath for one hour and transfered the contents to 100 ml with distilled water. From this the P and K were determined by using spectrophotometer and flame photometer, respectively and expressed as per cent content (%).

III. 2.2.3. Calcium (Piper, 1966)

The Ca content was determined from the HCl extract (0.5 ml) and added 2.5 ml $SrCl_2$ in 50 ml standard flask and read in Atomic Absorption Spectrophotometer and expressed as per cent content (%).

III. 2.2.4. Magnesium (Piper, 1966)

The Mg content was determined from the HCl extract (2.5 ml) and added 2.5 ml $SrCl_2$ in a 50 ml standard flask and read in Atomic Absorption Spectrophotometer and expressed as per cent content (%).

III. 2.2.5. Zinc, Iron, Manganese and copper (Piper, 1966)

Zinc, Fe, Mn and Cu were determined directly from the HCl extract using Atomic Absorption Spectrophotometer and expressed as mg kg^{-1} .

III. 2.2.6. Root cation exchange capacity (root CEC) (Drake, 1951)

The root CEC at 90 days growth was compared in three soils. For the determination of root CEC, the fresh fine roots collected from the uprooted plants were cleaned in distilled water and excess moisture was removed by placing the roots between the folds of filter paper and gentle pressing to remove water. The roots then taken in a muslin cloth and after this 2.5g was immersed in 200 ml distilled water for 40 min with dipping and raising repeatedly. The roots thus treated was washed repeatedly in distilled water for the removal of H^+ ions and complete removal of H^+ was tested with litmus colour change of the washed solution. After this the root samples were dipped in 1 N KCl having a pH exactly 7 and kept for 40 minutes for ion exchange and the completion of ion exchange was known by the maintenance of a constant pH. The solution with root samples was titrated with 0.01 N KOH until the pH was changed back to 7 again. After this, the solution in excess in the beaker was drained off and the roots were washed and kept for air-drying in an oven at 80 ° C over-night and weighed. The root CEC was expressed as (cmol(+)kg^{-1}) of dry plant roots.

III. 2.2.7. FTIR Spectroscopy (Pellatization method using Varian 660 – IR- FTIR) - (Bio Rad, 1996).

The influence of rubber seedlings on changes in carbon functional groups by Fourier transform infrared spectroscopy (FTIR) spectra were taken for the three different pH soil at initial and 240 days and identified the functional group of carbon compounds. For this the soil samples (2 mm sieved) were powered in an agate mill. Two milli gram of the homogenized agate milled fine power of the soil samples were mixed thoroughly with 200 mg of KBr (FT-IR grade). Pellets were prepared using a hydraulic press at 12 bar. The pelletized KBr samples were dried in an oven at 100 ^{0}C for two hours prior to analysis to avoid the interferences from moisture absorption. FTIR Spectra was recorded with a Spectrophotometer (Varian 660 – IR FTIR). The resolution was 4 cm $^{-1}$ and 20 scans (Ellerbrock *et al.*, 1999 a). All spectra were corrected to reduce the effect of mineral contents, using the subtraction method.

111. 3. Management of soil acidity (Incubation and glasshouse experiment)

Soil samples having initial pH of 4.4 (extremely acidic) and 5.5 (strongly acidic) collected from the field were used for the incubation and glasshouse experiment to study the influence of lime on nutrient availability and growth of seedlings respectively. Lime requirement of these two soils were calculated based on the exchangeable Al method (Kamprath, 1970) and was 3.5 t ha^{-1} for pH 4.4 soil and 1.08 t ha^{-1} for pH 5.5 soil.

III. 3.1. Incubation experiment

An incubation experiment was conducted to compare the effect of lime incorporation in the extremely acidic (pH 4.4) and strongly acidic (pH 5.5) soil. Five hundred gram of soil was incubated with powdered shell lime ($Ca(OH)_2$) (one gram for pH 4.4 soil) and (three hundred milligram for pH 5.5 soil), mixed completely and kept for an incubation period of two months. Field capacity of the soil was 28 and 29 per cent for pH 4.4 and 5.5, respectively and this was maintained by adding distilled water equivalent to loss of weight. After incubation, soil samples were analysed for nutrient availability, cation exchange capacity and exchangeable Ca, Mg and K as per the procedure outlined by Jackson (1958). Exchangeable Al was estimated from 1M KCL extract as per the procedure of McLean (1965). Exchange acidity was measured by titration with 0.05 M NaOH using phenolphthalein as indicator (Mc Lean, 1965). The data were statistically analysed by t-test (Snedecor and Cohran, 1967).

III. 3.2. Influence of lime application on growth and nutrient availability in the rhizosphere of rubber plants - (glass house experiment with rubber seedlings)

Based on the results from the incubation study, a response study with rubber seedlings in extremely acidic soil (pH 4.4) were conducted in the glass house of Rubber Research Institute of India. Polythene bags were filled with 10 kg soil having pH 4.4. Powdered shell lime (20 g) as per the equivalent of lime requirement (3.5 t ha^{-1}) was applied and mixed with the soil. Sprouted seeds were planted in the polybags, two weeks after the incorporation of lime. 30 plants each were maintained in the lime treated and no lime group and similar management methods were followed for both the group. After five months of growth, the seedlings were bud grafted with scion from RRII 105. Further, three months after budding, observations on growth parameters (diameter and height) were recorded from 12 uniform plants from lime treated and no lime groups. The plants were uprooted and fresh weight (g) and dry weight (g) of the shoot (leaf+ stem+ petiole) and roots were recorded. Nutrient concentration (major and secondary nutrients as per cent and micronutrients as mg kg^{-1} respectively) of the shoot and root were determined (Piper, 1966) and nutrient uptake (shoot, root and total) on dry weight (g) basis were estimated and compared. After uprooting the plants, rhizosphere soil (0-10 cm from the top) samples were also drawn from the polybags with the observation plants and analysed for pH, organic carbon, available nutrients, cation exchange capacity, exchange properties, nutrient fractions and total nutrients as per the standard procedures followed in the study described earlier.

The data were tabulated and statistically analysed by t-test (Snedecor and Cochran, 1967).

111. 4. Effect of pH and base status on transformation of fertilizer nitrogen and phosphorus

The same three bulk soils collected with three different pH and base status were used in the experiments on influence of pH and base status on nitrogen transformation and phosphorous release pattern in three different pH and base status soil were conducted.

III. 4.1. Transformation of urea in three soils

Experimental details

Six hundred gram of 2 mm sieved soil was weighed into plastic basins and incubated with 25 mg of urea calculated on effective area basis as per the fertilizer doses 40 kg ha^{-1} hectare N in the form of urea followed in young rubber plants. The fertilizer urea was mixed well and kept for incubation for 20 days. A control with no fertilizer was also taken similarly. All soils were maintained at field capacity by adding distilled water on weight loss basis. At periodic interval *viz.* 24 hours, 2, 4, 7, 10, 15, 20 days, soil (10g) was extracted with 50 ml 2M KCl by shaking for one hour in a mechanical shaker. From the extract, 20 ml were distilled with MgO to quantify the NH_4-N using Kjeltech auto N- analyser. After this, into the same solution Devarda's alloy was added and estimated the NO_3-N using Kjeltech auto N- analyser.

III. 4.2. Effect of pH and base status on the availability of phosphorous from rock phosphate and superphosphate in three soils

Experiment Details

An incubation study was conducted to know the release pattern of phosphorous from two different sources *viz.* rock phosphate and super phosphate in three soils. Six hundred gm of soil was weighed into plastic basin and two fertilizer sources *viz*, rock phosphate (55.5 g) and super phosphate (62.5 g) calculated on effective area as per the fertilizer recommendation followed for young rubber plants (40 kg P_2O_5 ha^{-1}) were mixed thoroughly and incubated for 30 days. At 5, 10, 15, 20, 25 and 30 days interval, the soil samples (2g) were extracted with 20 ml Bray-II extractant and analysed the available P using ascorbic acid method at 660 nm in Spectrophotometer.

Fig. 2 (b). Rhizosphere soil

CHAPTER IV

IV. RESULTS AND DISCUSSION

1V-1. Rhizosphere chemistry of nutrient elements of young rubber plants in the main field and adaptations at the rhizosphere.

Twenty six locations covering the different districts of Kerala (Fig. 2.a) were selected for the study and included two from Palakkad, eleven from Thrissur, one from Kottayam, seven from Pathanamthitta and five from Kollam districts.

Soil pH, soil organic carbon (SOC), available P, available K and available Ca in the rhizosphere and bulk soils were given in Table 2. Significantly higher pH was recorded in the rhizosphere than bulk soil. In the rhizosphere soil, the pH ranged from 4.71-5.67 which includes the very strongly acidic (4.5-5.0), strongly acidic (5.0-5.5) and moderately acidic (5.5-6.0) ranges. However, for the bulk soil it was different and ranged from 4.16 (extremely acidic) to 5.66 (moderately acidic) soils. In majority of the locations (19 nos) the pH increased in rhizosphere soil as compared to bulk soil and the increase was towards the value between 5.0-5.5. The extremely acidic pH is modified to very strongly acidic and the rhizosphere pH is tended to be near to 5.0 – 5.5 indicating alkalization of rhizosphere as compared to that of bulk soils. Rhizosphere alkalization is a process observed in many acid soils (Michaud *et al.*, 2007). The rhizosphere pH change depends on different factors and among this the major ones were, adaptation to P-deficiency and Al-stress (Haynes, 1990), increase of P and K availability (Jungk, 2001), production of organic acids and organic acid anions for maintaining the cation/anion balance and uptake to achieve the electronuetrality in plants to activate the ion uptake and transportation in plasma membrane

(Schottelndreier and Falkengren-Grerup, 1999) and root respiration (Hinsinger *et al.*, 2003). The reasons for rhizosphere pH alterations is due to the maintanance of cation/anion balance which is a determining factor of the concentration of cations and anions in the soluble and exchangeable forms in soil (Youssef and Chino, 1987; 1988). The increase in rhizosphere pH is also associated with excess anion uptake especially NO_3^-, $H_2PO_4^-$/HPO_4^-, carboxylation and decarboxylation of organic acids and organic anions (Hinsinger *et al.*, 2003; Gerendas and Schurr, 1999). It was also reported that as a strategy of Al toxicity alleviation, Al-resistant plants prefer the anion uptake by alkalization of their rhizosphere in the acid soils (Calba and Jaillard, 1997; Degenhardt *et al.*, 1998; Foy, 1988). The rhizosphere pH increase to compensate for deficiency of P, is a strategy of plants to overcome nutrient limitations (Bagayoko *et al.*, 2000). Bagayoko *et al.* (2000) also reported the rhizosphere pH increase in cereals and legumes is to adjust the nutrient limitation in acid soil and for the alleviation of Al stress.

Table 2. Comparison of rhizosphere and bulk soil for pH, OC and available P, K and Ca

Locations	pH		OC (%)		Available nutrients (mgkg$_{-1}$)					
					P		K		Ca	
	R	B	R	B	R	B	R	B	R	B
1	5.45	5.34	1.92	2.51	183	8	179	31	370	356
2	5.39	5.28	2.36	2.52	74	19	88	46	509	430
3	4.64	4.51	1.31	1.13	180	11	263	154	373	266
4	4.94	4.48	1.39	1.45	30	16	315	253	266	400
5	5.31	4.83	1.49	1.57	295	48	118	101	419	216
6	5.01	5.05	1.05	1.2	196	175	102	96	201	269
7	5.05	5.51	1.05	1.84	71	76	102	148	201	481
8	5.43	5.23	2.96	3.59	190	58	92	84	387	396
9	5.14	5.23	1.43	1.63	95	58	215	85	233	268
10	5.14	5.48	1.44	1.44	175	8	123	111	313	223
11	4.92	4.41	1.55	1.41	23	29	136	105	372	101
12	5.33	5.45	2.69	3.15	22	26	104	143	273	309
13	5.01	4.87	1.61	1.51	11	5	97	70	160	107
14	5.67	5.66	1.58	1.78	98	60	205	200	746	544
15	5.34	4.97	1.91	2.1	395	50	144	99	205	45
16	5.17	5.62	2.42	1.37	71	13	111	76	107	55
17	5.16	5.22	1.71	1.62	36	37	109	115	155	116
18	4.76	4.76	1.38	1.27	89	1	107	65	178	75
19	4.71	4.54	2.55	2.63	38	30	108	92	395	463
20	4.52	4.36	2.51	2.17	40	63	100	76	275	218
21	4.91	4.81	1.15	0.99	40	10	76	94	332	359
22	4.69	4.76	1.93	1.86	348	171	50	46	242	61
23	5.27	4.76	1.61	1.96	351	285	114	37	231	229
24	5.01	4.77	1.28	1.20	93	94	234	139	213	158
25	4.94	4.85	1.68	1.86	146	25	107	111	111	50
26	4.72	4.76	1.76	1.95	50	42	66	80	107	55
Range	4.64-5.67	4.36-5.66	1.05-2.96	0.99-3.59	22-395	1-285	50-315	31-253	107-746	45-544
Mean	5.06	4.98	1.78	1.82	142	55	137	113	283	240
Tstat	3.35**		NS		2.92**		1.96*		NS	

There was no significant difference in SOC between rhizosphere and bulk soil. Among the locations, the SOC change was an increase/decrease or no change between rhizosphere and bulk soil. The SOC in the rhizosphere ranged from 1.05 – 3.15 per cent and in the bulk soil the values ranged from 1.13-3.59 per cent with a mean value of 1.78 in the rhizosphere and 1.83 in the bulk soil and both were in the medium to high category. Among the 26 locations about 21 locations, the SOC was between 1.0-2.0 per cent in the rhizosphere as well as in the bulk soil. It was also reported (Cocco *et al.* 2013) that if there is pH increase associated with solubilization of P by VAM infection, then the carbon change was unaffected. Therefore the observation of no change in SOC between rhizosphere and bulk in rubber may be an evidence of VAM association in P –solubilization in rubber

Significant higher concentration in available P was observed in rhizosphere than bulk soils. The available P ranged from 30-395 mgkg^{-1} in the rhizosphere and 1-285 mgkg^{-1} in the bulk soil and the rhizosphere P was higher as per the fertility rating followed in rubber (Karthikakuttyamma *et al.*, 2000). In eleven locations the available P recorded very high increase as compared to bulk soil. There was not a definite trend in the available P status in rhizosphere and bulk soils. When some locations showed very low available P in the rhizosphere and bulk soil, in some other locations the available P was very high in the rhizosphere and bulk soil. However, almost 24 locations recorded higher available P in the rhizosphere as compared to bulk soil. This may be due to the mobilization of P in the rhizosphere of rubber plants. Phosphorous uptake by plants is a factor of root zone concentration of P and therefore the root mediated soil changes in the rhizosphere is having important role in availability of P for plant uptake (Ruan *et al.*, 2000).

There are different mechanisms in P- solubility in the rhizosphere (Hinsinger, 2001a). In white lupin (Marschner *et al.,* 1986; 1997) root exudate production was reported as a root induced changes for P availability for the plant nutrition. The increased concentration of oxalate for the solubilization of aluminium phosphate in P-deficient soil as an adaptation mechanism was reported and the resulted increase of P-availability in rhizosphere enhanced the growth of Melastoma (*Melastoma malabathricum* L.) plants (Watanabe and Osaki, 2002). An increase of P in the rhizosphere was reported in two tree species *viz*, Velvet ash (*fraxinus velutina*) and Black locust *(Robina pseudoacacia)* (Du *et al.,* 2013) and increase of P due to uptake of ions for cation- anion balance was reported by Haynes (1990). The changes in pH in the rhizosphere and its importance in the release of P was reported (Marschner *et al.,* 1986). The tree *Garuga pinnata* also showed higher P in the rhizosphere and the cause of this effect was explained due to the root activities (Philips and Fahey, 2006) and the acquisition of P by the production of enzyme phosphatase and organic acid anions (Dinesh *et al.,* 2010) and P-acquisition in White lupin (Gardner et al., 1983) were also reported. The increased P in the rhizosphere of rubber plants may be an adaptive strategy to enhance P- availability in the P-deficient acidic rubber growing soils.

The available K recorded significant increase in rhizosphere than bulk soil. The values ranged from 50 - 315 mg kg^{-1} in the rhizosphere soil and 31-200 mgkg^{-1}

in the bulk soil with a mean value of 137 mg kg^{-1} and 113 mg kg^{-1} in rhizosphere and bulk soil, respectively. As per the rating followed in rubber (Karthikakuttyamma *et al.*, 2000), the available K was in the medium to high category in the rhizosphere and low to high in the bulk soil. In 24 locations available K was high in the rhizosphere than bulk soil. Difference in thermal stability of the mineral Kaoline between rhizosphere and bulk soil was observed by XRD techniques and associated changes of clay minerals having a role in availability of K was reported (April and Keller. 1990). Increase of K in the rhizosphere was reported for two tree species (Du *et al.*, 2013) and K increase in rhizosphere associated with pH changes in rye grass was observed by Marschner *et al.* (1986). Higher K availability in the rhizosphere related to mineral weathering were reported in trees (Turpault *et al.*, 2008).

There was no significant difference in available Ca between rhizosphere and bulk soils. The values ranged from 107-595 mg kg^{-1} in the rhizosphere and 45544 mg kg^{-1} in the bulk soil with a mean value of 283 mg kg^{-1} and 240 mg kg^{-1} in rhizosphere and bulk soil, respectively. In majority of the locations, the available Ca was found between 100 and 400 mg kg^{-1} in the rhizosphere and less Ca in the bulk soil. No significant difference in the Ca availability between rhizosphere and bulk soil for Norway spruce (*Picea abies*) was reported by Zhang and George (2002).

Table 3. Comparison of rhizosphere and bulk soil for available Mg, Zn, Cu, Fe and Mn

Locations	Available nutrients(mgkg-1)									
	Mg		Zn		Cu		Fe		Mn	
	R	B	R	B	R	B	R	B	R	B
1	60	112	2.68	2.41	18.3	22.6	77	62	39	30
2	88	84	1.50	1.31	7.5	7.2	17	18	53	64
3	74	83	0.61	0.66	2.5	2.8	13	12	40	35
4	83	100	2.78	2.79	5.1	14.9	72	30	72	35
5	147	60	3.95	3.05	19.9	39.2	28	25	24	20
6	61	72	1.30	2.23	28.8	45.5	28	33	15	28
7	61	81	3.06	4.94	25.1	31.3	37	42	34	47
8	73	57	2.21	3.83	16.9	50.9	32	35	38	29
9	43	56	1.99	1.57	11.0	14.0	34	42	17	16
10	70	59	1.02	0.88	11.8	16.1	17	14	26	25
11	50	23	2.67	0.79	22.1	24.1	24	19	27	21
12	37	71	0.71	0.69	4.4	4.1	23	22	15	14
13	47	36	0.88	0.83	4.1	3.5	23	20	17	13
14	56	30	3.28	3.59	20.6	29.7	30	36	22	17
15	50	17	1.54	1.44	9.0	11.8	20	21	23	14
16	77	12	5.20	0.83	10.5	6.3	32	34	14	13
17	78	62	1.46	1.09	25.1	6.1	85	91	23	20
18	42	33	0.40	0.37	6.24	4.4	27	15	2	1
19	151	90	1.99	1.57	11.3	8.3	41	29	47	29
20	41	57	1.57	1.70	10.6	35.7	67	81	26	27
21	79	68	2.55	1.83	17.2	14.3	50	27	24	24
22	11	13	0.79	0.86	8.3	9.2	62	60	15	14
23	116	78	1.06	1.24	13.8	17.1	11	55	6	8
24	84	49	1.49	1.23	21.0	28.1	18	16	23	18
25	44	69	1.37	1.18	28.6	29.8	43	44	9	6
26	62	28	0.74	1.04	27.6	26.4	48	52	6	6
Range	37-151	12-112	0.40-5.20	0.37-4.94	4.1-28.8	3.5-50.9	13-85	12-91	2-72	1-64
Mean	68.0	58	1.88	1.72	14.4	19.4	36	36	25	22
CD(P=0.05)	NS		NS		NS		NS		NS	

There was no significant variation in available Mg content between rhizosphere and bulk soil (Table 3). The available Mg concentration ranged 11-151 mg kg^{-1} in the rhizosphere and 12-112 mg kg^{-1} in the bulk soil with a mean value of 68 and 58 mg kg^{-1} in rhizosphere soil and bulk soil, respectively. Majority of the sampling locations (24 nos), the available Mg was between 35-88 mg kg^{-1} in the rhizosphere and this was not observed in bulk soil. In bulk soil still lower concentration of available Mg was observed. No difference in the available Mg between rhizosphere and bulk soil was observed and was reported that the concentration gradient of cation was a function of concentration of the nutrients in the medium (Zhang and George, 2002).

There was no significant difference in available Zn concentration between rhizosphere and bulk soils. The values ranged from 0.40 -5.2 mg kg^{-1} in the rhizosphere and 0.37- 4.94 mg kg^{-1} in the bulk soil with a mean value of 1.88 and 1.72 mg kg^{-1} in the rhizosphere and bulk soil, respectively. Most of the locations (20 nos), the values were found between 1.00 - 3.5 mg kg^{-1} in the rhizosphere and was above the critical level of 1 mg kg^{-1}. The higher Zn concentration up to 5.20 mg kg^{-1} in the rhizosphere and 3.83 mg kg^{-1} in the bulk soil was observed. Majority of locations (19 nos) recorded values above the critical level in the rhizosphere and in one location, very low concentration 0.40 $mgkg^{-1}$ in the rhizosphere and 0.37 $mgkg^{-1}$ in the bulk soil was also observed (Table 3). It indicated that the available Zn concentration is in the high status in rhizosphere and bulk soils as per the fertility rating followed in rubber. Gahoonia (1993) reported that pH change in the rhizosphere have mainly affected the concentration of Zn and increased the availability by solubilization of the elements. A slight increase in the rhizosphere was observed but it was not significant.

There was no significant difference in available Cu between rhizosphere and bulk soils. The values ranged from 2.5- 28.8 mg kg^{-1} in the rhizosphere and 2.8 - 50.8 mg kg^{-1} in the bulk soil (Table 3). No change in Cu concentration in the rhizosphere was observed in a study conducted for forest trees (Little *et al.*, 2004). A decrease of Cu in the rhizosphere related to alkalization of rhizosphere related to nitrate absorption and decrease of Al in the rhizosphere was reported for annual crops (Bravin *et al.*, 2009). Also the changes in Cu is associated with organic matter which recorded no change between rhizosphere and bulk soil in our study. In the present study there was decrease in Cu concentration in the rhizosphere, but the difference was not significant. The decrease of Cu is a strategy of plants to avoid the bioavailability of Cu to plants for reducing Cu toxicity (Zhao *et al.*, 2006).

There was no significant difference in available Fe status between the rhizosphere and bulk soils. The values ranged from 11-77 mg kg^{-1} in the rhizosphere and 12-91 mg kg^{-1} in bulk soils (Table 3). Majority of locations (21 nos), the values were between 11-50 mg kg^{-1}. Available Fe concentration was also above the sufficiency range followed in rubber. No alterations in Fe concentration in the rhizosphere was reported (Little *et al.*, 2004)

There was no significant difference in available Mn between the rhizosphere and bulk soil. The values ranged from 2-72 mgkg^{-1} in the rhizosphere and 1-64 mgkg^{-1} in the bulk soil indicating vide variations among locations in available Mn concentration. No significant difference in Mn in the rhizosphere was reported for different species (Chima *et al.*, 2016)

Table 4. Comparison of rhizoshpere and bulk soil for exchange properties

Locations	CEC (cmol(+) kg_{-1})		Exchangeable bases (cmol(+) kg_{-1})					
			Ca		Mg		K	
	R	B	R	B	R	B	R	B
1	9.0	7.3	3.38	2.59	0.73	1.06	3.2	0.77
2	10.7	10.2	4.18	3.77	1.04	0.86	2.05	0.77
3	8.5	5.1	0.58	1.38	0.25	0.66	5.88	2.94
4	13.5	8.9	2.87	2.56	0.79	0.84	5.50	3.71
5	6.4	6.1	1.48	1.08	0.71	0.33	1.67	1.23
6	6.7	6.8	1.45	0.82	0.55	0.37	1.67	1.41
7	7.1	6.2	1.60	3.05	0.38	0.72	3.58	1.66
8	8.7	7.3	2.43	1.41	0.75	0.43	1.15	1.41
9	8.5	8.6	1.36	0.73	0.32	0.20	3.71	1.54
10	6.2	4.9	2.32	1.54	0.75	0.52	2.56	1.92
11	7.1	6.7	3.67	0.88	0.43	0.20	2.67	2.30
12	6.1	5.7	1.76	1.92	0.28	0.30	1.92	1.92
13	6.3	5.7	0.99	0.98	0.46	0.46	2.69	1.92
14	4.1	4.2	5.19	4.39	0.72	0.33	3.33	3.07
15	9.0	6.4	0.71	0.46	0.37	0.20	2.05	1.41
16	10.8	6.6	5.66	3.02	0.59	0.17	1.92	1.92
17	6.6	6.3	2.12	1.99	0.64	0.45	1.15	1.54
18	5.6	5.9	0.99	0.99	0.28	0.28	1.66	1.67
19	9.5	8.2	2.80	3.60	0.39	0.45	1.02	1.23
20	10.2	8.1	0.70	1.49	0.26	0.45	0.89	1.15
21	6.5	6.1	1.82	2.72	0.70	0.64	1.15	1.54
22	8.0	4.3	3.64	2.32	0.36	0.50	1.15	0.77
23	6.3	5.7	1.77	1.91	1.05	0.71	2.05	0.77
24	4.1	4.9	1.63	0.85	0.77	0.37	2.05	3.07
25	9.2	6.1	1.1	0.78	0.80	0.30	2.56	2.30
26	7.5	6.6	0.86	0.46	0.51	0.22	1.23	1.54
Range	4.1-13.5	4.2-10.2	0.58-5.66	0.46-4.39	0.25-1.05	0.17-1.06	0.89-5.88	0.77-3.71
Mean	7.8	6.5	2.19	1.83	0.57	0.46	2.33	1.75
Tstat	2.54**		NS		NS		1.97*	

There was significant variation in CEC between rhizosphere and bulk soil (Table 4). The values ranged from 4.0 -13.5 cmol (+) kg^{-1} in the rhizosphere and 5.1-10.5 cmol (+) kg^{-1} in the bulk soil. For majority of the locations (15 nos) the CEC values for rhizosphere soil were above 7.0 and for bulk soil, majority of locations (19 nos) the CEC was below 7.0. In a study on the effect of different tree species in the rhizosphere soil properties, higher CEC in the rhizosphere than bulk soil was reported (Calvaruso *et al.*, 2011) and the increase of CEC in the rhizosphere was explained by an adaptive mechanism (Calvaruso *et al.*, 2009) in comparison of two species *viz. Norway spruce* (*Picea abies*) and *Oak trees* (*Quercus fagacea*). The mechanism was the decrease of inter layer Al associated with clay sized fractions due to root activities. A higher CEC in the rhizosphere was recorded for two plants *viz. Tsuga* (*Tsuga Canadensis*) and *Yushania* (*Yushama angustifolia*) in the rain forest conditions in the temperate region (Chiu *et al.,* 2002). Increase of CEC in the rhizosphere was also recorded by Chung and Zasoski (1994).

No significant difference in exchangeable Ca was recorded in rhizosphere as compared to bulk soil (Table 4). There was no definite pattern in the concentration of exchangeable Ca between rhizosphere and bulk soil. The values ranged from 0.58-5.66 cmol (+) kg^{-1} in the rhizosphere and 0.46-3.77 cmol(+) kg^{-1} in the bulk soil. Majority of the locations (20 nos) the values found above 1.00 cmol (+) kg^{-1} and generally the exchangeable Ca concentration was very high in almost all locations. The higher exchangeable Ca as a result of stem flow and soil solution through the coarse roots and flow to the fine roots was reported (Cocco *et al.*, 2013).

No significant difference in exchangeable Mg was recorded between rhizoshere and bulk soil. The values ranged from 0.25-1.5 cmol (+) kg^{-1} in the rhizosphere and 0.2-1.06 cmol(+) kg^{-1} in the bulk soil with a mean value of 0.57 cmol(+) kg^{-1} and 0.46 cmol (+) kg^{-1} in rhizosphere and bulk soil, respectively. The changes in the exchangeable Mg reported was associated with mineral weathering and Al-polymerization (Cocco *et al.*, 2013).

There was significant difference in exchangeable K between the rhizosphere and bulk soil. The exchangeable K was higher in the rhizosphere soil and the concentration ranged from 0.89-5.88 cmol(+) kg^{-1} as compared to bulk soil (0.70-3.71 cmol(+) kg^{-1}) (Table 4). A mean value of 2.33 in rhizosphere and 1.74 in bulk soil was observed. Increase of exchangeable K was observed in two plants in rain forest in temperate condition (Chiu *et al.,* 2002). An increased concentration of exchangeable K was observed in the *Ailanthus triphysa* tree rhizosphere (Dinesh *et al.,* 2010) and attributed due to the root exudate activities and mineral changes. The increase in the available K in rhizosphere soil in the present study is also associated with increase of exchangeable K in the rhizosphere and supporting the mineral weathering for enhanced K availability.

Table 5. Comparison of rhizosphere and bulk soil for acidity characteristics

Locations	Exchangeable Al (cmol (+) kg^{-1})		Exchange acidity (cmol (+) kg^{-1})		ECEC (cmol (+) kg^{-1})	
	R	B	R	B	R	B
1	0.10	0.79	0.14	1.11	7.41	5.21
2	0.30	0.45	0.38	0.82	7.57	5.85
3	1.46	2.87	1.72	3.25	8.17	7.85
4	0.31	0.40	0.72	0.72	11.1	7.51
5	1.34	1.40	1.61	1.71	5.20	4.04
6	0.95	0.84	1.23	1.00	5.62	3.44
7	0.05	0.40	0.72	0.29	5.61	5.83
8	0.25	0.74	0.81	0.72	4.58	3.99
9	1.36	1.36	1.43	1.43	6.75	3.83
10	0.75	0.50	0.77	0.72	6.38	4.48
11	0.22	1.96	0.52	2.09	6.99	5.34
12	0.30	0.60	0.48	0.68	4.26	4.83
13	1.11	1.01	1.19	1.05	5.25	4.37
14	0.05	0.05	0.24	0.24	9.29	7.84
15	1.81	2.52	2.20	3.09	4.94	4.59
16	0.05	2.5	0.14	2.82	8.16	7.61
17	0.25	0.75	0.81	0.77	4.16	4.73
18	1.88	2.06	2.40	2.29	4.81	5.00
19	0.40	0.20	0.48	0.29	4.61	5.48
20	1.26	1.76	2.63	2.10	4.11	4.85
21	0.25	0.50	0.48	0.14	3.92	5.4
22	0.91	0.96	1.24	1.34	6.06	4.55
23	1.26	1.41	1.77	1.53	6.13	4.8
24	0.45	1.06	1.04	1.03	4.9	5.35
25	0.62	0.95	1.80	1.19	6.08	4.33
26	1.34	2.01	1.47	2.13	3.94	4.23
	0.05-1.88	0.40-2.87	0.14-2.63	0.14-3.09	3.92-9.29	3.44-7.85
Mean	0.73	1.16	1.09	1.33	6.0	5.2
	-2.21**		NS		NS	

There was a significant decrease in the exchangeable Al concentration in the rhizosphere than bulk soil. The exchangeable Al values ranged from 0.05-1.88 cmol(+) kg^{-1} in the rhizosphere and in the bulk soil, the values ranged from 0.052.87 cmol (+) kg^{-1} with mean values of 0.73 cmol (+) kg^{-1} and 1.16 cmol (+) kg^{-1} , respectively (Table 5). Wide variations in the exchangeable Al was recorded in the rhizosphere and bulk soil. Lower exchangeable Al in the root zone of *Erica arborea* L. was reported in the rhizosphere *vs*. bulk study (Cocco *et al.*, 2013) and attributed due to the protonation on the complexing of the exchange sites. A decrease of exchangeable Al in the rhizosphere especially in acid soil as Al tolerance / resistant mechanism was reported in the study of acid soil adaptations of tropical plants (Onthong and Osaki, 2006). The decrease of exchangeable Al was attributed as the formation of Al- organic acid complex, the major one is citric acid in the root zone near proximity of roots. A decrease (2 to 3 fold) of exchangeable Al in the rhizosphere in the study of enhancement of pH and nutrient availability by root induced alterations in cereals and legumes in acid soil was reported (Bagayoko *et al.,* 2000). In acid soil, the reduction of exchangeable Al in the rhizosphere may be either due to the absorption of Al by plants or otherwise the complex formation of Al with the exuded organic acids as an adaptation mechanisms of rhizosphere alterations (Schottelndreier and Grerup, 1999).

There was no significant difference in the exchange acidity between rhizosphere and bulk soil (Table 5). The values ranged from 0.14-2.63 and 0.143.09 cmol (+) kg^{-1} in the rhizosphere and bulk soil with a mean value of 1.09

and 1.33 cmol (+) kg^{-1}, respectively. Exchange acidity varied much between the rhizosphere and bulk soil. There was not a definite trend in the exchange acidity content and both increase and decrease towards rhizosphere was observed. In some locations the rhizosphere and bulk soils recorded very high (above 2.0 cmol (+) kg^{-1}) exchange acidity. Significant changes in exchange acidity was observed in *Erica arborea* L. due to the difference in the protonation in the exchange sites (Cocco *et al.*, 2013).

The effective cation exchange capacity (ECEC) values also showed no significant difference between rhizosphere and bulk soil. The values ranged from 3.92-11.1 and 3.4-7.84 cmol (+) kg^{-1}in rhizosphere and bulk soil with a mean value 6.0 and 5.2 cmol(+) kg^{-1} respectively. In many species, the increase in ECEC in the rhizosphere was reported but the changes in the present study was not significant and it may be due to species difference. Significant difference in the ECEC in the rhizosphere and bulk soil was reported for tree species and attributed that the clay and organic matter is related to the changes in ECEC (Chima *et al.*, 2016).

Table 6. Comparison of rhizosphere and bulk soil for total P and fractions of P

Locations			P fractions (mgkg^{-1})							
	Total P (%)		Al-P		Fe-P		Ca-P		Org.P	
1	1.00	0.40	55	30	25	30	550	25	200	225
2	1.45	1.20	60	50	25	45	650	750	300	375
3	1.10	0.50	225	25	100	25	188	25	475	375
4	1.70	0.20	400	20	225	25	250	50	250	525
5	0.10	0.50	20	25	85	100	120	175	850	190
6	0.15	0.15	62.5	90	150	195	125	375	330	120
7	0.30	0.25	25	85	375	175	300	200	650	480
8	0.40	0.30	220	115	275	200	300	175	100	400
9	0.25	0.45	140	90	150	150	275	163	975	800
10	0.20	0.15	45	25	125	25	225	88	450	400
11	0.30	0.35	175	15	300	75	550	75	300	140
12	0.90	0.60	100	100	50	70	113	175	975	400
13	0.70	0.50	25	25	25	25	225	25	300	375
14	0.35	0.25	50	40	200	450	170	165	300	125
15	0.05	0.05	2.5	75	125	190	575	225	375	200
16	0.20	0.60	35	20	125	75	175	50	200	375
17	0.30	0.20	20	13	25	25	150	25	195	250
18	0.40	0.30	30	10	50	25	88	13	150	150
19	0.25	0.10	30	1	100	25	125	175	225	125
20	0.10	0.10	15	20	25	50	75	125	350	325
21	0.50	0.30	108	30	50	25	150	25	123	175
22	2.25	0.75	105	60	175	115	180	70	150	192
23	0.25	0.10	45	35	50	100	125	275	250	125
24	0.20	0.10	60	30	100	125	350	75	500	560
25	0.10	0.10	35	35	135	75	300	225	500	265
26	0.10	0.15	10	18	50	25	300	100	250	220
Range	0.10-2.25	0.10-1.2	2.5-400	10-115	25-375	25-200	75-650	13-750	100-850	125-800
Mean	0.52	0.33	80	41	120	94	255	148	374	303
T stat	NS		2.09**		NS		2.46**		NS	

Total P, P-fractions (Saloid-P, Al-P, Fe-P and Ca-P) and organic-P between rhizosphere and bulk soil was presented in Table 6. The total P values ranged from 0.10-2.25 per cent in the rhizosphere and 0.1-1.20 per cent in the bulk soil. In the rhizosphere, total- P was not much varied and majority of locations (19 nos) the values were between 0.10 – 0.50 per cent whereas for the bulk soil the variation was more. There was significant increase in Al-P content in the rhizosphere and the values ranged from 2.5- 400 mg kg^{-1} in the rhizosphere and 10-115 mg kg^{-1} in the bulk soil with a mean value 80 and 41 mg kg^{-1} respectively. There was no significant difference in Fe-P between rhizosphere and bulk soil. The values ranged from 25-375 mg kg^{-1} in the rhizosphere and 25-200 mg kg^{-1} in the bulk soil with a mean value of 120 and 94, respectively. There was significantly higher Ca-P in the rhizosphere as compared to bulk soil. The values ranged from 75-650 mg kg^{-1} in the rhizosphere and 13-750 mg kg^{-1} in the bulk soil with a mean value of 255 and 148 mg kg^{-1} respectively. There was wide variation in the Ca-P content in the rhizosphere and bulk soil. An increase of Ca-P solubility in association with root exudate was reported (Richardson, 1994; Richardson *et al.*, 2009). The Ca-P was reported as the most easily available form for plants and hence the higher Ca-P in the rhizosphere is an adaptation of P-acquisition in rubber plants. There was no significant difference in organic P between the rhizosphere and bulk soil. The values ranged from 100-850 mg kg^{-1} in the rhizosphere and 125-800 mg kg^{-1} in the bulk soil with a mean value of 374 and 303 mg kg^{-1} respectively. There was no definite trend in increase or decrease of organic-P in the rhizosphere and bulk soil. It was reported that some species were using inorganic P more than organic P and vice-versa (Liu *et al.*, 2014). According to Shen *et al.* (2011) that the dissolution of Ca-P and Al-P mainly depending on the mineral particles and pH. The role of inorganic mineral release for P availability in the case of alkalization of rhizosphere was reported (Devau *et al.*, 2010; Chen et al., 2016; Junk et al., 1993). Fang *et al.* (2017) reported phosphorus fractions in Chinease fir plantation forest. For this detailed study of characterization of P- sources for the uptake of rubber plants and the enzyme activity and organic P utilization is to be studied further.

Table 7. Comparison of rhizosphere and bulk soil for total K and fractions of K

Locations	Total K (%)		K fractions (mgkg$_{-1}$)					
			WS-K		Exch.K		Fixed K	
1	0.39	0.15	34.6	2.8	41.4	11.7	10.7	9.5
2	0.24	0.34	17.6	6.8	21.9	9.4	9.5	7.76
3	1.64	0.97	118.0	30.0	65.0	31.4	59.6	62.6
4	1.25	1.15	84.0	71.0	78.0	87.0	81.5	31.0
5	1.59	1.54	10.6	18.3	26.7	30.5	43.3	41.4
6	1.78	1.63	1.9	4.8	17.6	22.2	60.4	68.2
7	2.07	1.44	19.4	33.7	61.5	23.4	19.8	20.7
8	1.83	2.55	10.2	9.3	17.2	18.0	14.7	16.4
9	1.88	1.78	20.4	16.7	32.8	25.0	35.8	31.3
10	1.20	1.15	15.4	6.7	26.7	19.4	10.6	11.5
11	1.88	1.49	19.2	5.8	39.1	26.7	27.9	58.5
12	1.20	1.58	22.2	34.6	23.4	34.5	23.3	21.6
13	1.20	1.74	10.2	10.2	11.7	28.5	51.6	59.1
14	1.68	1.97	29.8	19.2	41.9	45.8	21.2	25.0
15	1.44	1.01	16.7	23.2	39.7	18.0	22.4	29.5
16	2.21	1.11	14.8	15.7	21.9	13.3	33.1	19.8
17	1.39	1.49	23.0	31.0	48.1	48.1	61.6	69.5
18	1.49	1.54	14.8	12.0	25.0	31.6	38.4	26.8
19	1.20	0.91	26.0	45.0	13.5	40.2	10.0	9.0
20	0.68	1.06	35.0	23.0	64.0	66.0	11.0	9.0
21	1.01	1.11	27.0	41.0	57.0	39.2	25.0	19.0
22	0.87	0.47	6.7	4.8	19.4	11.11	11.54	68.2
23	2.12	2.6	20.2	55.5	26.7	105	34.62	41.4
24	1.15	1.25	12.5	21.2	29.6	53.12	41.35	36.5
25	1.06	1.44	32.7	11.5	27.6	29.55	28.85	32.7
26	1.44	1.39	14.4	26.9	15.7	17.59	22.12	42.3
Mean	1.38	1.34	25.3	22.3	34.4	34.1	31.1	33.4
Range	0.24-2.21	0.15-2.6	1.9-118	2.8-71.0	11.7-78	9.4-87	9.5-81.5	9.0-69.5
	NS		NS		NS		NS	

WS-K –Water soluble K   Exch. K – Exchangeable K

There was no significant difference in total-K and K-fractions (water soluble-K, exchangeable K and fixed K) between rhizosphere and bulk soil (Table-7). Total-K ranged from 0.24-2.21 per cent in the rhizosphere and 0.15-2.6 per cent in the bulk soil. In majority of locations (22 nos) the total-K was between 1.01-2.07 per cent in the rhizosphere. Water soluble K was ranged from 1.9-118. Mg kg^{-1} in the rhizosphere and 2.8-71.0 mg kg^{-1} in the bulk soil with a mean value of 25.3 and 22.3, respectively. The exchangeable K was ranged from 11.7-78 mg kg^{-1}in the rhizosphere and 9.4-87 mg kg^{-1} in the bulk soil with a mean value of 34.4 and 34.1 mg kg^{-1}, respectively. Most of the locations, an increase towards rhizosphere was observed. There was also no significant difference in fixed-K was observed between rhizosphere and bulk soil. The values ranged from 9.5-81.5 mg kg^{-1} and 9.0-69.5 mg kg^{-1} in the bulk soil with a mean value of 31.3 and 33.4 mg kg^{-1} respectively. The enhanced concentration of non-exchangeable K in the rhizosphere was reported (Jungk and Claassen, 1986), but in rubber no significant difference was observed even though there was changes in total K and K fractions.

Table 8. Comparison of rhizosphere and bulk soil for total N, inorganic N fractions and available N

Locations	Total N (%)		Inorganic N fractions (mgkg-1)				Available N (kgha-1)	
			NH_4- N		NO_3-N			
1	0.16	0.17	2.2	1.5	1.0	0.8	162	204
2	0.24	0.26	7.0	4.9	4.3	2.5	197	204
3	0.12	0.11	26.2	4.5	7.5	3.9	246	167
4	0.16	0.16	6.0	2.1	10.8	2.2	125	163
5	0.18	0.17	4.0	31.3	5.2	23.5	221	180
6	0.14	0.17	9.1	10.6	13.0	1.8	139	137
7	0.17	0.20	2.7	2.1	2.2	2.0	199	185
8	0.30	0.20	10.2	7.6	5.0	5.4	239	187
9	0.32	0.20	12.8	7.4	9.9	4.6	208	160
10	0.15	0.16	28.7	31.3	6.5	14.3	188	157
11	0.17	0.18	7.2	9.9	2.0	3.2	167	108
12	0.37	0.17	24.2	7.8	1.6	8.8	277	212
13	0.18	0.22	4.3	10.4	3.6	9.1	145	169
14	0.19	0.20	13.0	9.1	7.8	7.8	183	179
15	0.17	0.13	22.2	11.7	20.9	17.0	165	173
16	0.26	0.13	15.2	8.8	9.9	5.1	188	151
17	0.19	0.15	9.0	5.8	10.3	7.9	151	174
18	0.12	0.17	3.9	1.3	3.9	1.8	144	162
19	0.30	0.26	6.9	18.6	3.2	20.6	190	141
20	0.21	0.25	10.6	8.9	7.2	3.7	162	212
21	0.15	0.17	21.8	4.7	2.5	6.9	106	225
22	0.26	0.19	5.2	11.7	3.9	10.4	260	300
23	0.33	0.21	23.5	27.4	15.7	13.0	189	276
24	0.17	0.15	15.7	26.1	9.1	14.4	218	186
25	0.21	0.22	12.8	23.2	1.4	8.3	200	216
26	0.24	0.26	23.7	7.1	5.7	8.1	190	197
Mean	0.21	0.19	12.6	11.4	6.7	8.0	187	186
Range	0.12-0.37	0.11-0.26	2.2-28.7	1.5-31.3	1.0-20.9	0.8-23.5	106-277	137-300
CD(P=0.05)	NS		NS		NS		NS	

There were no significant difference in total-N, inorganic N-fractions and available-N between rhizosphere and bulk soil (Table-8). Total N ranged from 0.12-0.37 per cent in the rhizosphere soil and 0.11-0.26 per cent in the bulk soil with a mean value of 0.21and 0.19 per cent respectively. Available-N ranged from 106-277 kg ha^{-1} in the rhizosphere and 108-276 kg ha^{-1} in the bulk soil with a mean value of 187 and 186 kg ha^{-1}, respectively. NH_4 - N^+ was ranged from 2.2 -28.7mg kg^{-1} in the rhizosphere and 1.5-31.3 mg kg^{-1} in bulk soil with a mean value of 12.6 and 11.4 mgkg^{-1} respectively. There was wide variation in NO_3 - N in rhizosphere and bulk soil. Nitrate N ranged from 1.0-20.9 mg kg^{-1} in the rhizosphere and 0.8-23.5 mg kg^{-1} in the bulk soil with a mean value of 6.7 and 8.0 mg kg^{-1}, respectively. Different pattern of increase /decrease of either NH_4-N or NO_3^-N in the rhizosphere related to acidification/ alkalization was observed in different studies (Haynes, 1990; Dinesh *et al.,* 2010; Wang and Zabowski, 1998; Schottelndreier and Grerup, 1999; Hinsinger *et al.,* 2003)) but in rubber the associated increase of NO_3 as an effect of alkalization was not significant. Nitrate reduction and associated mechanisms is to be further studied to confirm uptake of N forms for rubber plants.

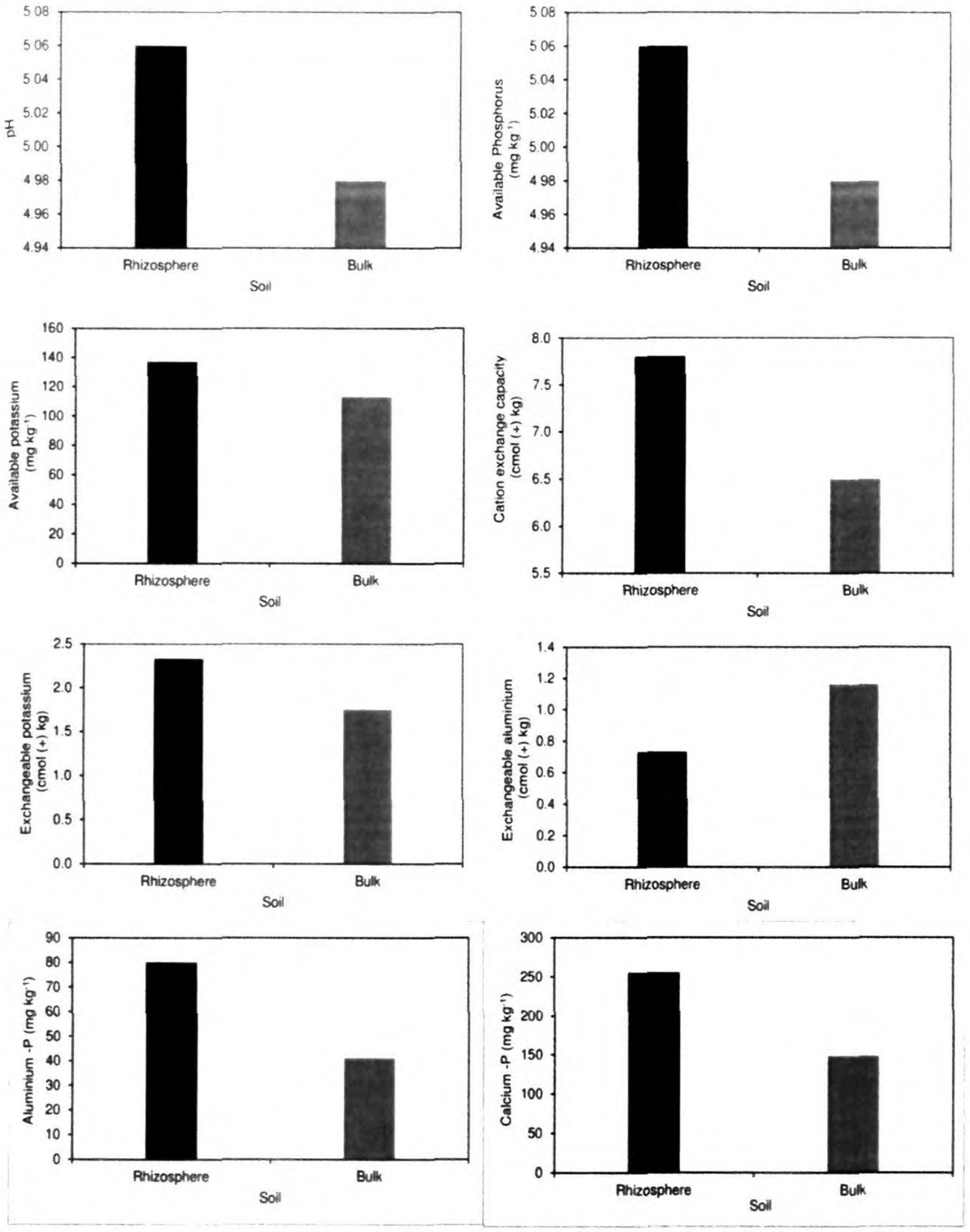

Fig.3. **Comparison of rhizosphere and bulk soils for pH, available phosphorus, potassium, cation exchange capacity, exchange properties and phosphorus fractions**

In the rhizosphere of rubber plants the pH, available P and K, CEC and ExK, Al-P and Ca-P were significantly higher and exchangeable Al was lower than bulk soil (Fig.3). In other species and genotypes within the species, the enhanced nutrient availability in the rhizosphere were different for different elements (Zhang and George, 2002; Cocco *et al*, 2013; Schottelndreier and Grerup, 1999; Haynes, 1990; Chiu *et al.*, 2002; Shi *et al.*, 2012; Dinesh *et al.*, 2010; Chung and Zasoski, 1994; Wang and Zabowski, 1998; Calvaruso *et al.*, 2011) from the elements that observed in rubber. However in some studies similarity for particular nutrients were also observed. This indicated that specific rhizosphere chemistry/ modifications were operating in rubber plants based on the plant activities and crop needs. The rhizosphere activities of plants were different in acid, neutral and alkaline soils along with the species specificity for growth and productivity. The pattern of alterations/modifications in the rhizosphere chemistry between species is a genetic character and the reasons for these changes were also different due to differences in the physiological and metabolic activities of each plants (Bagayoko *et al.*, 2000; Zhao *et al.*, 2010)). Since rhizosphere is the zone where larger extent of biological and chemical reactions as a result of exudates depending on root activities, nutrient uptake and microorganisms, this zone is different from the bulk soil (Wang and Zabowski, 1998) and hence it is specific for each plants. Little *et al.*, 2004) reported the rhizosphere nutrient elements changes in forest trees and an entirely different nutrient dynamics as observed in rubber. Wang *et al.* (2001) reported specific rhizosphere activities for two tree species in a saline soil and the difference in activities were because of the tree species as the initial conditions of the soil was similar in which the trees were grown and subsequent changes in the presence of trees were the different phenomenon observed. The genotypic difference in the modifications/adaptations in the rhizosphere for the acquisition of nutrients by solubilisation is reported (Smith, 2001) and this depends on different mechanisms specific for each plants (Sadana *et al.*, 2002; Rengel, 2002; Jones *et al.*, 2004 and Marschner *et al.*, 2005b). Nutrient availability and root activities were the factors of soil characteristics, plant activities and root-microbes interactions (Jones, *et al.*, 2004). The study of effect of organic acid exudates and its influence on rhizosphere soil properties in two tree species *viz.* white spruce (*Picea glauca* (*Moench*) Voss) and subalpine fir (*Abies lasiocarpa* (*Hook*) *Nutt.*) (Tuason and Arocena, 2018) was also reported. For tree species also the activities and adaptations/modifications in the rhizosphere level was reported as very important (Dinesh *et al.*, 2010) as this root zone reactions were the factors determine the sustainability in growth and survival of the plants.

In rubber plants, the alkalization of the rhizosphere by the increase of pH than the bulk soil in the acidic rubber growing soils may be mainly for the mechanism of increased P- availability and to avoid Al- stress. The observed changes in soil properties in rhizosphere in the present study were interrelated to each other. When pH increased the associated P-increase and decrease of exchangeable Al was observed. Along with this the inorganic P- fractions like AlP and Ca-P increased in rhizosphere is an evidence of the utilization of inorganic P in rubber. The possibility of root exudate of organic acid anions such as citrate, malate, oxalate associated with pH change and Al stress alleviation mechanisms is having relation to the observed nutrient changes in the rhizosphere of rubber plants. The increase in available K related to mineral weathering, exchangeable K and CEC in relation to ion-exchange equilibriums associated with pH increase were also related to each other.

IV. 2. Comparison of growth of young rubber plants in soils having wide variation in pH, exchangeable Al and base status

Three soils having distinctly different pH and base status were selected for the study (Fig.4). The initial properties of the three soils are given in Table 1. The soils were extremely acidic (pH 4.4), strongly acidic (pH 5.5) and neutral (pH 7.4). The organic carbon (OC) was in the medium range in all the three soils. The available P status was in the low range in all the three soils. At the same time, in the two acidic soils the values were similar and were slightly lower in neutral soil. The available K, Ca, and Mg were comparable in the acidic soils, whereas, the available K was high and available Ca and Mg was very high in neutral soil. The exchangeable Al was extremely high in the extremely acidic soil (2.6 cmol (+) kg^{-1} soil) and there was no exchangeable Al content in the neutral soil. Among the two acidic soils, the exchangeable Al (1.64 cmol (+)kg^{-1}) and exchangeable acidity (0.85 cmol (+)$kg-^{1}$) in strongly acidic soil was low compared to the extremely acidic soil where the values were 2.89 cmol (+) kg^{-1} and 2.20 cmol (+)kg^{-1}, respectively.

Table 9. Chemical properties of the three soils with distinctly different pH and base status

	Soil 1 (pH 4.4)	Soil 2 (pH 5.5)	Soil 3 (pH 7.4)
Organic carbon (%)	1.13	1.21	1.04
Available P (mgkg^{-1})	20.1	21.9	14.4
Available K (mgkg^{-1})	38.2	47.9	66.0
Available Ca (mgkg^{-1})	42.4	52.4	6066.0
Available Mg (mgkg^{-1})	9.90	18.8	490.0
Available Zn (mgkg^{-1})	1.06	1.4	2.9
Available Mn (mgkg^{-1})	10.4	7.4	64.8
Available Fe (mgkg^{-1})	17.3	33.7	43.6
Available Cu (mgkg^{-1})	18.0	21.4	3.1
Cation Exchange Capacity (cmol (+) kg^{-1}	5.44	8.03	29.1
Exchangeable Ca (cmol (+) kg^{-1})	0.29	0.71	18.6
Exchangeable Mg (cmol(+) kg^{-1})	0.08	0.31	1.76
Exchangeable K (cmol(+)kg^{-1})	0.43	0.31	1.71
Base saturation (%)	33.8	43.8	95.6
Exchangeable Al (c mol(+)kg^{-1})	2.89	1.64	0
Exchangeable acidity (c mol(+) kg^{-1})	2.2	1.2	0.23

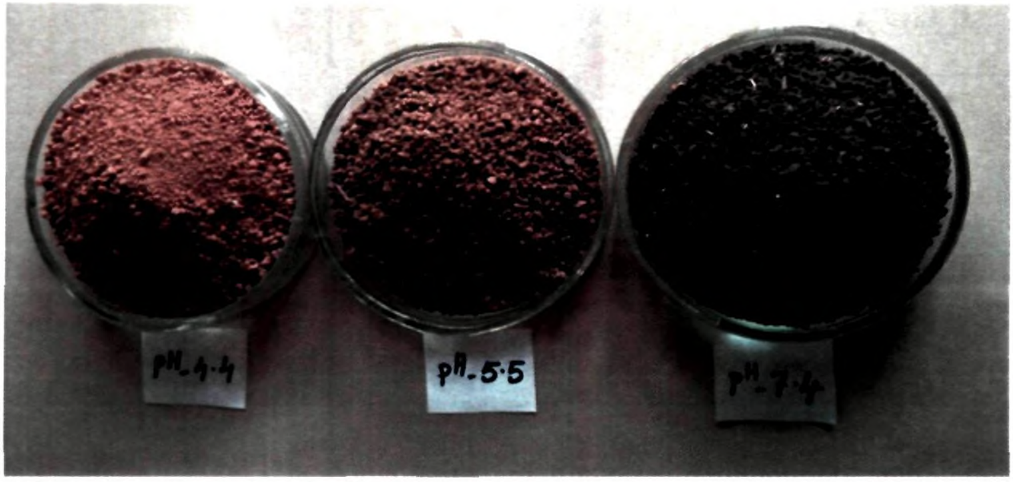

Fig.4. Three soils with distingtly different soil pH and base status

Physical properties of the three soils are presented in Table 10. The physical properties of the neutral soil was distinctly different from the other two soils having acidic pH. While the two acidic soils recorded around 50.0 per cent gravel, the neutral soil was devoid of gravel. Fine sand content was also distinctly different between the three soils.

Table 10. Physical properties of the three soils with distinctly different pH and base status

	Soil 1 (pH 4.4)	Soil 2 (pH 5.5)	Soil 3 (pH 7.4)
Gravel content (%)	54.2	45.8	No gravel
Coarse sand (%)	42.3	55.0	36.2
Silt (%)	10	7.5	5.0
Fine sand (%)	12.4	12.4	29.5
Clay (%)	35.0	24.5	29.0
Field Capacity (%)	28	29	24
Moisture content (%)	18.0	16.3	16.8

IV. 2.1. Comparison of growth of sprouted seeds under laboratory conditions

The growth parameters (shoot length, root length and biomass) of sprouted seedlings for a period of thirty days in the laboratory experiment are given in Table 11. No significant difference in shoot length or root length was observed even though there was some numerical difference between the three soils. There was no significant difference in the shoot, root and total biomass for the three soils in the initial growth and establishment of the seedlings up to 30 days indicating that the extremely low pH or high exchangeable Al level in the extremely acidic soil is not affecting the growth of sprouted seeds. The seed endosperm is sufficiently large enough to meet the nutrient requirement for the initial growth which may be one of the reasons. It is interesting to note that the young roots are not affected by the soil environment indicating that the excess H^+ ions or Al^{3+} ions might have been complexed or chelated with organic exudates and inactivated at the rhizosphere. Chelation and inactivation of toxic ions at the root surface (Ryan *et al.*, 1993) or at the rhizosphere (Jones, 1998) was reported.

Table.11. Growth of sprouted seeds on the 30th day in three soils

Soil with different pH	Shoot length (cm)	Root length (cm)	No of roots	Biomass (g)		
				Shoot	Root	Total
Soil 1 (pH4.4)	32.8	14.5	26.9	0.86	0.21	1.07
Soil 2 (pH 5.5)	29.9	11.9	21.3	0.80	0.26	1.06
Soil 3 (pH7.4)	29.1	13.1	26.3	0.89	0.24	1.13
CD(P=0.05)	NS	NS	NS	NS	NS	NS

IV.2.2. Comparison of growth of young rubber plants

IV.2.2.1. Plant growth

The growth of the seedlings in terms of diameter at three intervals is given in Table 12. There was no significant difference in the diameter of plants at 45 days. However, the diameter at 90 and 240 days was different in three soils. At the 90th day, the diameter in soil with pH 4.4 was less than the soil with pH 5.5 and 7.4. Diameter in soil with pH 5.5 and 7.4 were on par. At the 240th day, the diameter was significantly different in three soils and the highest diameter was recorded in pH 7.4 soil followed by pH 5.5 soil.

Table.12. Diameter of seedlings grown in three soils

Soil with different pH	Diameter(cm)		
	45th Day	90th Day	240th Day
Soil 1 (pH4.4)	3.6	4.9	6.7
Soil 2 (pH 5.5)	3.6	6.2	7.9
Soil 3 (pH 7.4)	3.8	6.3	9.9
CD (P=0.05)	NS	0.4	0.4

The diameter (Fig. 5) of the plants in each soil steadily increased from 45 days up to 240 days and the magnitude of diameter increase was different among the three groups from the almost similar diameter of the 45th day. The rate of increase was higher for plants grown in soil having pH 7.4 than pH 5.5.

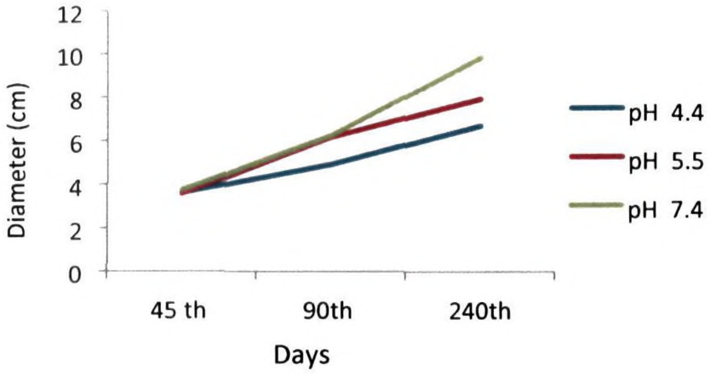

Fig. 5. Comparison of diameter from 45th to 240th day in three soils

The shoot and root length in three soils at three intervals is given in Table 13. Shoot length was not significantly different in three soils at 45th day. But the shoot length was significantly low at 90 and 240 days in soil having 4.4 pH. Shoot length was on par at pH 5.5 and pH 7.4 soils both at 90 and 240 days. A steady increase in shoot length was observed in three soils (Fig. 6) and (Fig.7).

Table 13. Shoot and root length of seedlings grown in three soils

Soil with different pH	Shoot length (cm)			Root length (cm)		
	45th Day	90th Day	240th Day	45th Day	90th Day	240th Day
Soil 1 (pH 4.4)	34.3	45.1	76.6	24.3	46.7	51.9
Soil 2 (pH5.5)	41.2	67.6	122.7	30.6	59.4	68.6
Soil 3 (pH 7.4)	44.0	63.7	114.1	33.0	56.1	61.1
CD(P=0.05)	NS	6.3	7.1	3.1	4.0	9.1

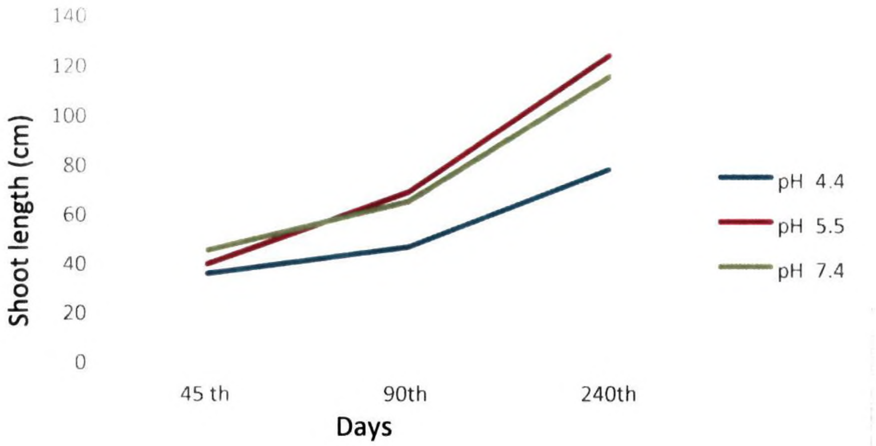

Fig.6. Comparison of shoot length from 45th to 240th day in three soils

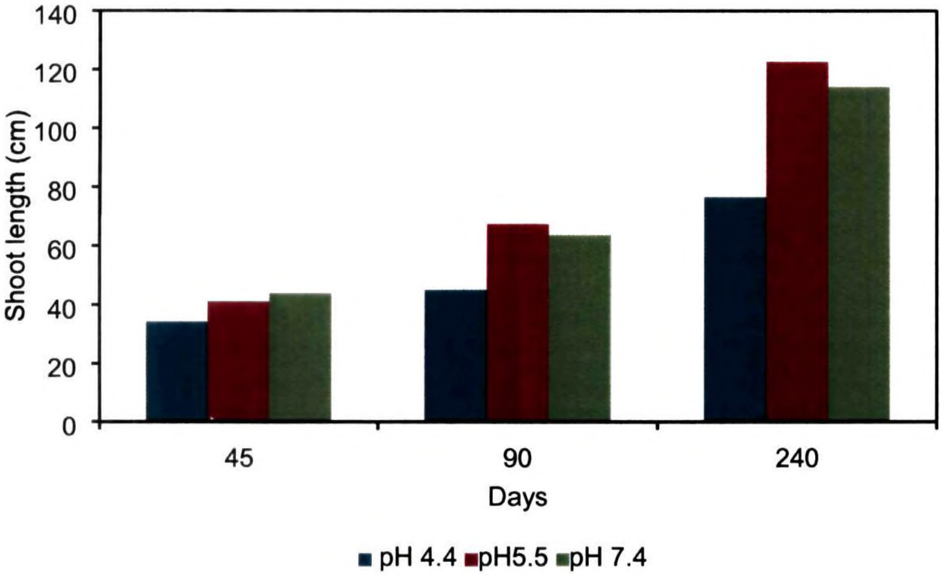

Fig.7. Comparison of shoot length in three soils

The highest root length was observed in pH 5.5 both at 90th and 240th day. But the difference in root length between plants grown in soil with pH 5.5 and 7.4 was not statistically significant. The soil with pH 4.4 recorded the lowest root length than other two soils in all three intervals and was significantly lower than the values recorded at pH 5.5 and 7.4. There was a steady increase of root length from 45 to 240 days (Fig. 8) and (Fig.9).

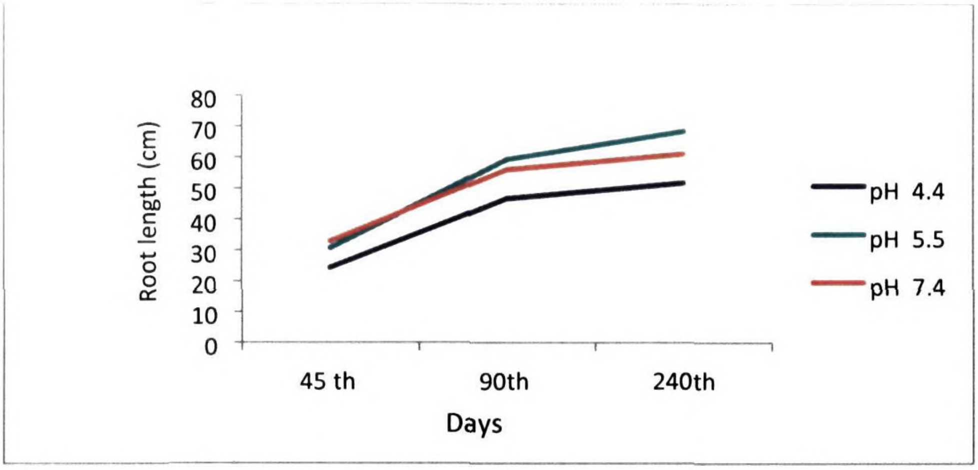

Fig. 8. Comparison of root length from 45th to240th day in three soil

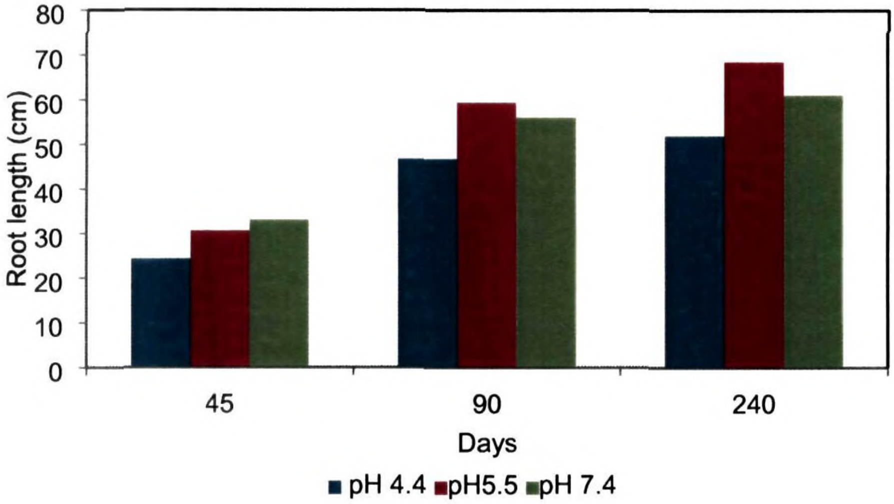

Fig. 9. Comparison of root length in three soils

The shoot, root and total biomass in three soils at different interval is given in Table 14. There was no significant difference in the shoot, root and total biomass at 45th day as that of the biomass at 30th day in laboratory study which indicates that the initial growth was not influenced by the different soil conditions. However, the shoot, root and total biomass at 90th day showed significant difference between three soils. Statistically significant highest shoot biomass was recorded in pH 7.4 soil followed by pH 5.5 soil. However, the root biomass was higher in plants grown in soil with pH 5.5 than pH 7.4 and the lowest shoot, root and total biomass was recorded in pH 4.4 soils. At the 240th day, the shoot, root and total biomass in pH 5.5 and pH 7.4 were on par and here also the lowest values were recorded for pH 4.4 soil.

Table. 14. Shoot, root and total biomass (g) of seedlings grown in three soils

Soil with different pH	Biomass (g)								
	45th Day			90th Day			240th Day		
	Shoot	Root	Total	Shoot	Root	Total	Shoot	Root	Total
Soil 1 (pH 4.4)	2.10	0.93	3.0	3.3	2.1	5.4	11.8	6.2	18.0
Soil 2(pH5.5)	1.99	0.89	2.9	5.1	2.9	7.9	21.1	10.4	31.5
Soil 3 (pH7.4)	1.89	0.74	2.6	6.2	2.5	8.6	22.2	10.2	32.6
CD(P=0.05)	NS	NS	NS	0.4	0.2	0.5	2.1	1.5	3.4

The changes in shoot biomass (Fig. 10) and root biomass (Fig. 11) in each soil recorded a steady increase from 45th day up to 240 days period. The changes from 90 to 240 days were very high compared to 45 to 90 days and less increase was observed in soil with extremely acidic pH (pH 4.4).

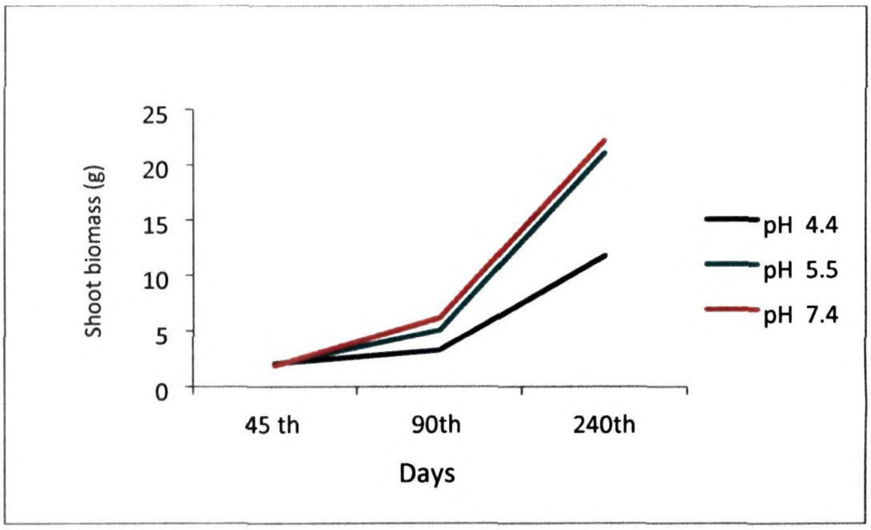

Fig.10. Comparison of shoot biomass from 45th to 240th day in three soils

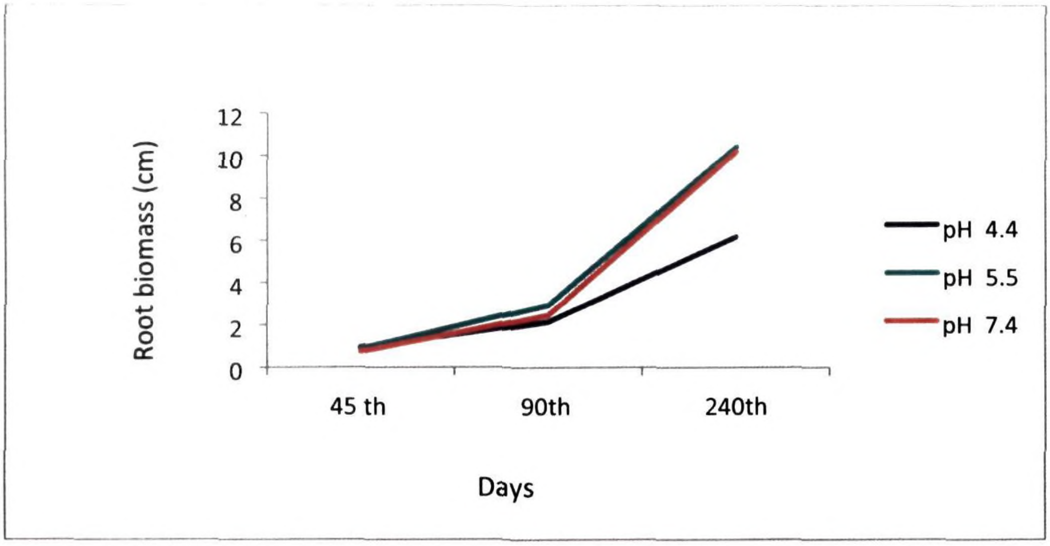

Fig.11. Comparison of root biomass from 45th to 240th day in three soils

The shoot/root ratio in three soils (Table 6) at 90th day was significantly different between each other and highest ratio was recorded by plants grown in neutral soil (pH 7.4). This might be due to the significantly high shoot biomass recorded at pH 7.4 during the 90th day. Similar pattern of growth of rubber seedlings was reported by Correia *et al.* (2017). Though shoot biomass was very high, a corresponding increase in root biomass was not recorded and hence the shoot /root ratio was high in pH 7.4 soil. However, when it reached 240th day the shoot/root ratio recorded similar values in all three soils. It was inferred from this observation that there were some changes according to the soil conditions to favour a particular growth pattern in the case of shoot/root partitioning and can be attributed to biomass allometry for new flushes of leaf and branches as reported earlier (Tempeton, 1968; Sethuraj, 1985; Sharaf *et al.*, 2017). The importance of improved growth in the initial years (Krishnan, 2015; Paardekooper, 1989; Sethuraj and George, 1980), vigorous plant growth for good yield and reducing the immaturity period of young rubber by increasing the soil fertility even though costly was reported (Noordin, 2017).

Table.15. Shoot/root ratio of seedlings grown in three soils

Soil with different pH	Shoot/root ratio		
	45thDay	90thDay	240thDay
Soil 1 (pH4.4)	2.28	1.53	1.91
Soil 2 (pH5.5)	2.39	1.74	2.03
Soil 3 (pH7.4)	2.63	2.54	2.22
CD (P=0.05)	NS	0.13	NS

Plants grown in pH 5.5 soils with less base status attained comparable growth with pH 7.4 soil having extremely high base status indicating that pH 5.5 is favourable for growth of rubber plants even though the base nutrients were less as compared to pH 7.4. Sharaf *et al.* (2017) reported that when pH value reaches to 5.0 the Al in the soil solution undergoes precipitation to unreacted gibbsite and becomes less toxic. In acid mineral soils, the limitation such as increase of H^+ and Al^{3+} toxicity and impaired root growth restricts the plant growth. The influence of soil acidity on growth of the plants is species specific as reported in different plants (Bernal and McGrath, 1994; Butchee *et al.*, 2012). Growth of the Europian beech (*Fagus sylvatica* L) and Norway spruce (*Picea abies karst*) was different to same H^+ and Al^{3+} concentration. Among the two acidic soils, the growth is affected in extremely acidic pH (pH 4.4) than the strongly acidic pH (pH 5.5) soil. Marshner (1991) and Pan *et al.* (1989) reported that when exchangeable Al was high, not only the fresh root formation was affected but also the shoot growth was hindered due to release of Cytokinin content from roots along with the starvation for water and necessary nutrients. Also, Cronan (1991) observed that when Al was high, it replaces the Ca and Mg from the exchange positions of the roots and decreased its uptake and this seriously affect the plant growth in terms of reduced cambium growth and girth increment (Shortle and Smith, 1988). The leaf and root growth and functions also will be affected (Raynal *et al.*, 1990). At higher concentration of Al, retardation in growth due to the lack of tolerance to Al and acidity was reported by Shamshuddin and Fauziah (2010). These can be attributed as the reasons for poor growth in extremely acidic soil (pH 4.4) compared to the strongly acidic soil (pH 5.5) and the neutral soil (pH 7.4). Vice-versa, the highest growth in neutral soil (pH 7.4) recorded in the present study also can be of the reason of high Ca and Mg and the favourable pH of the soil medium. In a study on the incorporation of ground basalt which when dissolves increases the Ca supply can avoid the toxic effects of Al (Alva *et al.*, 1986; Sharaf *et al.*, 2017) indicates the beneficial effect of high Ca content in the soil solution. The observations indicates that rubber is performing well in strongly acidic soils but soils with extremely acidic pH along with higher exchangeable Al and H^+ ion concentration retards the growth. Also, growth of rubber plants is superior in soil with pH 7.4 having high status of Ca and Mg indicating its wide adaptability. High root CEC values in pH 7.4 soil compared to the extremely acidic soil supports the observation (Table 16). The root cation exchange capacity values differ between plants grown in the three soils. The values were low in plants grown in extremely acidic soil with very low base status compared to the other soil. Plants grown in neutral soil with high base status recorded the highest root cation exchange capacity values.

Table 16. Root cation exchange capacity of plants on the 90th day in three soils

Soil with different pH	Root CEC (Cmol(+)kg^{-1})
Soil 1 (pH 4.4)	15.0
Soil 2 (pH 5.5)	26.0
Soil 3 (pH 7.4)	34.6
CD (P=0.05)	4.72

IV. 2.2.2. Plant nutrients

The nutrient concentration of the root on the 90th day of growth in three different soils having distinctly different pH and base status is provided in Table 17. There was no significant difference in the N concentration between three soils. Similarly, Cu and Mn concentration was also not significantly different between three soils. Phosphorus, K, Ca, Mg, Zn, Fe and Al concentration between three soils were significantly different. Wide variation in the concentration of Ca and Mg was recorded between the three soils. Highest values were recorded in neutral soil with high status of Ca and Mg indicating that with increased availability, higher concentration was recorded in the roots. Zinc and Al concentration was highest in extremely acidic soil followed by strongly acidic and the lowest in neutral soil. Highest P concentration was observed in pH 7.4. Also highest K and Ca was recorded in pH 7.4 followed by pH 5.5 and the lowest was in pH 4.4. Highest Fe concentration was observed in pH 7.4 and two acidic soils recorded on par values. Highest Al concentration was recorded in pH 4.4 and the values for pH

5.5 and 7.4 were on par. In extremely acidic soil, the high exchangeable Al might have contributed for the high values of Al in the root.

Table 17. Effect of soil pH and base status on the nutrient concentration of roc (90th day)

Nutrient	Soil 1(pH 4.4)	Soil 2(pH 5.5)	Soil 3(pH 7.4)	CD (P=0.05)
N (%)	0.78	0.70	0.69	NS
P (%)	0.11	0.11	0.16	0.02
K (%)	0.88	1.22	1.45	0.19
Ca (%)	0.28	1.37	1.73	0.20
Mg (%)	0.17	0.4	0.29	0.01
Zn (mg kg^{-1})	41	22	27	9
Cu (mg kg^{-1})	29	24	17	NS
Fe (mg kg^{-1})	1387	1380	2508	539
Mn (mg kg^{-1})	27	38	46	NS
Al (mg kg^{-1})	2028	1800	1514	76

Effect of soil pH and base status on the nutrient concentration of roots at the 240th day is given in Table 18. Contrary to the observation on the 90th day, no significant difference was recorded in the concentration of K, Ca and Mg between the three soils. This observation is in contrast to the general expectation that the plants grown in soil with pH 7.4 with very high base status will be having high concentration of the cations especially K, Ca and Mg. Though significantly high values were recorded on the 90th day, the difference got narrowed down and was on par between three pH during the 240th day. Iron concentration in the roots is very high for soil with pH 7.4. High concentration of Fe in the neutral soil (pH

7.4) compared to the extremely acidic soil (pH 4.4) is a significant observation and this might be affecting the uptake and accumulation of other nutrient elements affecting the balance among the nutrients.

Table 18. Effect of soil pH and base status on the nutrient concentration of root (240th day)

Nutrient	Soil 1 (pH 4.4)	Soil 2 (pH 5.5)	Soil 3 (pH 7.4)	CD (P=0.05)
N (%)	0.91	0.65	0.68	NS
P (%)	0.15	0.16	0.18	NS
K (%)	0.58	0.56	0.70	NS
Ca (%)	0.52	0.46	0.55	NS
Mg (%)	0.23	0.18	0.18	NS
Zn (mg kg^{-1})	30	52	33	9
Cu (mg kg^{-1})	39	76	40	13.5
Fe (mg kg^{-1})	3476	6205	8369	1120
Mn (mg kg^{-1})	112	102	82	NS
Al (mg kg^{-1})	3085	3057	1800	77

The nutrient concentration of the shoot on the 90th day of growth in three different soils having distinctly different pH and base status is provided in Table 19. There was significant difference for all nutrients except Cu in the shoot after 90 days growth. Highest N, P, K, and Ca concentration was observed in plants)grown in neutral soil (pH 7.4). The values for N and P concentration were comparable for the two acidic soils. Between two acidic soils K and Ca concentration were high in pH 5.5 soil. While the Mg concentration in soil was extremely high in pH 7.4 soil, the shoot Mg was comparable to that of the other two acidic soil on 90 days growth. Similar values for Cu concentration in shoot was observed in three soil. Plants grown in pH 4.4 soil, recorded high concentration of Fe, Mn and Al indicating high accumulation in shoot. In barley (*Hordeum vulgare*) roots iron uptake was associated with phytosiderophore release locally (Marschner *et al.*, 1983). Along with this the growth of plants were affected indicating that the extreme acidity is a limiting factor for rubber plants. At the same time the pH 5.5 and neutral soil recorded on par values for Al concentration.

Table 19. Effect of soil pH and base status on the nutrient concentration of shoot (90th day)

Nutrients	Soil 1 (pH4.4)	Soil 2 (pH5.5)	Soil 3 (pH7.4)	CD (P=0.05)
N (%)	1.19	1.18	1.41	0.13
P (%)	0.12	0.11	0.23	0.02
K (%)	1.11	1.52	1.89	0.24
Ca (%)	0.63	1.79	1.95	0.41
Mg (%)	0.16	0.16	0.13	0.02
Zn (mg kg^{-1})	30	24	30	4.00
Cu (mg kg^{-1})	15	17	17	NS
Fe (mg kg^{-1})	361	202	269	27
Mn (mg kg^{-1})	199	58	12	38
Al (mg kg^{-1})	629	400	371	47

The nutrient concentration of the shoot on the 240th day of growth in three different soils having distinctly different pH and base status is provided in Table

20. Except for N and Mg all other nutrients recorded significant difference between the three soils. The P concentration was extremely low in soil having 4.4 pH. It was on par in soil with pH 5.5 and 7.4. At extremely low pH (4.4), the availability and absorption is limited probably by the high P fixation as reported earlier (Ulaganathan *et al.*, 2005). Regarding K, the values were on par between the two acidic soils and significant difference was recorded with soil having 7.4 pH. Regarding Ca, the values were significantly different between two acidic soils with the extremely acidic soil recording the lowest value. However, the values were on par between pH 5.5 and 7.4 soils. Even with very high available Ca level in pH 7.4 soil, the concentration of Ca in the shoot was on par with the values recorded by plants grown in soil with pH 5.5. The Ca concentration in the plant increases with age and probably as the time advances there is more likely chance of increasing the Ca concentration with increased availability in the soil. Zinc concentration was significantly different between the three soils and the highest value was recorded in extremely acidic soil with pH 4.4. Increased Zn availability in extremely acidic soil may be the reason for this (Shuman, 1977). Regarding Cu, Fe, Mn and Al, significant difference was recorded among the three soils. As reported in the literature, increased concentration of these ions under extremely acidic soil conditions might have promoted the uptake and highest concentration was recorded in soil with pH 4.4. It is pertinent to note that the Fe concentration is on par between pH 5.5 and 7.4 soil.

Table 20. Effect of soil pH and base status on the nutrient concentration of shoot (240th day)

Nutrient	Soil 1 (pH 4.4)	Soil 2 (pH 5.5)	Soil 3 (pH 7.4)	CD (P=0.05)
N (%)	1.31	1.18	1.38	NS
P (%)	0.10	0.19	0.22	0.03
K (%)	0.74	0.85	1.03	0.19
Ca (%)	0.71	1.03	1.29	0.02
Mg (%)	0.23	0.22	0.19	NS
Zn (mg kg^{-1})	30	47	38	8
Cu (mg kg^{-1})	30	23	19	6
Fe (mg kg^{-1})	537	278	187	60
Mn (mg kg^{-1})	189	149	107	36
Al (mg kg^{-1})	1643	343	171	58

Effect of soil pH and base status on the nutrient uptake of root at the 90th day is given in Table 21. There was no significant difference in N, Zn and Cu uptake between three soils. Phosphorus uptake was significantly different between the three soils. Very low K and Ca uptake was recorded in pH 4.4 as compared to pH 5.5 and pH 7.4 and consequent reduced growth in pH 4.4 was recorded.

Magnesium uptake was significantly lower in pH 4.4 soil. Significant difference in Al was observed between three soils. Plants grown in the acidic soil recorded more uptake of Al in root compared to plants grown in soil with pH 7.4.

Table 21. Effect of soil pH and base status on the uptake of nutrients of root (90^{th} day).

Nutrients (mg plant^{-1})	Soil 1 (pH 4.4)	Soil 2 (pH 5.5)	Soil 3 (pH 7.4)	CD (P=0.05)
N	16.7	20.7	17.0	NS
P	2.41	3.06	4.10	0.15
K	18.7	35.9	36.0	1.01
Ca	6.0	39.9	42.7	0.87
Mg	0.46	1.26	0.71	0.04
Zn	0.09	0.063	0.067	NS
Cu	0.06	0.07	0.04	NS
Fe	2.96	4.05	6.14	0.19
Mn	0.056	0.14	0.11	0.01
Al	4.35	5.27	3.72	0.06

Effect of soil pH and base status on the nutrient uptake by roots at the 240th day is given in Table 22. No significant difference was recorded in N, Ca, Mg, Zn and Mn uptake between three soils. Significant difference was recorded for P, K, Cu, Fe and Al among three soils. Highest P, K and Fe uptake was recorded in pH 7.4 followed by pH 5.5 and lowest in pH 4.4. Low availability of P and K and consequent low uptake in extremely acidic soil is the most growth limiting factor and the most reported acid soil infertility. However, the Al uptake was higher in pH 5.5 among the two acidic soils because of the higher biomass in pH 5.5 and almost equal Al concentration in pH 4.4 and pH 5.5.

Table 22. Effect of soil pH and base status on the uptake of nutrients of root (240th day)

Nutrients (mg plant^{-1})	Soil 1 (pH 4.4)	Soil 2 (pH 5.5)	Soil 3 (pH 7.4)	CD (P=0.05)
N	58.6	62.9	71.4	NS
P	8.43	15.3	17.9	0.64
K	36.0	57.1	68.7	2.5
Ca	59.4	48.0	57.3	NS
Mg	14.1	18.9	18.9	NS
Zn	0.19	0.54	0.34	NS
Cu	0.24	0.73	0.40	0.02
Fe	21.8	64.4	77.8	2.2
Mn	0.63	1.07	0.84	NS
Al	19.3	31.9	18.3	0.50

Effect of soil pH and base status on the shoot nutrient uptake at the 90th day is given in Table 23. There was significant difference in the uptake of all nutrients among three soils. However, wide variation in the uptake of N, P, K, and Ca was recorded between the three soils with highest values in pH 7.4. Highest N, P, K and Ca uptake were recorded in pH 7.4 followed by pH 5.5 and lowest in pH 4.4. In pH 5.5 and pH 7.4 soil, the Mg uptake was on par and it was low in pH 4.4. Among the micronutrients, Zn uptake was highest in pH 7.4 and the values were on par for pH 4.4 and pH 5.5. Iron and Mn uptake were high in pH 7.4 followed by pH 4.4.

Table 23. Effect of soil pH and base status on the uptake of nutrients of shoot (90th day)

Nutrients (mg plant^{-1})	Soil 1 pH4.4	Soil 2 pH 5.5	Soil 3 pH 7.4	CD (P=0.05)
N	38.7	59.9	89.3	8.9
P	3.67	5.78	8.82	0.89
K	35.7	77.7	116.4	14.0
Ca	20.4	91.6	119.7	21.8
Mg	5.06	8.36	7.96	1.14
Zn	0.10	0.12	0.19	0.02
Cu	0.05	0.09	0.11	0.03
Fe	1.16	1.03	1.66	0.34
Mn	0.65	0.29	0.72	0.18
Al	2.04	2.03	2.30	0.32

Effect of soil pH and base status on the uptake of nutrients by shoot at the 240th day is given in Table 24. There was significant difference in N, K, Ca, Mg, Zn, Cu, Fe, Mn and Al between three soils. Plants grown in pH 4.4 soil, P was significantly lower than the other two soils and the pH 5.5 and pH 7.4 were on par. Among the three soils, it was observed that the uptake of nutrients were very low in pH 4.4. Uptake of Al was very high in pH 4.4 indicating that low pH with high exchangeable Al content in extremely acidic soil favored high accumulation of Al. At the same time, low values were recorded for N, P, K, Ca, Mg, Zn and Cu and recorded poor growth compared to plants grown in pH 5.5 or pH 7.4.

Table 24. Effect of soil pH and base status on the uptake of nutrients of shoot (240th day)

Nutrients (mg plant^{-1})	Soil 1 (pH 4.4)	Soil 2 (pH 5.5)	Soil 3 (pH 7.4)	CD (P=0.05)
N	155	250	304	10.1
P	7.8	39.4	48.4	10.9
K	87	180	228	5.0
Ca	81	218	285	6.2
Mg	26.6	45.1	42.7	8.0
Zn	0.35	1.01	0.84	0.02
Cu	0.35	0.49	0.42	0.01
Fe	6.50	5.85	4.11	0.32
Mn	2.16	3.17	2.35	0.09
Al	19.41	7.31	3.89	0.25

Effect of soil pH and base status on the total uptake of nutrients by rubber seedlings on the 90th day is given in Table 25. Significant difference in uptake for N, P, K, Ca, Zn, Fe and Mn was recorded. Plant species showed various mechanisms for iron uptake was reported (Marschner and Romheld, 1994). Among the three soils, uptake of N, P, K and Ca were very high in plants grown in neutral soil (pH 7.4). Between two acidic soils, pH 5.5 recorded high values for N, P, K and Ca.

Table 25. Effect of soil pH and base status on the total uptake of nutrients (90th day)

Nutrient (mg plant^{-1})	Soil pH 4.4	Soil pH 5.5	Soil pH 7.4	CD (P=0.05)
N	55.5	80.6	103.9	1.5
P	6.2	8.9	18.7	0.23
K	54.4	105.4	152.4	32.1
Ca	26.4	131.4	162.4	3.3
Mg	5.51	9.61	8.73	0.18
Zn	0.19	0.18	0.25	NS
Cu	0.11	0.16	0.15	NS
Fe	4.12	5.08	7.80	0.19
Mn	0.71	0.40	0.83	0.03
Al	6.38	7.31	6.05	0.08

The total uptake of nutrients by the plants on the 240th day is presented in Table 26. Treatment difference was significant on the uptake of all the nutrients. Regarding uptake of K, values were significantly different between pH 5.5 and pH 7.4 and between pH 4.4 and pH 5.5. For N, P, K, Ca and Mg, highest uptake was recorded for soil with pH 7.4. Regarding Zn, Cu, Fe and Mn, highest uptake was recorded by plants grown in soil with pH 5.5 and the lowest value was recorded by plants grown in soil having 4.4 pH. Aluminium uptake was significantly lower with soil having 7.4 pH and the values were on par for soils with pH 4.4 and pH 5.5. Poor growth due to extreme acdity and impaired Ca uptake was reported in two annual crops and a graminaceious species (Kidd and Proctor, 2000).

Table 26. Effect of soil pH and base status on the total uptake of nutrients (240th day)

Nutrient (mg plant^{-1})	Soil pH 4.4	Soil pH 5.5	Soil pH 7.4	CD (P=0.05)
N	213.6	315.6	375.3	12.9
P	16.1	56.0	66.3	1.4
K	123	237	301	2.0
Ca	141	267	342	149
Mg	41.4	64.1	61.6	1.46
Zn	0.54	1.54	1.18	0.03
Cu	0.59	1.28	0.82	0.03
Fe	28.0	70.2	89.1	2.26
Mn	2.87	4.23	3.19	0.12
Al	38.6	39.2	22.2	0.64

Rhizosphere activity difference and associated production of organic acids making changes in the rooting zone influencing the nutrient concentration and uptake was reported for many tree species (Shi *et al.*, 2012). In the same way, in the present study, at the extremely acidic pH (pH 4.4), the Ca concentration and uptake in plants were very less and the growth was also affected. The pH range of 6.5-7.5 is the optimum pH for the availability of most of the nutrients and this was reflected in the growth of rubber plants. At the same time, nutrient concentration and uptake of nutrients was on par between pH 4.4 soil and pH 7.4 neutral soil indicating that the acidic pH 5.5 is favorable for rubber plants and the pH 4.4 is adversely affecting the uptake of nutrients and growth of rubber plants.

Fig. 12. Root structure of seedlings in polybag

IV. 2.3. Changes in rhizosphere soil properties and nutrient availability

The changes in soil properties during 90th day and after eight months growth of plants was different in three soils. Changes in the soil properties in pH 4.4 soil is given in Table 27. The initial soil pH 4.4 (in the extremely acidic range) was increased to very strongly acidic range (4.84). The soil organic carbon was maintained in the medium status (1.13 %) itself even though there was an increase from the initial status (0.92 %). In the case of K, Ca and Mg, the availability was significantly increased from the initial status. The trend in increase in availability was different among the three nutrients. The increase in Ca and Mg availability was more compared to K. The P availability was not changed from the initial status after eight months of growth.

Table 27. Changes in the rhizosphere pH and nutrient availability in pH 4.4 soil

Soil properties	Initial	Three months	Eight months	CD (P=0.05)
pH	4.36	4.67	4.84	0.12
Organic carbon (%)	1.13	0.94	0.92	0.09
Available P (mg kg^{-1} soil)	20.1	20.9	21.9	NS
Available K (mg kg^{-1} soil)	38.2	53.1	60.4	8.4
Available Ca (mg kg^{-1} soil)	42.4	85.7	146.2	30.3
Available Mg (mg kg^{-1} soil)	9.0	17.2	27.6	3.9

Changes in the soil properties of pH 5.5 soil are given in Table 28. There were no significant change in pH in this soil, instead it was maintained in the strongly acidic (5.0- 5.5) range as of the initial status. The SOC was not changed after eight months and the availability of P, K, Ca and Mg were significantly increased. The increase in the availability from the initial status was higher for Ca followed by P, K and Mg.

Table 28. Changes in rhizosphere pH and nutrient availability in pH 5.5 soil

Soil properties	Initial	Three months	8 months	CD (P=.05)
pH	5.51	5.28	5.35	NS
SOC (%)	1.20	1.08	1.22	0.08
Available P (mg kg^{-1} soil)	21.9	14.6	72.2	16.0
Available. K (mg kg^{-1} soil)	47.9	75.4	63.8	11.8
Available Ca (mg kg^{-1} soil)	52.4	219.9	212.9	72.1
Available Mg (mg kg^{-1} soil)	16.1	24.5	27.5	5.6

Changes in nutrient availability in pH 7.4 soil is given in Table 29. The change in soil pH was high and it was significantly reduced to 6.2. The SOC per cent showed an increase but it was maintained in the medium status as per the sufficiency range ratings followed for rubber (Kartikakuttyamma *et al.*, 2000). Available P and K were increased. The very high Ca and Mg status was drastically decreased after eight month time from the initial status. The high uptake of Ca and K was attributed by the lowering of the pH 7.4 to acidic range because of the liberation of proton for cation- anion maintenance as found in the soil nutrient changes in pH 7.4 in rooting medium specific to plant activity (Haynes, 1990).

Table 29. Changes in rhizosphere pH and nutrient availability in pH 7.4 soil

Soil properties	Initial	Three months	8 months	CD (P=0.05)
pH	7.4	6.14	6.16	0.13
SOC (%)	1.04	1.18	1.24	0.14
Available P (mg kg^{-1}soil)	14.4	54.5	71.2	29.3
Available K (mg kg^{-1}soil)	66.0	142.9	99.0	15.5
Available Ca (mg kg^{-1}soil)	6056.0	3272.1	2505.0	331.3
Available Mg (mg kg^{-1}soil)	467.3	454.9	351.1	42.1

The rhizosphere alkalanization for nutrient availability was reported (Bravin *et al*, 2009). The SOC status was improved in extremely acidic and neutral soils and maintained in the strongly acidic soil. Naik *et al.* (2009) reported that the low pH and high Al content were influencing the carbon changes in the rhizosphere. The available P was increased to 72.2 and 71.2 mg kg^{-1} in pH 5.5 and

7.4, respectively irrespective of the initial status. But in the pH 4.4 soil, P availability was not increased. This may be due to P-fixation, a limiting factor in extremely acidic soils. Onthong and Osaki (2006) reported that when pH was very low, the formation of fixed P with Al and Fe decreased the P availability to plants. In the case of K, the availability was increased to a similar concentration from the almost similar initial status in two acidic soils whereas; in the neutral soil the increase in K availability was higher from a higher initial status. But all three were within the medium range as per the sufficiency range ratings followed in RRII (Karthikakuttyamma *et al.*, 2000). Calcium and Mg availability was reached to the medium level in two acidic soils indicating improvement in availability at the rhizosphere with plant growth. Rubber plants also could come up well in high base status soil and with plant growth for eight months, decrease of Ca and Mg of the neutral soil indicate that such a high status was tolerated by rubber plants.

Increased rhizosphere availability of P, K, Ca and Mg was reported (Naik *et al.*, 2009; Jungk and Claassen, 1986). Determination of the availability of element concentration and the corresponding changes in the rhizosphere are the important requirement to know the plant availability of nutrients (Bravin *et al.*, 2012). The observed alterations in the rhizosphere are an evidence of specific adaptations in the rubber plants for extremely varying soil conditions.

Changes in soil organic carbon (FTIR spectrum identification)

Changes in soil organic carbon from initial soil and after eight months compared by FTIR spectrum identification are described in figures (13-15). Identification of soil components and soil organic matter characterization by functional group differentiation are the important applications of Infrared spectroscopy (IR) in which Fourier transform infrared spectroscopy (FTIR) is important. Functional group present in the organic substances and the mineral particle associated groups contained in the soil can be identified using FTIR. In this study the FTIR spectrum of the soils were identified before the initiation of plant growth and after 240 days of plants growth in three soils. The spectrum of all three soils comprised of the clay mineral (left portion) organic matter (middle portion) and minerals (right portion) in the peaks obtained in three soils. The spectrum of the two acidic soil (pH 4.4 and pH 5.5) were similar and these were different from the neutral soil (pH 7.4). In pH 4.4 and pH 5.5, 6 peaks in the left portion were similar. This corresponds to the clay minerals and naturally these were identical in the acidic soils dominated in Kaolinite clay mineral. But in pH 7.4 among the 6 peaks two were present and instead of other peaks there was a broad peak corresponds to the center point at intensity of 3400 cm^{-1}associated with the hydrogen bonding with the functional group OH (Dick *et al.*, 2003) and it is a determining factor of the presence of exchangeable cations like K, Na, Ca and Mg. This was the confirmation of the characteristic difference in pH 7.4 soil from pH 4.4 soil and pH 5.5 soil in the clay minerals particles and high Ca and Mg content. Also there were additional three peaks between 2800 cm^{-1} and 3000 cm^{-1} in pH 7.4 which corresponds to functional group of aliphatic C-H stretching and the presence of the fats and lipids which were the typical relation to soil organic matter properties. Similar intensities of the spectrum regarding the recent applications of IR spectroscopy for the studies of various composition of soil was reported (Artz *et al.*, 2006; Tinti *et al.*, 2015).

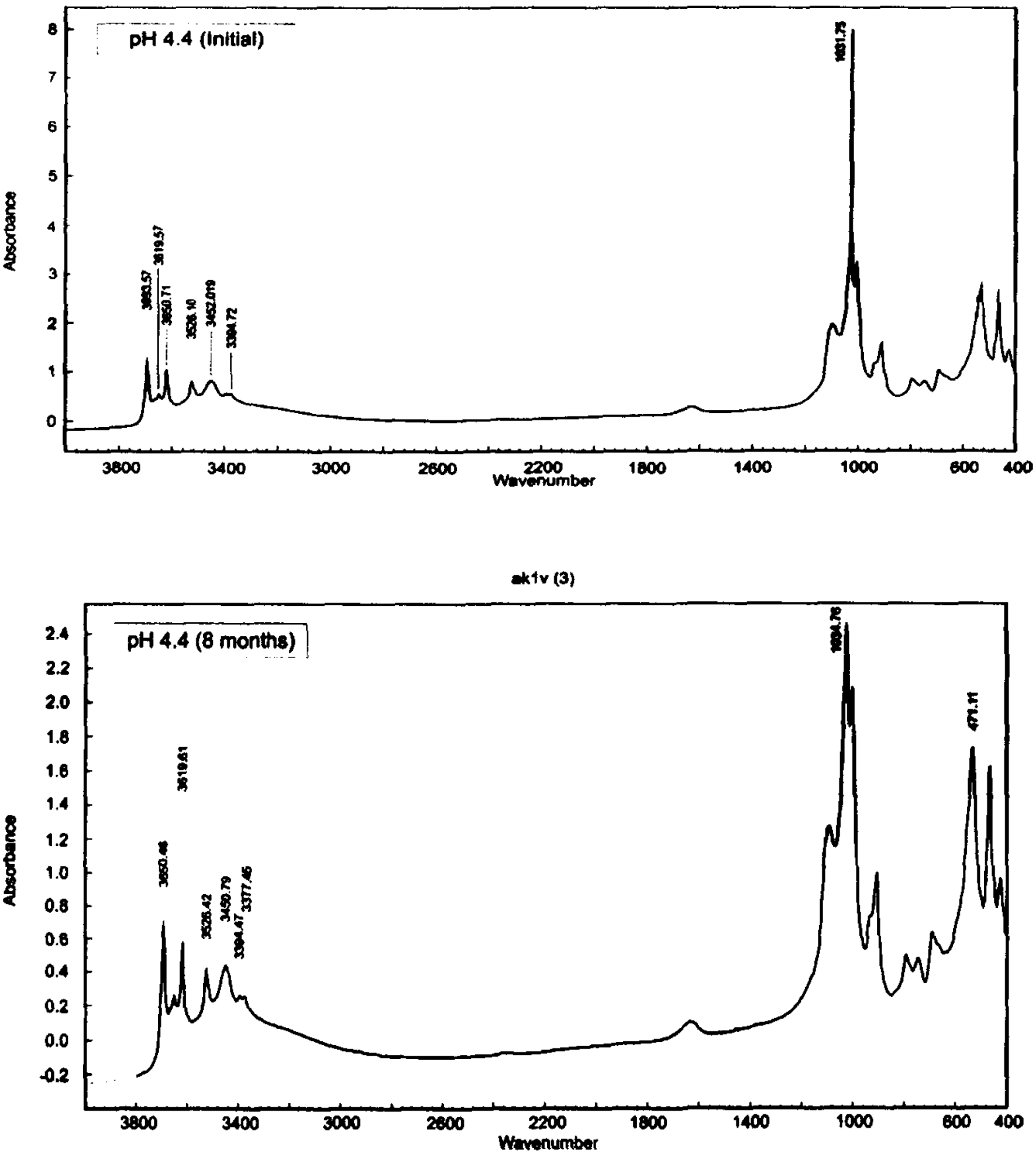

Fig. 13. FTIR spectrum of changes in soil organic carbon in the initial and after eight months growth of rubber plants in pH 4.4 soil

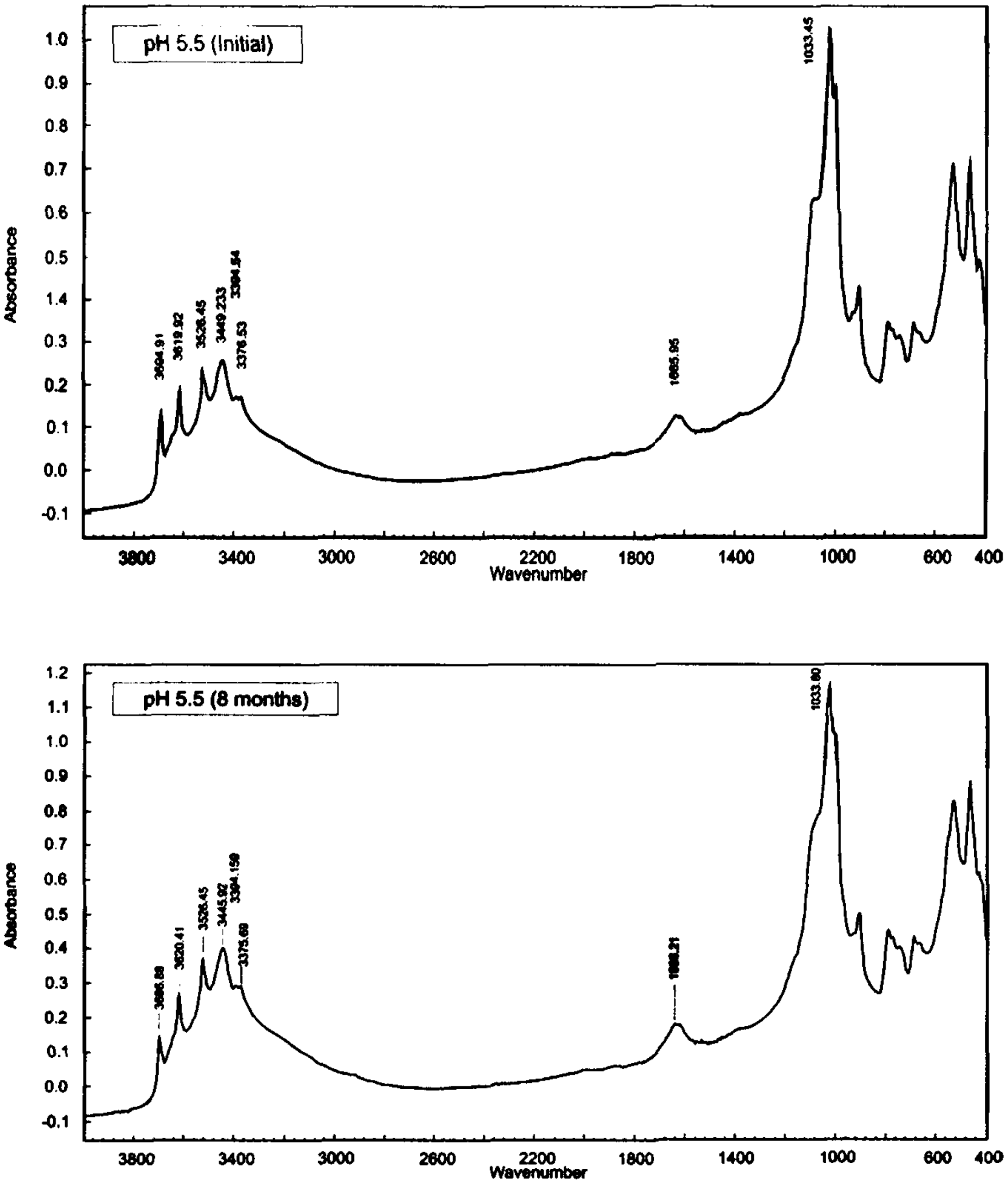

Fig. 14. FTIR spectrum of changes in soil organic carbon in the initial and after eight months growth of rubber plants in pH 5.5 soil

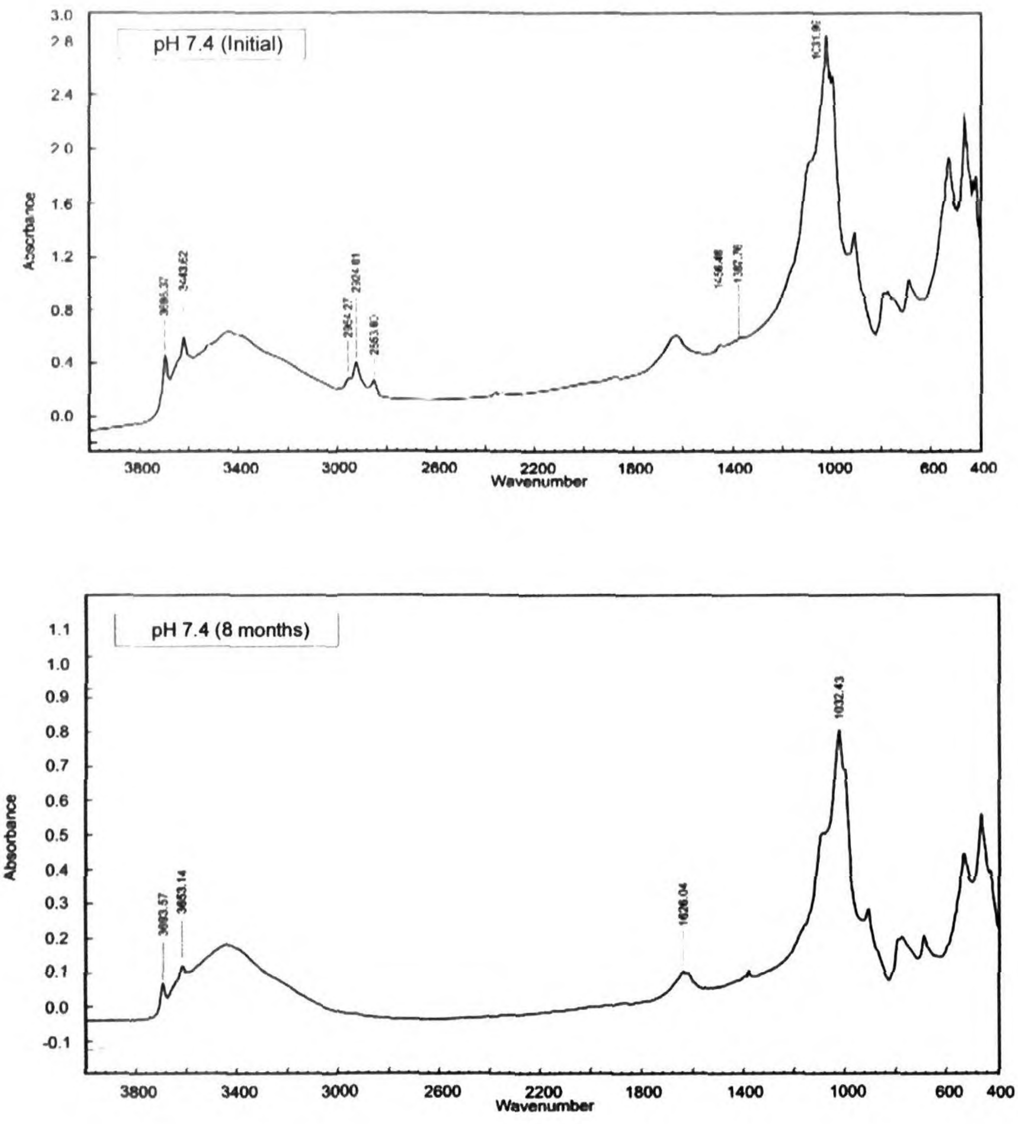

Fig. 15. FTIR spectrum of changes in soil organic carbon in the initial and after eight months growth of rubber plants in pH 7.4 soil

Comparing the spectrum before and after seedling growth, there was no change in pH 4.4 soil and pH 5.5 soil. However the pH 7.4 soil showed differences in two spectrums and the peaks in the range of 2800 cm^{-1} and 3000 cm^{-1} was absent after plant growth. This indicated the mineralization of soil organic matter and this was considered as the index of SOM stability and changes of stable and labile C in soil (Spaccini *et al.*, 2001) and it was also used to measure the index of hydrophobicity of SOM by the area of the band 3000- 2800 $^{\text{cm-1}}$ divided by OC value (Capriel, 1997). Hence it can be concluded that the stable and labile C in the SOM in pH 7.4 was mineralized by the growth of rubber seedlings which can be observed as the increase of SOC after plant growth in pH 7.4. The peaks associated with minerals in right portion was similar in all three soils in pre and post period of seedling growth. The peak at 1630 $^{\text{cm-1}}$ was reported as recalcitrant carbon (Tinti *et al.*, 2015; Artz *et al.*, 2006). A similar peak was observed in three soils of the present study and this was present in before and after seedling growth in three soils. The spectrum identification can be confirmed the difference of pH 7.4 soil from other two acidic soil and the increase of SOC in pH 7.4 soil from the characteristics peaks obtained. The sample used here was the rhizosphere soil after plant growth and the effect was reflected in the peaks indicated the influence of seedlings in pH 7.4. FTIR can be used to the detailed study of soil components in rubber and is beneficial also.

IV. 3. Effect of lime application on nutrient availability and growth of young rubber plants.

IV. 3.1. Comparison of effect of lime application on nutrient availability in extremely acidic and very strongly acidic soil (Incubation experiment under laboratory conditions)

Initial properties of the two different soil are given. Two soils *viz.* extremely acidic (pH 4.4) and strongly acidic (pH 5.5) with similar organic carbon status were selected for the study (Table 9). The available P, K and Mg were in the medium range in both the soils and Ca was in the low range in both the soils.

In the extremely acidic soil the exchangeable aluminium was very high (2.89 cmol(+) kg^{-1}) compared to strongly acidic soil (1.63 cmol(+) kg^{-1}).

Nutrient availability upon incubation of the soil with and without lime for two months is given in Table 30. The extremely acidic soil pH was improved to strongly acidic pH range whereas, the pH change was not significant in the strongly acidic pH soil. No change in OC was observed between lime applied and no lime treatment in both soils. Availability of P and Ca improved in soil having 4.4 pH. However, in soil having a pH of 5.5, improvements in the availability of Ca alone was significantly different between lime applied and no lime treatment. Magnesium availability decreased significantly with lime treatment in extremely acidic (pH 4.4) soil and there was no significant change in strongly acidic (pH 5.5) soil. Reduced Mg availability with liming was reported earlier by Syamala (2006). Significant improvement in the availability of P and Ca by liming in sunflower grown soil was reported by Barman *et al.* (2014) and increase in P availability in Indian Spinach was reported by Sarker *et al.* (2014). Dinkecha and Tsegaye (2017) reported a significant difference in pH, available P and Ca before and after lime application in acidic soils in central highlands of Ethiopia. Application of lime stone alone in young rubber growing soils reported a reduction in Mg availability indicating the antagonistic effect of excessive Ca on Mg availability (Joseph, 2009). While liming improved the pH and nutrient availability except OC and K in extremely acidic soil (pH 4.4), the strongly acidic soil (pH 5.5) recorded no effect after liming other than Ca enrichment.

Table 30. Changes in nutrient availability with lime after two months of incubation in two acidic soils

Soil properties	Soil with pH 4.4			Soil with pH 5.5		
	+Lime	No Lime	t-stat	+Lime	No lime	t-stat
pH	5.45	4.42	**	5.49	5.51	NS
Organic Carbon (%)	0.93	1.00	NS	1.07	1.07	NS
Available nutrients (mg kg^{-1}soil)						
Phosphorus	58.33	13.33	**	80.67	75.00	NS
Potassium	31.57	25.50	NS	60.94	46.69	NS
Calcium	811.92	37.72	**	374.47	176.32	**
Magnesium	8.99	12.36	-*	21.17	26.47	NS

Influence of lime treatment on the exchange property of the soil incubated is presented (Table 31). Treating and incubating the soil with lime for two months increased significantly the CEC, exchangeable Ca and K and reduced the exchangeable Mg in soil having initial pH of 4.4. In soil having initial pH of 5.5, incubating with lime did not improve the exchangeable Ca and no difference could be recorded between lime treated and no lime treatments. In both soils, the exchangeable K was increased with lime application. Reduced values of exchangeable Al and acidity was recorded in both soil. In pH 5.5 soil, the exchangeable Al was brought to zero from 0.638 cmol (+)kg$^{-1.}$ High significant decrease in exchangeable Al and acidity was recorded in soil having pH 4.4. Similar study of drastic decrease of exchangeable Al and acidity was also reported (Dinkecha and Tsegaye, 2017). Reduction in Mg availability with lime/Ca application was reported in earlier studies also (Joseph *et al.*, 2009; Syamala *et al.*, 2003). A further possible explanation for the decrease in exchangeable Mg as suggested by Sumner *et al.* (1978) is that liming causes Mg -fixation. Also decrease of soil Mg is possible by the increase in Ca: Mg ratio as a result of liming. Similar trend of decrease of exchangeable Mg, Al and acidity and an improvement of exchangeable K were observed in this study.

Table 31. Changes in exchange properties with lime after two months of incubation in two acidc soils

Exchange properties (c mol (+)kg^{-1}soil)	Soil with pH 4.4			Soil with pH 5.5		
	+Lime	No Lime	T stat	+Lime	No Lime	T stat
Cation exchange capacity	6.61	5.07	**	6.27	5.22	NS
Exchangeable calcium	4.20	2.01	**	2.13	1.09	NS
Exchangeable magnesium	0.09	0.12	- *	0.21	0.25	- *
Exchangeable potassium	0.62	0.50	**	1.12	0.90	**
Exchangeable aluminium	0.12	2.84	- **	0	0.68	- **
Exchange acidity	0.21	2.20	- **	0.05	0.88	- **

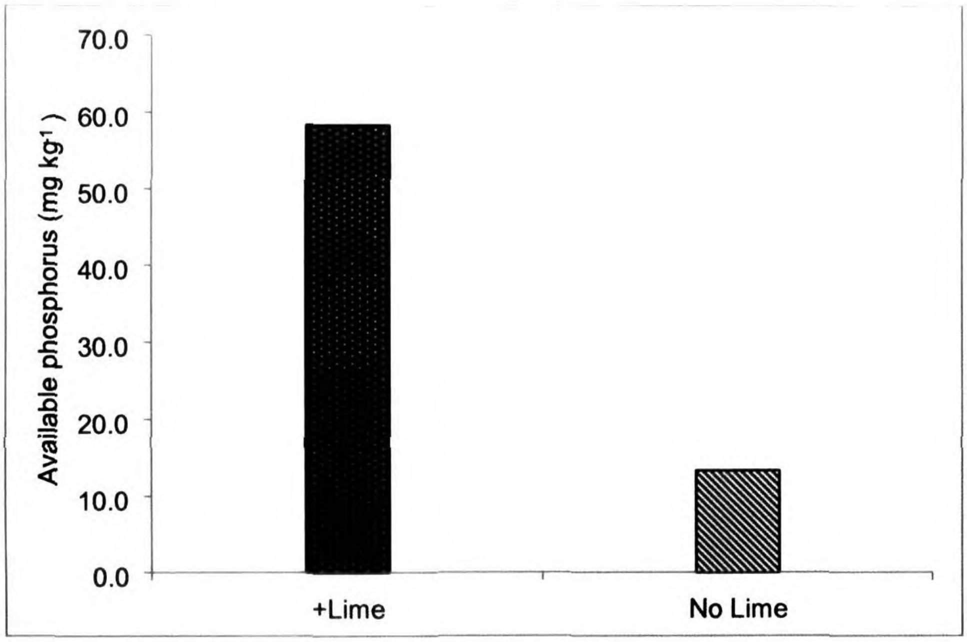

Fig. 16. Changes of available phosphorus after lime application in pH 4.4 soil (incubation study)

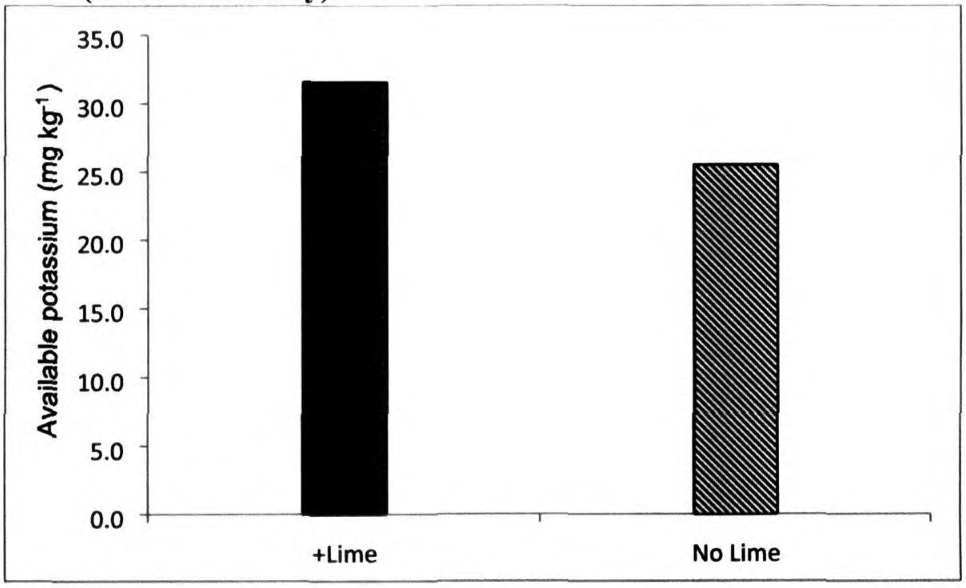

Fig. 17. Changes of available potassium after lime application in pH 4.4 soil (incubation study)

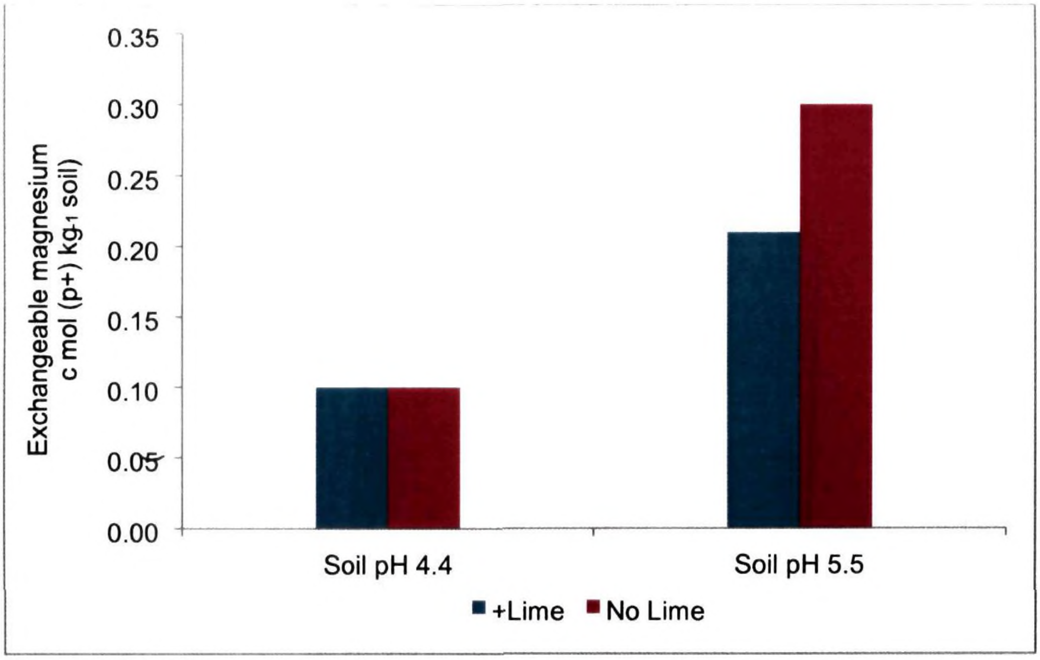

Fig. 18. Changes of exchangeable magnesium after lime application in pH 4.4 and pH 5.5 soil (incubation study)

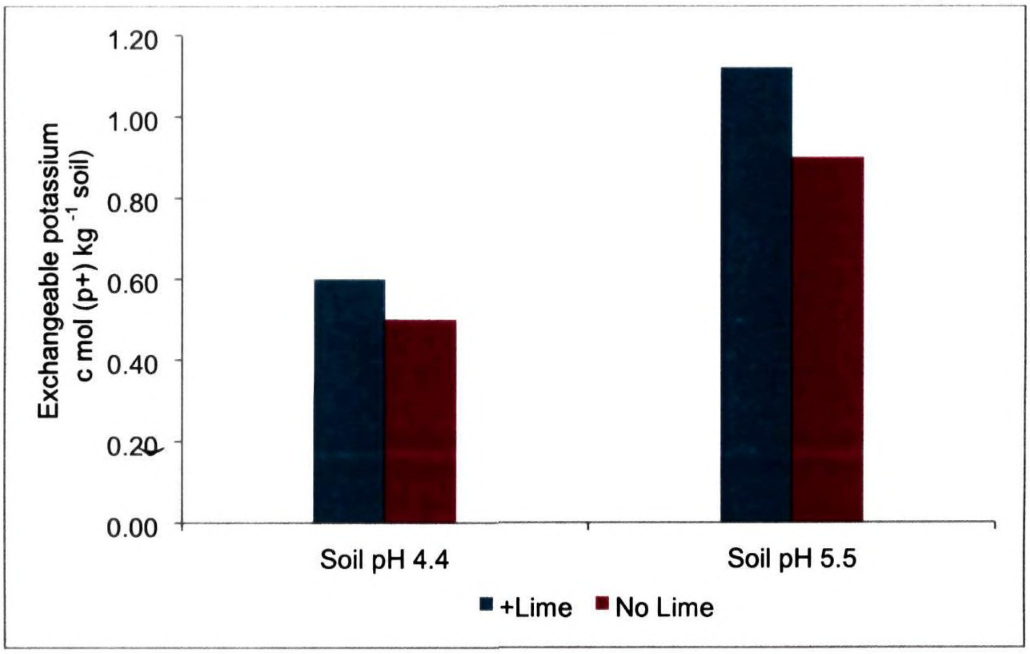

Fig. 19. Changes of exchangeable potassium after lime application in pH 4.4 and pH 5.5 soil (incubation study)

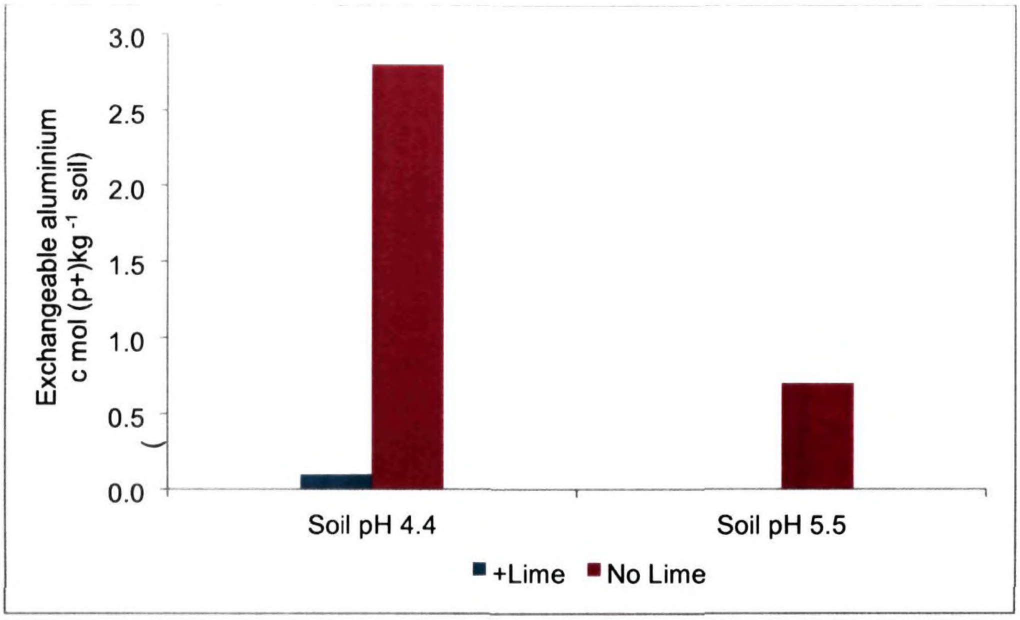

Fig. 20. Changes of exchangeable aluminium after lime application in pH 4.4 and pH 5.5 soil (incubation study)

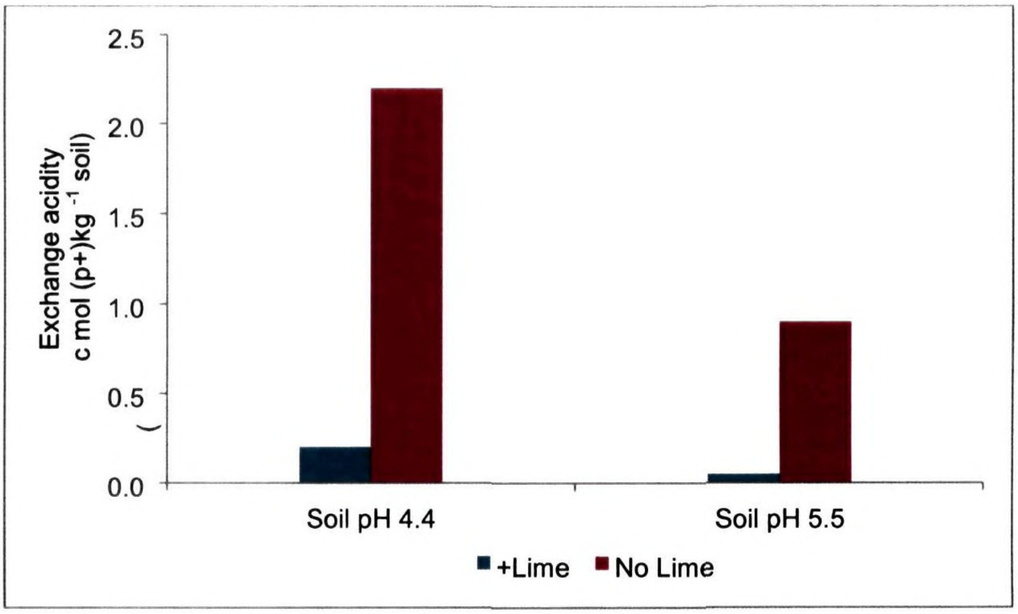

Fig. 21. Changes of exchange acidity after lime application in pH 4.4 and pH 5.5 soil (incubation study)

IV. 3.2. Effect of lime application on rhizosphere chemistry and growth of young rubber plants grown in extremely acidic soil

The data generated on the effect of lime application in soil having pH 4.4 on the growth of rubber seedlings is presented in Table 32. Diameter (Fig. 22) and height (Fig. 23) of the plants were significantly high in lime treated plants. A similar study was reported (Zhiyong *et al.*, 2016) where the growth of young Schima superba trees over 11 years attained a height increment of 5.9 m from 3.7 m at 4t ha^{-1} lime treatment and an increase of basal diameter from 2.4 to 4.9 cm. Improvement in the growth of rubber seedlings, young rubber plants after lime application were reported earlier (Joseph *et al.*, 2009: Syamala *et al.*, 2003). In scot pines (*Pinus sylvetris* L.) an increase of growth was recorded in more productive area than a low productive area with lime treatments (Borja and Nilson, 2009).

Table 32. Effect of application of lime on the growth of rubber plants

Treatment	Diameter (cm)	Height (cm)	Shoot weight (g)	Root weight (g)	Shoot/ root ratio
No lime	5.14	34.3	7.81	6.67	1.20
+ Lime	5.84	43.8	9.12	7.38	1.19
t value	2.66*	3.19**	NS	NS	NS

Similarly, the concentration of P (Fig. 24), Ca and Cu in shoot were improved with lime application and concentration of Mg (Fig.25) in shoot was reduced by lime application (Table 33). Reduced availability and consequent reduction in the uptake of Mg might have resulted in the significantly lower concentration of Mg in the lime treated plants.

Table 33. Effect of application of lime on the nutrient concentration of shoot

Treatment	N	P	K	Ca	Mg	Zn	Mn	Fe	Cu
	%					μgg^{-1}			
No Lime	2.09	0.07	1.16	1.06	0.18	16.6	75.2	991.2	12.7
+ Lime	2.25	0.10	1.07	1.24	0.13	18.3	88.4	792.3	17.3
t value	NS	2.82*	NS	2.19*	-4.7**	NS	NS	NS	2.6*

Changes in root nutrient concentration between lime treated and not treated plants are presented in Table 34. Liming significantly improved the concentration of N and Cu in the root and reduced the concentration of Mg and Zn. Similarly, Mg concentration was reduced in both root and shoot with liming. Reduced availability of Mg in soil and consequent reduced uptake recorded in this experiment as well as in earlier studies (Syamala, 2006; Joseph *et al.*, 2009) points to the strong antagonism between Ca and Mg. Increased Ca and Mg at the root absorbing site and at the transportation channel in plant system contributing towards low uptake of Mg in the presence of high concentration of Ca in the soil solution (Joseph *et al.*, 2009).

Table 34. Effect of application of lime on the nutrient concentration of root

Treatment	N	P	K	Ca	Mg	Zn	Mn	Fe	Cu
	%					μgg^{-1}			
No lime	0.86	0.05	0.51	0 65	0.14	15.5	49.2	1319	8.67
+ Lime	0.97	0.04	0.50	0 67	0.09	11.9	51.6	1035	12.78
t value	2.16*	NS	NS	S	-3.04**	-2.67*	NS	NS	2.77*

Nutrient uptake being a function of the concentration and the dry weight, the variation in uptake is directly related to these parameters. Phosphorus, Mg, Mn and

Cu uptake recorded significant difference between no lime and plus lime treatments (Table 35). While P, Mn and Cu recorded higher values with lime application, Mg recorded low values as expected due to the reduced concentration in the root and shoot. In the case of canola (*Brassica napus* L.), lime induced manganese deficiency which is different from that observed in rubber plants. This clearly indicated the difference in response of lime to different plants. The plant response study showed differences in the soil properties between lime and no lime treatments. The increase of P and Cu and a decrease of Mg was consistent in shoot, root and total uptake. An increase in the ratio of Ca: Mg was reported and such exchange are reasons to depress plant Mg uptake (Colemann *et al.*, 1958). Increased lime application results in an increase of Ca content of the plant tissue and a lowering of K content (Dean, 1986).

Table 35. Effect of application of lime on the total uptake of nutrients

Treatment	N	P	K	Ca	Mg	Zn	Mn	Fe	Cu
	mg plant^{-1}								
No lime	220	8	125	144	24	0.23	0.91	16.3	0.16
+ Lime	280	12	131	151	18	0.26	1.2	15.1	0.25
t stat	NS	2.8*	NS	NS	-2.1*	NS	2.4*	NS	3.9*

Difference in rhizosphere nutrient availability, nutrient fractions of P and K in rhizosphere soil between lime applied and no lime treatments after eight months of plant growth is presented in Table 36. The pH, OC, available P (Fig. 26) and Ca were improved with lime application and the difference was significantly different between two treatments. However, available K (Fig. 27) was reduced and the difference was statistically significant indicating the possibility of an antagonism between Ca and K similar to Mg. Also a decrease of available K with increasing charge density due to liming was reported (Magdoff and Barltell, 1980). The P fractions *viz.* saloid P, Al-P, Fe-P and Ca-P were improved with liming and the difference was significant. The release of unavailable P for plant uptake after liming has been termed as ‘P-sparing effect’ (Perrott and Mansell, 1989; Mansell *et al.*, 1984). It was more evident from the increase of all P-fractions. It was reported that a rearrangement in P-fractions had occurred after liming (Quin *et al.*, 1984). Application of lime significantly affected the different P-fractions and was involved in the transformation of P-fractions (Kiflu *et al.*, 2017).

Table 36. Effect of application of lime on the availability of nutrients in the rhizosphere

Parameters	+ lime	No Lime	t-stat
pH	5.30	4.40	6.35**
OC(%)	1.03	0.86	6.26**
Available nutrients (mg kg^{-1}soil)			
P	64	20	10.31**
K	85.5	112.3	-6.05**
Ca	586	73	16.05**
Mg	9.84	20.14	-7.52**
Phosphorus fractions (mg kg^{-1})			
Saloid –P	4.02	0.025	6.97**
Aluminium -P	11.7	2.03	10.86**
Iron-P	172.5	105.0	3.54*
Calcium -P	60	20	8.77**
K fraction (mg kg^{-1})			
Water soluble -K	17.16	38.99	-13.69**
Exchangeable- K	36.64	58.87	-6.99**
Fixed –K	21.34	19.10	2.29**

Water soluble K fraction and exchangeable K fraction reduced significantly with lime application after the growth of plants for eight months. McLean (1956) reported a decrease in water soluble K after the addition of calcium hydroxide in a pH of 5.5-6.0. In the present study, the fixed K fraction was improved with liming. A decrease in available K and fractions of K except fixed K was observed after plant growth even though incubation study showed an increase in exchangeable K. It was reported that the application of lime sometimes increases potassium fixation in soils. When the hydrogen ions and the hydroxyl-aluminium ions are removed due to increase in pH after application of lime, the potassium ions moves closer to the colloidal surface and becomes fixed (Magdoff and Bartlet, 1980).

Changes in the exchange properties of the soil with liming after eight months of plant growth (Table 37) indicated significant increase in cation exchange capacity (Fig.28) and exchangeable Ca status and decrease in the exchangeable Mg and K (Fig. 29). Myers *et al.* (1988) reported a reduction in exchangeable Mg upon liming and was attributed as the antagonistic effect of excess calcium availability. As expected, exchangeable Al (Fig.30) and exchange acidity decreased with lime application. Suresh *et al.* (1996) reported that the application of phosphogypsum reduced the exchangeable Al content in the rubber growing soils.

Table 37. Effect of application of lime on the exchange properties of the rhizosphere soil after eight months of plant growth

Exchange properties (c mol (+)kg^{-1}soil)	+ lime	No Lime	t-stat
Cation exchange capacity	4.99	4.70	NS
Exchangeable Ca	3.76	2.27	4.46**
Exchangeable Mg	0.07	0.16	-8.77**
Exchangeable K	0.41	0.82	-9.37**
Exchangeable Al	0.29	1.57	-9.82**
Exchange acidity	0.83	2.15	-8.58**

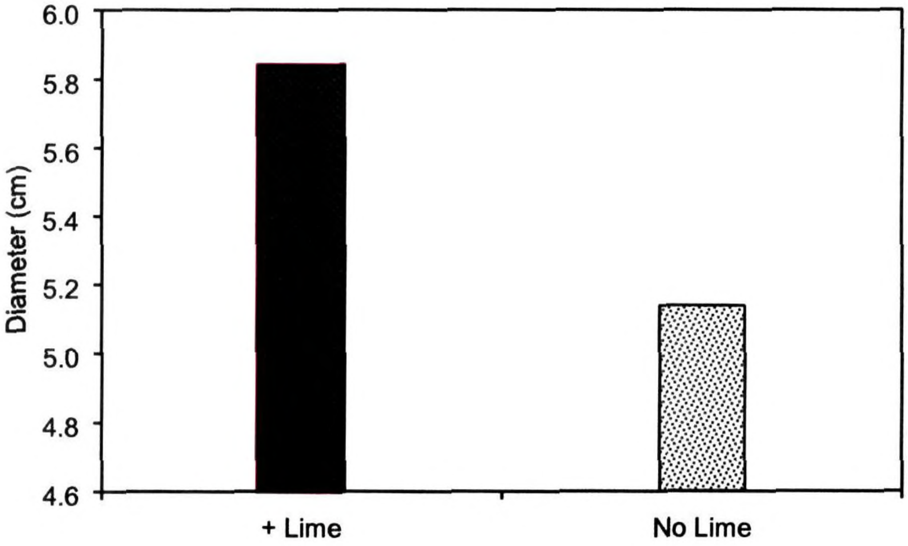

Fig. 22. Effect of application of lime on diameter of rubber plants in pH 4.4 soil

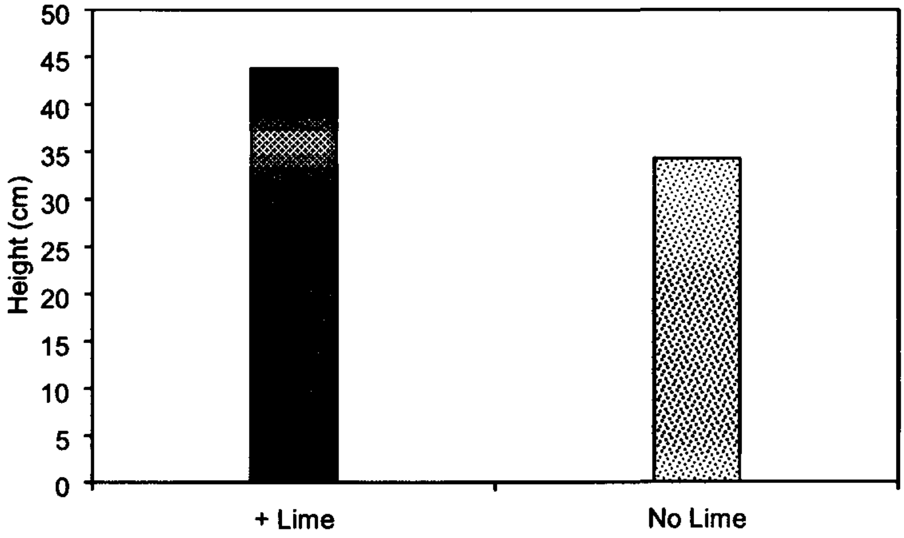

Fig. 23. Effect of application of lime on height of rubber plants in pH 4.4 soil

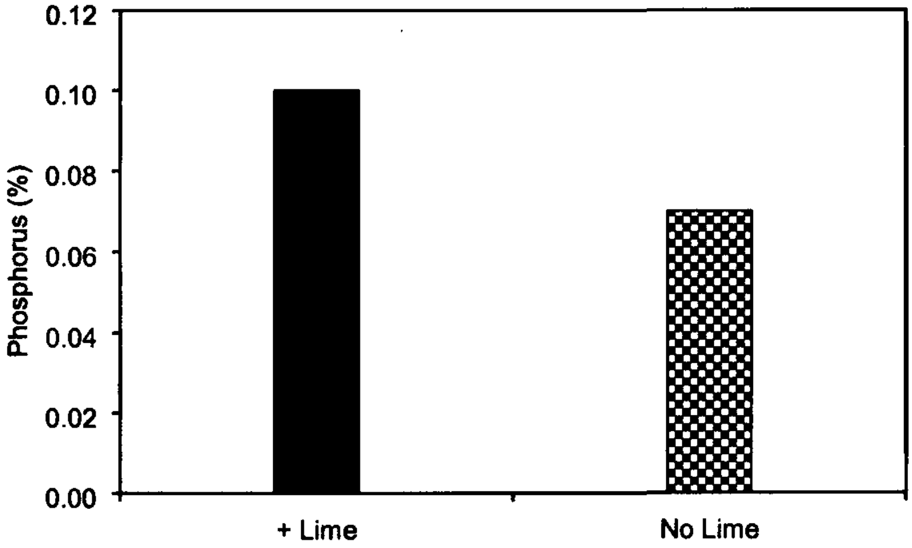

Fig. 24. Effect of application of lime on phosphorus content in shoot of rubber plants after eight months growth in pH 4.4 soil

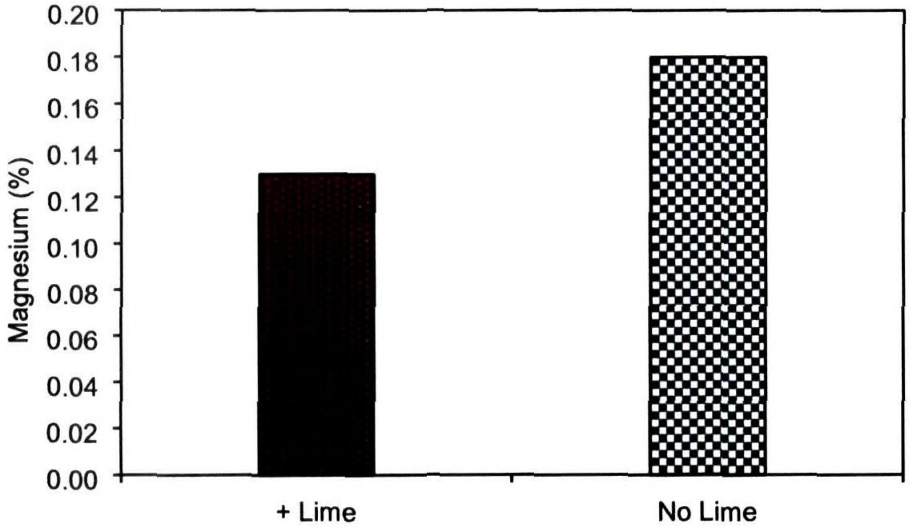

Fig. 25. Effect of application of lime on magnesium content in shoot of rubber plants after eight months growth in pH 4.4 soil

Effect of lime in extremely acidic and strongly acidic rubber growing soils were different. Incubating the soil with lime improved the exchange properties of the soil and improved the availability of P, and Ca and reduced the availability of Mg in extremely acidic soil. In strongly acidic pH, no significant difference in nutrient availability except Ca enrichment observed. Acidity can be alleviated well in both soils by reducing exchangeable Al and exchangeable acidity through liming. The extremely acidic pH soil is improved to strongly acidic pH through liming in rubber growing soils. In the response study, liming increased the diameter and height of the rubber plants. Liming had a negative effect on Mg and K availability and increased P uptake and decreased Mg uptake in rubber plants.

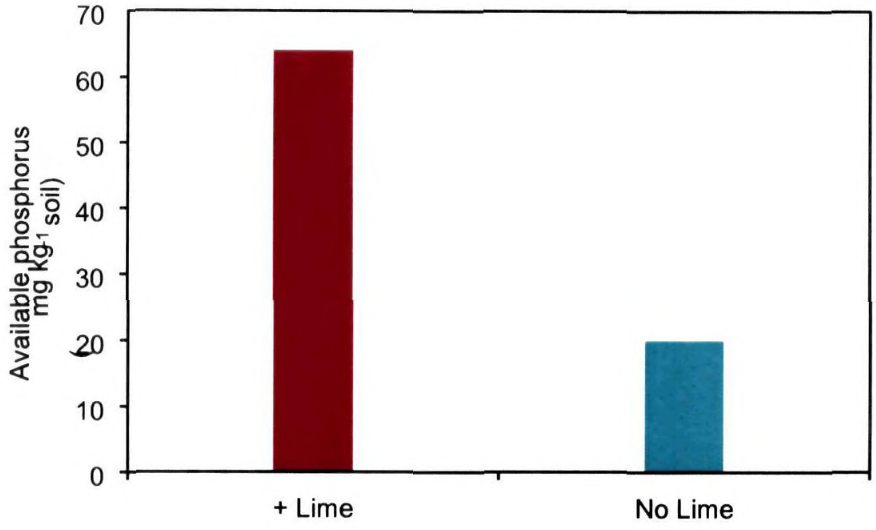

Fig. 26. **Effect of application of lime on phosphorus availability in the rhizosphere of rubber plants after eight months growth in pH 4.4 soil**

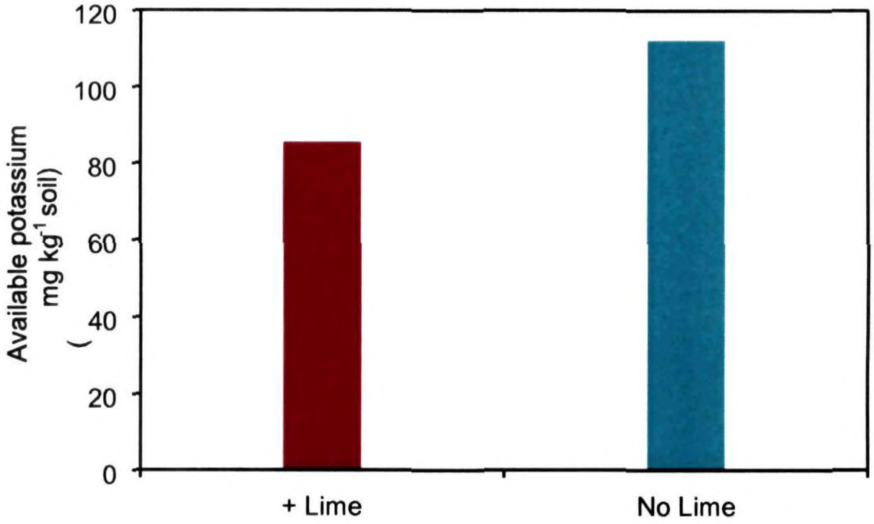

Fig. 27. **Effect of application of lime on potassium availabilityin the rhizosphere of rubber plants after eight months growth in pH 4.4 soil**

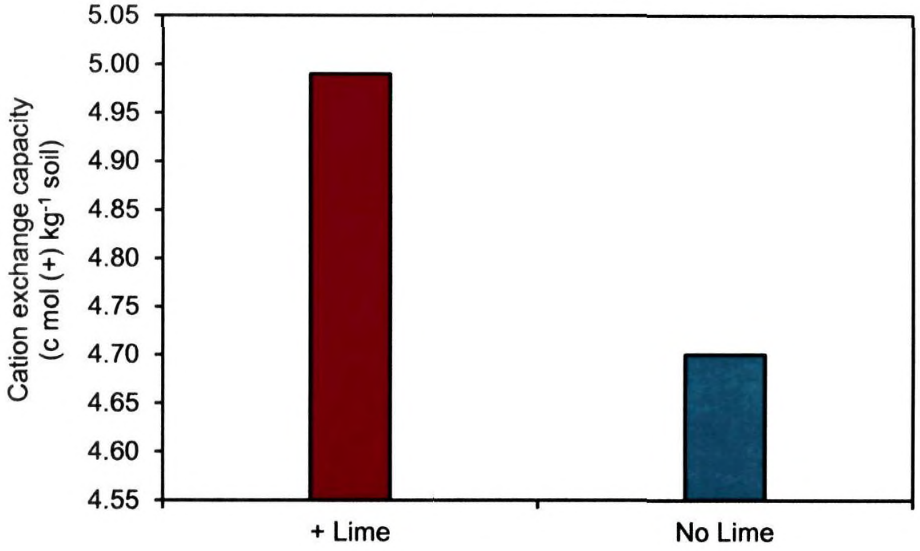

Fig. 28. Effect of application of lime on cation exchange capacity in the rhizosphere of rubber plants after eight months growth in pH 4.4 soil

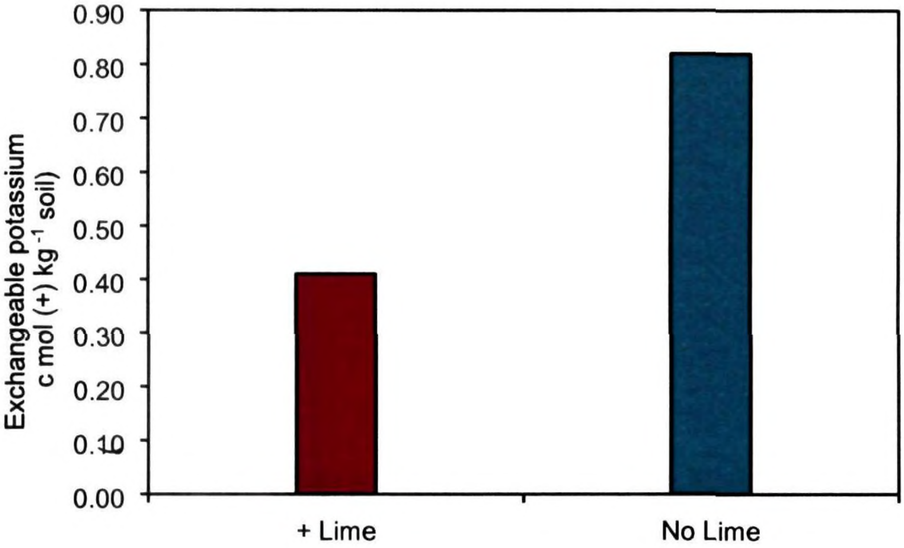

Fig. 29. Effect of application of lime on exchangeable potassium in the rhizosphere of rubber plants after eight months growth in pH 4.4 soil

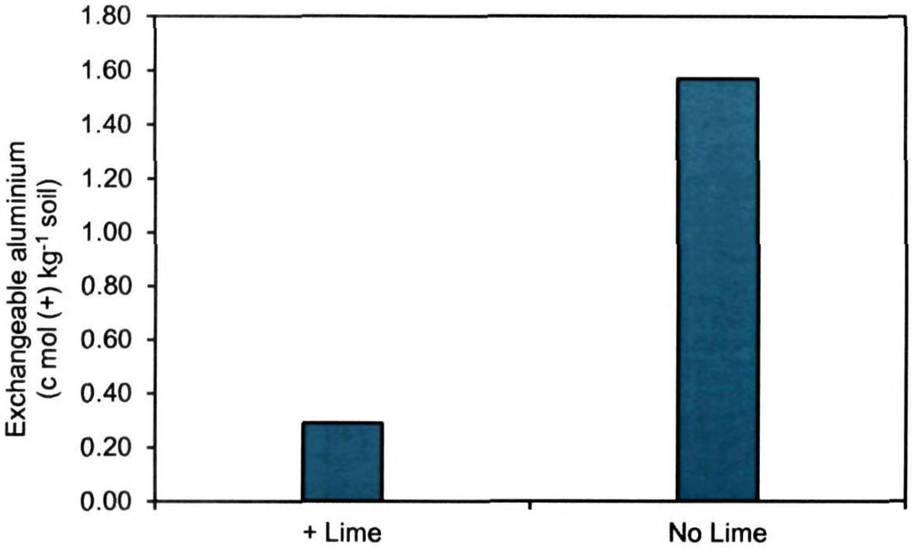

Fig. 30. Effect of application of lime on exchangeable aluminium in the rhizosphere of rubber plants after eight months growth in pH 4.4 soil

IV.4. Effect of pH and base status on transformation of fertilizer nitrogen and phosphorus

IV.4.1. Effect of pH and base status on mineralization of urea

Nitrogen is one of the key fertilizer input used by the farmers today. Nitrogen present mainly in organic form (98%) in soil. Remaining 2 per cent inorganic part comprises of NH_4^+ (immobile) and NO_3^- (highly mobile) forms. More than half of the N fertilizer applied is lost and results not only in an environmental hazard but also a substantial economic loss (Watson *et al.*, 1987). Ammoniacal N (Table 38) measurements in three soils with application of urea at periodical interval (Fig. 31) indicated that on the first day, highest value was recorded by soil having pH 5.5. Highest value was recorded on the seventh day in pH 4.4 soil and there after started decreasing. In pH 5.5 and 7.4 soils, decreasing trend was recorded. Nitrate nitrogen content in soils with application of urea (Table 39) indicated that highest value was recorded on the 20th day in all three soils. On the first and second day, nitrate -N (Fig.32) was very low. The rate of nitrification of fertilizer materials is influenced by the initial pH, the amount of N applied and the effect on soil pH. According to Pang *et al.* (1973) in an incubation study, the slope of the distribution curve of ammonium form was very similar to that of a normal distribution curve. With increasing time of incubation the ammonium form decreased and the oxidized form increased. Similarly, there was virtually no NO $^{3-}$ or NO $^{2-}$ after two weeks incubation in acid soil (Pang *et al.* 1973). Unlike the acid soil, in neutral soil the majority of applied N was in the form of ammonium. However, some transformation of ammonium to oxidised form took place in the first two weeks. (mg plant-1)

Table 38. Effect of soil pH and base status on ammoniacal nitrogen with application of urea in three soils.

Soil with different pH	Amoniackal nitrogen (mg kg^{-1}) Days							Mean
	1	2	4	7	10	15	20	
Soil 1 with pH4.4	9.1	19.4	16.6	15.4	19.4	18.7	18.2	16.7
Soil 2 with pH5.5	11.1	19.2	27.1	16.2	20.0	19.3	12.5	17.9
Soil 3 with pH7.4	11.0	17.3	41.3	14.8	11.4	12.1	10.6	16.9
Mean	10.4	18.6	28.3	15.5	17.0	16.7	13.7	
CD for pH	NS							
CD for days	1.9							
CD for pH x Days	3.29							

Nitrification is oxidation process carried out by soil microorganisms. So acceleration or deduction of nitrification rate is dependent on environmental conditions.

It may cause fluctuation in ammoniacal N. Under the aerobic condition NH_4^+N is converted to NO_3^-N rapidly. So NH_4^+N can be typically less than the NO_3^-N. The soil which has high organic matter content has high nitrification. When comparing three soils, NO_3^-N was lower in pH 4.4 and the other two soils were on par.

Table 39. Effect of soil pH and base status on the nitrate nitrogen with application of urea in three soils.

Soil with different pH	Nitrate nitrogen (mg kg^{-1}) Days							Mean
	1	2	4	7	10	15	20	
Soil 1 with pH4.4	0.11	0.28	0.31	0.22	0.95	1.04	8.81	1.68
Soil 2 with 5.5	0.18	0.55	0.91	0.29	0.88	3.01	8.80	2.09
Soil 3 with 7.4	0.22	0.66	1.25	0.74	1.03	2.16	7.89	1.99
Mean	0.17	0.50	0.83	0.52	0.95	2.10	8.50	
CD for pH	0.20							
CD for Days	0.30							
CD for pH x Days	0.52							

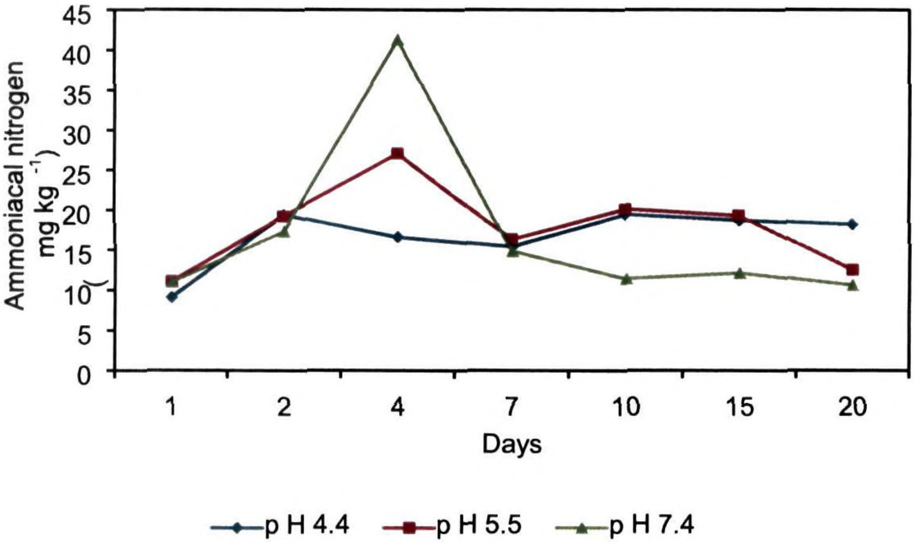

Fig. 31. **Effect of soil pH and base status on the ammoniacal nitrogen with application of urea in three soils.**

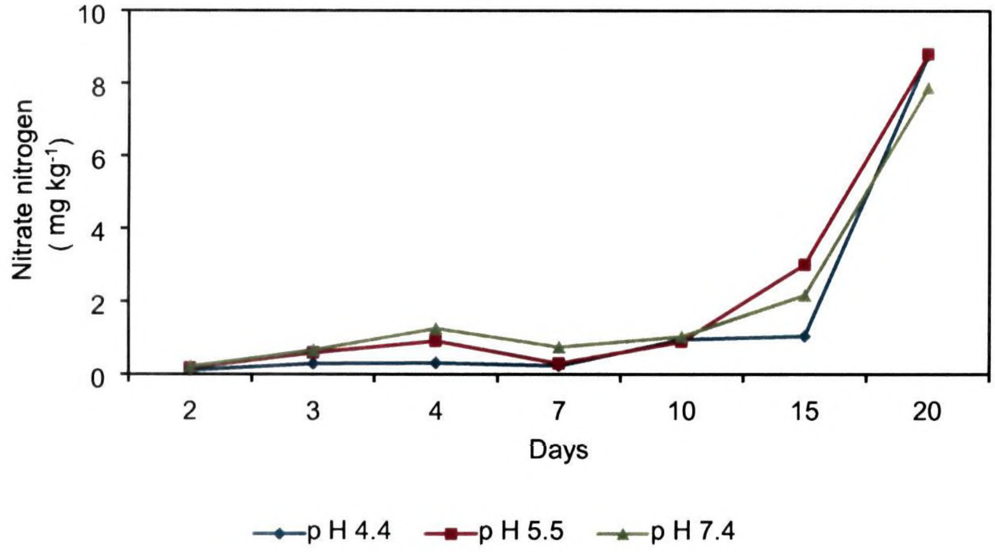

Fig. 32. **Effect of soil pH and base status on the nitrate nitrogen with application of urea in three soils.**

4.2. Effect of pH and base status on the availability of phosphorous from rock phosphate and super phosphate

The P availability from rock phosphate was the highest in soil having 5.5 pH and was the lowest in soil having pH 7.4 (Table 40). In pH 4.4 soil highest availability of phosphorus (Fig. 33) was recorded on the 10th day of incubation and thereafter it decreased and the lowest value was recorded on the 30th day of incubation. In soil having pH 5.5, the available P slowly increased and reached the peak on the 20th day and thereafter it decreased and the value recorded on the 30th day was significantly lower than the value recorded on the 5th day of incubation. Soil with pH value of 7.4 recorded the highest P availability on the 20th day and thereafter the value decreased. The lowest P availability was recorded by neutral soil compared to the other two soils. Among the three soils the highest P availability was recorded by soil having 5.5 pH on the 20th day of incubation. Comparatively pH 5.5 recorded higher P availability and it was observed from 10th day to 25th day and pH 7.4 recorded lowest P availability. The lowest availability of P in pH 7.4 may be ascribed due to the formation of complexes through the presence of very high Ca^{2+} concentration and becomes insoluble (Mehta *et al.* 2015; Kahn *et al.* 2009). Among the two acidic soil the low P availability in pH 4.4 may also be due to high P-fixation, but in pH 5.5 this was not observed and found to be a favourable pH for superphosphate reactions.

In comparison of two fertilizers, rock phosphate provides better P availability in two acidic soils and super phosphate was superior in pH 5.5 soil. In pH 7.4 soil super phosphate was inferior to rock phosphate even though both were obtained less P than pH 4.4 and pH 5.5. Enhancement of P availability by combined use of water soluble form with insoluble form or with organic forms to increase the efficiency of P fertilizers was reported (Begum *et al*, 2004)

Table 40. Effect of soil pH and base status on the available P with application of rock phosphate in three soils

Soil with different pH	Available P (mg kg^{-1}) Days						Mean
	5	10	15	20	25	30	
4.4	48.8	66.6	60.5	52.9	48.8	30.3	51.3
5.5	49.4	48.3	55.7	113.2	41.6	42.9	58.5
7.4	39.0	27.2	34.2	65.4	27.5	26.3	36.6
Mean	45.7	47.4	50.1	77.1	39.3	33.1	
CD for pH	2.1						
CD for days	3.0						
CD for pH x Days	5.2						

The P availability recorded with super phosphate treatment was lower than the treatment with rock phosphate. This might be due to fixation of P. The high content of Fe and Al in acid soils and Ca in the neutral soil contributed for the fixation of P released from the superphosphate. Among the three soils, the highest availability (Fig.34) was recorded by soil having 5.5 pH on the 20th day and was significantly superior to all other values (Table 41). In pH 4.4 soil, the highest availability was recorded on the 10th day and was on par with the values recorded on the 20th and 25th day. In soil having pH 5.5, the P availability increased and reached the peak on the 20th day and decreased on the 25th day and reduced drastically on the 30th day of incubation. Increase of P availability in the rhizosphere of tea by the dissolution of rock phosphate by the addition of N forms in Australian soils was reported (Zoysa *et al.*, 1998).

Table 41. Effect of soil pH and base status on the available P with application of super phosphate in three soils.

Soil with different pH	Available P (mg kg^{-1}) Days						Mean
	5	0	5	0	5	0	
4.4	29.3	35.1	26.2	34.2	34.3	11.3	28.4
5.5	29.4	55.8	60.5	80.4	71.6	12.3	51.7
7.4	19.0	13.8	14.7	13.4	23.5	16.7	16.8
Mean	25.9	34.9	33.8	42.7	43.1	13.4	
CD for pH	1.6						
CD for days	2.3						
CD for pH x Days	4.0						

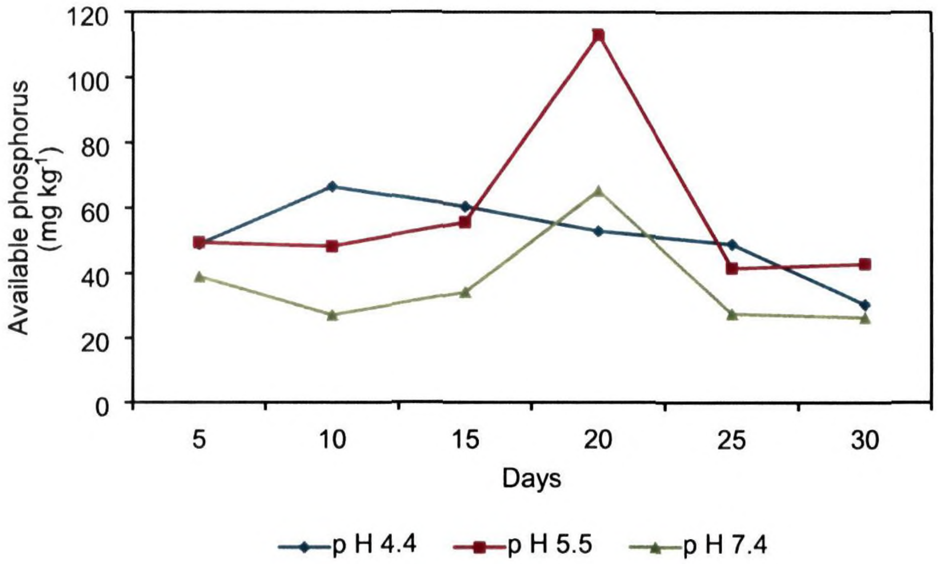

Fig. 33. **Effect of soil pH and base status on the available P with application of rockphosphate in three soils.**

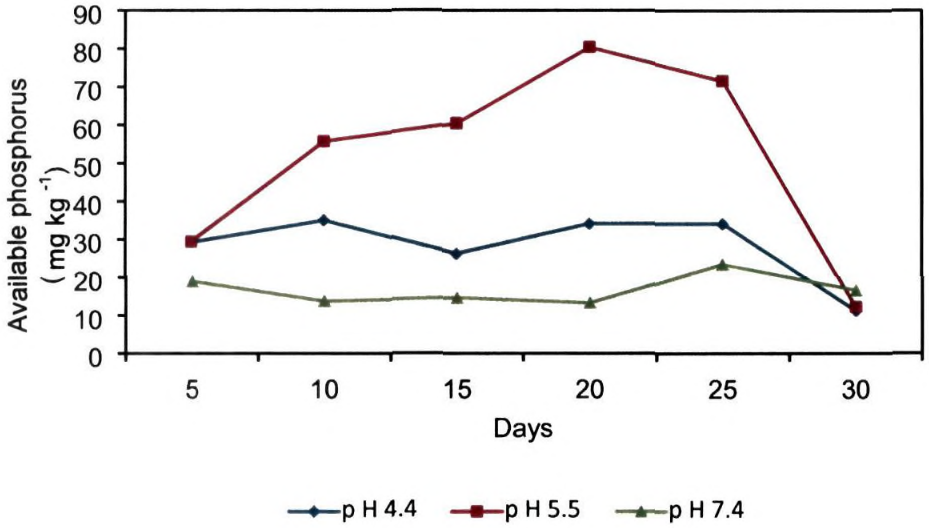

Fig. 34. Effect of soil pH and base status on the available P with application of superphosphate in three soils.

The two experiments on fertilizer changes in three soils indicated that the pattern of fertilizer reaction in three soils were different and the choice of fertilizers in three soils can be done based on the experiments with plant response further.

CHAPTER V

V. SUMMARY AND CONCLUSIONS

Natural rubber cultivation world over is mainly confined to humid tropics and the soils are primarily acid soils. The major constraints for plant growth in acid mineral soils are toxicity of protons, Al and Mn and deficiency of Mg, Ca, P and Mo. The economic life span of the rubber tree is 25-30 years and in majority of the situations, cycle after cycle, rubber is being continuously cultivated in the same land. Being a perennial tree crop the soil plant environment is greatly influenced by the tree root system. In general, the belief is that the rubber plants prefer an acidic soil environment. However, the plant nutrition is influenced by the soil root environment and growth retardation is being reported from the replanting fields. To address the topic on rhizosphere chemistry and adaptations of natural rubber to acidic soil conditions seven experiments under four main headings were conducted in the present study and the summary of the results and the conclusions drawn from the study are reported.

1. Rhizosphere chemistry of nutrient elements of young rubber plants in the main field and adaptations at the rhizosphere

Rhizosphere chemistry of young plants in the main field was studied by comparing the rhizosphere soil with bulk soil for pH, organic carbon, nutrient availability, exchange properties, soil acidity parameters and fractions of P and K.

- The rhizosphere and bulk soil values were significantly different for pH, available P, K, Al-P, Ca-P, cation exchange capacity, exchangeable K and exchangeable Al. The rhizosphere pH was 5.06 and the corresponding bulk soil pH was 4.98 and was significantly different between each other.

Higher pH measurement for rhisosphere indicates rhizosphere alkalinisation. The available P was significantly different between rhizosphere and bulk soil. The values were 142 mg kg^{-1} for rhizosphere and 55 mg kg^{-1} for the bulk soil indicating higher P availability in the rhizosphere. Similarly, K availability was high in rhizosphere soil (137 mg kg^{-1}) compared to the bulk soil (113 mg kg^{-1}).

- Al-P was significantly high in rhizosphere soil compared to the bulk soil. The values were 80 mg kg^{-1} and 41 mg kg^{-1}, respectively for the rhizosphere and bulk soil. Similarly, the Ca-P was significantly high in rhizosphere soil (255 mg kg^{-1}) compared to the bulk soil (148 mg kg^{-1}) indicating higher P availability in the rhizosphere.
- Cation exchange capacity recorded significant difference between rhizosphere and bulk soil. The rhizoshere soil recorded 7.8 cmol(+)kg^{-1} and the corresponding bulk soil recorded the CEC value of 6.5 cmol(+)kg^{-1} soil.
- Exchngeable Al for the rhizosphere soil was 0.73 cmol(+)kg^{-1} and the corresponding bulk soil recorded 1.16 cmol(+)kg^{-1} soil and the rhizosphere and bulk soil values were significantly different.

2. Comparison of growth of young rubber plants in soils having wide variation in pH, exchangeable Al and base status

Growth of young rubber plants were compared in soils having three different pH and base status to understand the pH preference of young rubber plants and its effect on growth. Growth of sprouted seeds, young rubber plants, shoot and root biomass, nutrient concentration and uptake of nutrients at 90 days and 240 days were compared between three soils having wide variation in pH, exchangeable Al and base status. The changes in soil chemical properties with growth of young rubber plants for 90 days and 240 days were also studied.

- Growth of sprouted seeds for thirty days indicated no significant difference with pH variation or exchangeable Al content or base status difference indicating that the extremely acidic condition per se is not affecting the formation of young roots or further growth of sprouted seeds.
- Growth of young rubber plants when monitored for a longer period indicated that the initial growth measured on the 45th day was comparable between three soils. But on the 90th and 240th day, the growth was significantly different between three soils. On the 240th day, the highest growth was recorded in pH 7.4 soil (9.9 cm) followed by soil having pH 5.5 (7.9 cm) and the lowest growth (6.7 cm) by extremely acidic soil (pH 4.4) and the reason can be attributed to the low availability of nutrients associated with extremely acidic soil conditions. Neutral soil with very high base nutrient content recorded highest growth indicating the preference of young rubber plants to a nutrient rich neutral soil.
- Root length was high in neutral soil on the 45th day and afterwards on the 90th and 240th day. Highest root length was recorded by plants grown in strongly acidic soil having the pH of 5.5. Similarly, shoot length was also significantly different during the observations on the 90th and 240th day and the highest values were recorded by plants grown in 5.5 pH soil.

- Significant difference in root, shoot and total biomass was recorded only on the 90th and 240th day of observation and no difference was recorded on the 45th day. Highest shoot biomass was recorded by plants grown in pH 7.4 soil followed by pH 5.5 soil. However, the root biomass was highest in plants grown in soil with pH 5.5 than soil with pH 7.4. Lowest shoot, root and total biomass was recorded by plants grown in extremely acidic soil with pH 4.4.
- Significant difference in the root concentration of Ca (0.28%), K (0.88%) and Mg (0.17%) compared to the plants grown in strongly acidic and neutral soil was recorded on the 90th day and this difference got narrowed down and on the 240th day no significant difference was recoded for N, P, K, Ca and Mg.
- Shoot concentration of N, P, K, Ca, and Mg on the 90th day recorded significant difference between plants grown in three soils with statistically significant high values recorded by plants grown in neutral soil. Calcium concentration of shoot was low in plants grown in extremely acidic soil (0.65%) compared to the plants grown in soil having pH 5.5 (1.79%) and pH 7.4 (1.95%) indicating accumulation of Ca with increased soil Ca availability. Nutrient concentration on the 240th day recorded significant difference for P, K, Ca and Al. Aluminium concentration was very high in plants grown in extremely acidic soil.
- Monitoring the changes in soil properties with growing rubber plants for 240 days indicated that in the extremely acidic soil the soil pH was slightly improved to 4.84 from the initial pH of 4.4 indicating alkalanization as

observed in the first experiment on comparison of rhizosphere and bulk soil properties in the main field. In the pH 5.5 soil the pH change was not significant. In the neutral soil with pH 7.4, the pH was reduced to 6.13 with a significant decrease in available Ca also.

- Changes in soil organic carbon from initial and 240 days compared by FTIR spectrum identification indicated that the stable and labile C in the soil having pH 7.4 was mineralised by the growth of rubber plants recording a concomitant increase in soil organic carbon on the 240th day.

3. Effect of lime application on nutrient availability and growth of young rubber plants

Growth of young plants were poor in the extremely acidic soil and accordingly an incubation experiment was conducted to study the changes in soil pH and nutrient availability with liming in the acidic soils. Also a response study with rubber seedlings to lime application was conducted in extremely acidic soil and the growth of young rubber plants, changes in pH and nutrient availability were documented.

3.1. Comparison of effect of lime application on nutrient availability in extremely acidic and very strongly acidic soil (Incubation experiment under laboratory conditions)

- The extremely acidic soil pH was improved to strongly acidic pH whereas, the soil pH change was not significant in the strongly acidic soil.
- Availability of P and Ca improved in soil having 4.4 pH. However, in soil having the pH of 5.5, improvement in the availability of Ca alone was significantly different between lime treated and no lime treatment.
- Magnesium availability decreased significantly with lime treatment in extremely acidic soil and there was no significant change in strongly acidic soil.

- Lime treatment significantly improved the cation exchange capacity, exchangeable Ca and K and reduced the exchangeable Mg in the extremely acidic soil. Exchangeable Al and exchange acidity were reduced significantly with liming.
- In the strongly acidic soil liming improved the exchangeable K and reduced the exchangeable Al and exchange acidity.

3.2. Effect of lime application on rhizosphere chemistry and growth of young rubber plants grown in extremely acidic soil

- Liming in the extremely acidic soil improved the growth of plants recording significantly higher diameter (5.84 cm) compared to no lime treatment (5.14 cm).
- Concentration of P, Ca, and Cu were improved with lime treatment and Mg concentration significantly reduced with liming.
- Nitrogen and Cu concentration in root were significantly improved with liming and Mg and Zn concentration were significantly reduced.
- pH, SOC, available P, Ca and fractions of P were significantly increased with liming. At the same time, availability of K, K fractions except fixed K and available Mg was reduced significantly with liming indicating the anatagonistic effect of excess supply of Ca on the availability of K and Mg.
- Monitoring the changes in exchange properties of soil with lime treatment and plant growth for 240 days indicated significantly high exchangeable Ca, low

values of exchangeable K and Mg. Similarly reduced exchangeable Al and exchange acidity was recorded.

4. Effect of pH and base status on transformation of fertilizer nitrogen and phosphorus

The transformation of fertilizer N from urea and availability of P with the application of rock phosphate and superphosphate were compared between three soils having different pH, exchangeable Al and base status.

4.1. Effect of pH and base status on mineralization of urea

- Incubation experiment was conducted to compare the ammoniacal and nitrate N status from urea addition among the three soils having distinctly different pH and base status. Ammoniacal and nitrate N status was different between extremely acidic soil and the other two soils having pH 5.5 and 7.4. Similar trend was recorded for nitrate N also.

4.2. Effect of pH and base status on the availability of P from rock phosphate and super phosphate

- Compared the phosphorus availability from rock phosphate and super phosphate addition among the three soils having distinctly different pH and base status. Phosphorous availability was less from both sources of P (rock phosphate and super phosphate) in pH 7.4 soil.

Rhizosphere soil recorded higher available P, exchangeable K, cation exchange capacity, effective cation exchange capacity and low exchangeable Al compared to the bulk soil indicating specific adaptive strategies to improve the exchange properties and availability of P and K and reduce the exchangeable Al status. Highest plant growth was observed in the neutral soil rich in plant nutrients compared to the extremely acidic soil with low availability of nutrients. Improvement in pH in the extremely acidic soil and reduction in pH in the neutral soil indicates rhizosphere modification in pH and associated changes in nutrient availability with growth of rubber plants. Liming improved the growth of plants in the extremely acidic soil and improved the exchange properties of the soil. Nitrogen and P availability with application of fertilizer indicated difference among the three soils and need to be reconfirmed under field condition.

From the present research programme, the evidence of specific rhizosphere chemistry and nutrient adaptation in rubber plants can be observed. Extreme acidity with high exchangeable aluminium was found to be a constraint for growth of rubber seedlings. Better performance of rubber seedlings in pH 5.5 was clear in these studies. High Ca and Mg status can be tolerated by rubber plants with superior growth among three soils. Both field study and seedling study response study confirmed the rhizosphere adaptations for soil pH in rubber plants. In extremely acidic soil alkalization and in neutral soil acidification was found when rubber seedlings were grown for eight months. The FTIR spectrum identification for changes in soil organic carbon, the important soil quality parameter found useful. The difference in the fertilizer reaction in three soil condition is an additional information for rubber soils. Validation of the results in field experiments is required to understand various mechanisms of rhizosphere adaptations in rubber.

REFERENCES

Alva, A. K., Asher, C. J. and Edwards, D.G. (1986). The role of calcium in alleviating Aluminium Toxicity. *Australian Journal of Agricultural Research*, **37**(4): 375-382.

Anderson, A. J., McLean, J. E., Jacobson, A. R and Britt, D. W. (2017). CuO and ZnO Nanoparticles modify interkingdom cell signalling processes relevant to crop production. *Journal of Agricultural and Food Chemistry*, **66**(26): 65136524.

April, R. and Keller, D. (1990). Minerology of the rhizosphere in forest soils of the Estern United States. *Biogeochemistry*, **9**(1): 1-18.

Artz, R.R.E., Chapman, S.J., Robertson, A.H.J., Potts, J.M., Laggoun-Defarge, F., Gogo, S., Comont, L and Disnar, J.R. (2006). FTIR spectroscopy can be used as a screening tool for organic matter quality in regenerating cutover peatlands. *Soil Biology and Biochemistry*, **40**(2): 515-527.

Bagayoko, M., Alvey, S., Newmann, G., Burkert, A. (2000). Root- induced increases in soil pH and nutrient availability to field-grown cereals and legumes on acid sandy soils of Sudano-Sahelian West Africa. *Plant and Soil*, **225** (1&2): 117-127.

Bakker, M. R., Kerisit, R., Verbist, K., and Nys, C. (2000). Effects of liming on rhizosphere chemistry and growth of fine roots and of shoots of sessile oak (*Quercus petraea*). *In the Supporting Roots of Trees and Woody Plants: Form, Function and Physiology* (pp. 405-417). Springer, Dordrecht.

Bakker, M.R., Dieffenbach, A. and Ranger, J. (1999). Soil Solution chemistry in the rhizosphere of roots of Sessile Oak (*Quercus petraea)* as influenced by lime. *Plant and Soil,* **209**(2): 209-216.

Barman, M., Shukla, L. M., Datta S. P. and Rattan, R. M. (2014). Effect of applied lime and Boron on the availability of nutrients in an acid soil. *Journal of Plant Nutrition*, **37**(3): 357-373.

Basri, M.H.A., Junejo, N., Abdu, A. and Kusum, M.A. (2013). Elevation and variability of acidic sandy soils pH: Amended with conditioner, activator, organic and inorganic fertilizers. *African Journal of Agricultural Research,* **8**(29): 4020-4024.

Begg, C.B.M, Kirk G.J.D, Mackenzie, A.F, Neue, H.U. (1994). Root-induced iron oxidation and pH changes in the lowland rice rhizosphere. *New Phytologist* **128**(3): 469-477.

Begum, M., Narayana Swami, G. and Biswas, D. R. (2004). Phosphorus supplying capacity of phosphate rocks as influenced by compaction with water-soluble P-fertilizers. *Nutrient Cycling in Agroecosystems*: **68**(1):73-84.

Bernal, M. P. and Mc Grath S.P. (1994). Effects of pH and heavy metal concentrations in solution culture on the proton release, growth and elemental composition of *Alyssum murale* and *Raphanus sativus* L. *Plant and Soil*, **166**(1): 83-92.

Bio Rad. (1996). FTS 135 WIN-IR foundation manual, *Bio Rad Technical Publication*, 091-0912 A: 128-130

Bird, J. A., Herman, D. J., & Firestone, M. K. (2011). Rhizosphere priming of soil organic matter by bacterial groups in a grassland soil. *Soil Biology and Biochemistry*, **43**(4): 718-725.

Black C. A. (1965). Method of Soil analysis. Part II. American Society of Agronomy, Inc. Publication, Madison, USA, pp-770-790.

Borja, I. and Nilson, P. (2009). Long term effect of liming and fertilization on ectomycorrhizal colonization and tree growth in old Scots pine (*Pinus sylvestris*. L) stands. *Plant and Soil*, **314**(1&2): 109-119.

Borovec, J. (2000). Chemical composition and phosphorus fractionation of sediments in the Bohemian forest lakes. *Silva Gabreta*, **4**: 179-184.

Braun, M., Dieffenbach, A. and Matzner, E. (2001). Soil solution chemistry in the rhizosphere of beech (*Fagus Silvatica L.*) as influenced by ammonium supply. *Journal of Plant Nutrition and Soil Science*, **164**(3): 271-277.

Bravin, M. N., Marti, A. L., Clairotte, M. and Hinsinger, P. (2009). Rhizosphere alkalizsation- a major driver of copper bioavailability over a broad pH range in an acidic copper contaminated soil. *Plant and Soil*, **318**(1&2): 257-268.

Bravin, M. N. Garnier, C. Lenoble, V. Gerard, F. Dudal, Y and Hinsinger, P. (2012). Root induced changes in pH and dissolved organic matter binding capacity affect copper dynamics speciation in the rhizosphere. *Geochimica et Cosmochimica Acta,* **84:** 256-268.

Bray, R.H. and Kurtz, L.T. (1945). Determination of total organic, and available forms of phosphorus in soils. *Soil Science*, **59**(1): 39-46.

Brink, S. C. (2016). Unlocking the secrets of the rhizosphere. *Trends in Plant Science*, **21**(3): 169-170.

Bromfield, S. M., Cumming, R. W., David, D. J. and Williams, C.H. (1983). The assessment of available manganese and aluminium status in acid soils under subterranean clover pastures of various ages. *Australian Journal of Experimental Agriculature,* **23**(1&2): 192-200.

Butchee, K., Arnall, D. B., Sutradhar, A., Godsey, C., Zhang, H. and Penn, C. (2012). Determining critical soil pH for grain Sorghum production. *International Journal of Agronomy*, **6**: 1-6.

Cabeza, R. A., Myint, K., Steingrobe, B., Stritsis, C., Schulze, J. and Claassen, N. (2017). Phophorus fractions depeletion in the rhizosphere of young and adult maize and oil seed rape plants. *Joural of Soil Science and Plant Nutrition*, **17**(3): 824-838

Cabrera, M. L., Kissel, D. E., and Bock, B. R. (1991). Urea hydrolysis in soil: Effects of urea concentration and soil pH. *Soil Biology and Biochemistry*, **23**(12): 1121-1124.

Calba, H. and Jailard, B. (1997). Effect of aluminium on ion uptake and H^+ release by maize. *New Phytologist*, **137**(4): 607-616.

Calvaruso, C., Turpault, M. P. and Frey-Klett, P. (2006). Root-associated bacteria contribute to mineral wealthing and mineral nutrion in trees: a budgeting analysis. *Applied Environmental Microbiology*, **72**(2): 1258-1266.

Calvaruso, C., Mareschal, L., Turpault, M. P., and Leclerc, E. (2009). Rapid clay weathering in the rhizosphere of Norway spruce and oak in an acid forest ecosystem. *Soil Science Society of America Journal*, **73**(1): 331-338.

Calvaruso, C., N'Dira, V., and Turpault, M.P. (2011). Impact of common European tree species and Douglas-fir (*Pseudotsuga menziesii (Mirb*) on the physicochemical properties of the rhizosphere. *Plant and Soil*, **342**(1-2): 469480.

Calvaruso, C. Collignon, C. Kies, A., and Turpault, M. P. (2014). Seasonal evaluaton of the rhizophere effect on major and trace elements in soil solutions on Norway spruce (*Picca abies (Karst).*) and beech (*Fegues syvatica*) in an acidic forest soil. *Open Journal of Soil Science*, **4**(9): 323.

Capriel, P. (1997). Hydrophobicity of organic matter in arable soils: influence of management. *European Journal of Soil Science*, **48**(3): 457-462.

Chang, C. and Jackson, M. L. (1957). Fractionation of soil P. *Soil Science,* **84**: 133-134.

Chen, D., Zhang, Y., Lin, Y., Zhu, W., and Fu, S. (2010). Changes in belowground carbon in Acacia crassicarpa and Eucalyptus urophylla plantations after tree girdling. *Plant and Soil*, **326**(1-2): 123.

Chen, L., Zhang, C., and Duan, W. (2016). Temporal variations in phosphorus fractions and phosphatase activities in rhizosphere and bulk soil during the development of Larix olgensis plantations. *Journal of Plant Nutrition and Soil Science*, **179**(1): 67-77.

Chima, U. D., Akhabue, E. F. and Gidean, I. K. (2016). Rhizosphere soil properties and growth attributes for trees species in a four year arboretum at the University of Port Harcourt, Nigeria. *Nigerian Journal of Agriculture, Food and Enviornaemnt,* **12**(2): 74-80.

Chiu, C. Y., Wang, M. A., Hwong, J. L., and King H. B. (2002). Physical and chemical propertices in the Rhizosphere and bulk soils of Tsuga and Yusihania in a temperate rain forest. *Communications in Soil Science Plant Analysis*, **33**(11-12): 1723-1735

Chung, J. B. and Zasoski, R. J. (1994). Ammonium-Potassium and Ammonium Calcium exchange equilibria in bulk and rhizosphere soil. *Soil Science Society of America Journal*, **58**(5): 1368-1375.

Cocco, S., Agnelli, A., Gobran, G. R., and Corti, G. (2013). Changes induced by the roots of *Erica arborea L.* to create a suitable environment in a soil developed from alkaline and fine-textured marine sediments. *Plant and Soil*, **368**(1-2): 297-313.

Colemann, N. T., Kamprath, E.J., and Weed, S. B. (1958). Liming. *Advances in Agronomy*, **10**: 475-522

Collignon, C., Calvaruso, C., and Turpault, M. P. (2011). Temporal dynamics of exchangeable K, Ca and Mg in acidic bulk soil and rhizosphere under Norway spruce (*Picea abies Karst.*) and beech (*Fagus sylvatica L.*) stands. *Plant and soil*, **349**(1-2): 355-366.

Correia, M. A. R., Maranhao, D.D.D., Flores, R.A., Silva junior, S.F.D., Arsujo, M.A.D and Leite, R.L.D.L. (2017). Growth, nutrition and production of dry matter of rubber tree (*Hevea brasiliensis*) as a function of K fertilization. *Australian Journal of Crop Science*, **11**(1): 95-101.

Cronan, C.S. (1991). Differential adsorption of Al, Ca and Mg by roots of red spruce (*Picea rubens Sarg*) *Tree Physiology*, **8**(3): 227-237.

Curl, E. A., and Truelove, B. (1986). Root exudates. In: *The rhizosphere*, Springer, Berlin, Heidelberg. pp. 55-92.

Curtin, D., Campbell, C. A. and Jalil, A. (1998). Effects of acidity on mineralization: pH-dependence of organic matter mineralization in weakly acidic soils. *Soil Biology and Biochemistry*, **30**(1): 57-64.

Darrah, P. R. (1993). The rhizosphere and plant nutrition: a quantitative approach. *Plant and Soil*, **155**(1): 1-20.

De Graaff M.A., Classen A. T., Castro H. F., Schadt, C. W. (2010). Labile soil carbon inputs mediate the soil microbial community composition and plant residue decomposition rates. *New Phytologist,* **188**(4): 1055–1064.

Dean, H.C. (1986). The effect of liming on the liberation of potassium in some Iowa soils. *Research Bulletin*, **197**: 203.

Degenhardt J., Larsen P. B., Howell S. H. and Kochian L. V. (1998). Aluminum resistance in the Arabidopsis mutantair-104 is caused by an aluminum induced increase in rhizosphere pH. *Plant Physiology*, **117**(1): 19–27.

Dessaux, Y., Grandclement, C., Faure. D (2016). Engineering the rhizosphere. *Trends in Plant Science*, **21**(3): 266-278.

Dessaux, Y., Hinsinger, P. and Lemanceau, P. (2009). Rhizosphere: Achievements and Challenges. Plant and Soil, 321(1): 535-541.

Devau N., Le Cadre, E., Hinsinger, P., Gérard, F. (2010). A mechanistic model for understanding root-induced chemical changes controlling phosphorus availability. *Annals of Botany*, **105**(7): 1183–1197.

Dick, D.P., Santos, H.Z. and Ferranti, E.M. (2003). Chemical characterization and infrared spectroscopy of soil organic matter from two southern Brazilian soils. *Revista Brasileira de Ciencia do Solo*, **27**(1): 29-39.

Dieffenbach, A. and Matzner, E. (2000). In situ soil solution chemistry in the rhizosphere of mature Norway Spruce (*Picea abies [L] krast*) trees. *Plant and Soil,* **155**(156):1-20.

Dinesh, R., Srinivasan, V, Hamza, S, Parthasarathy, V. A. and Aipe, K. C. (2010). Physico-chemical, biochemical and microbial properties of the rhizospheric soils of tree species used as supports for black pepper cultivation in the humid tropics. *Geoderma,* **158**(3&4): 252-258.

Dinkecha, K. and Tsegaye, D. (2017). Effect of liming on physiochemical properties and nutrient availability of acidic soils in Welmera Woreda

Central highlands of Ethiopia. *Biochemistry and Molecular Biology*, **2**(6): 102-109.

Dinkeleker, B., Römheld, V. and Marschner, H. (1989). Citric acid excretion and precipitation of calcium citrate in the rhizosphere of white lupin (*Lupinus albus* L.). *Plant Cell Environment*, **12**: 285–292.

Dotaniya, M. L., and Meena, V. D. (2015). Rhizosphere effect on nutrient availability in soil and its uptake by plants: a review. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, **85**(1): 1-12.

Doyle, M. O. and Otte, M. L. (1997). Organism-induced accumulation of iron, zinc and arsenic in wetland soils. *Environmental Pollution,* **96**(1): 1-11.

Drake, M., Vengris, J, and Colby, W. G. (1951). Cation-exchange capacity of plant roots. *Soil Science,* **72**(2): 139-148.

Du, C and Zhou, J. (2009). Evaluation of soil fertility using infrared spectroscopy: a review. *Environmental Chemistry Letters,* **7**(2): 97-113.

Du, Z. Y., Wang, Q. H., Xing, S J., Liu, F. C., Ma, B. Y., Ma, H. L., and Liu, D. X. (2013). Fine root distribution, characteristics and rhizosphere soil properties in a mixed stand of Robinia pseudoacacia and Fraxinus velutina in a saline soil. *Silva fennica,* **47**(3): 1-14.

Ellerbrock, R. H., Höhn, A. and Gerke, H. H. (1999). Characterization of soil organic matter from a sandy soil in relation to management practice using FTIR spectroscopy. *Plant and Soil*, **213**(1&2): 55-61.

Falkergern- Greup, U., Burnet, J, Diekmaan, M. (1998). Nitrogen mineralization in deciduous forest soil in south Sweden in gradients of soil acidity and deposition. *Environmental Pollution*, **102** (supplement1): 415-420.

Fang, X. M., Zhang, X. L., Zong, Y. Y., Zhang, Y., Wan, S. Z., Bu, W. S. and Chen, F. S. (2017). Soil phosphorus functional fractions and tree tissue nutrient concentrations influenced by stand density in subtropical Chinese fir plantation forests. *PloS one*, **12**(10). https//doi.org/10.13871/journal pone.0186905.

Fenn, L. B., and Assadian, N. (1999). Can rhizosphere chemical changes enhance heavy metal absorption by plants growing in calcareous soil. In *Proceedings of Extended Abstracts of 5th International Conference on the Biogeochemistry of Trace Elements. W.W. Wenzel, D.C. Adriano, B. Alloway, H.E. Doner, C. Keller, N.W. Lepp, M. Mench, R. Naidu, GM Pierzynski (eds.). Vienna, Austria* (pp. 154-155).

Flessa, H and Fischer, W. R. (1992). Plant-induced changes in the redox potentials of rice rhizospheres. *Plant Soil*, **143**(1): 55–60.

Foy, C.D. (1988). Plant adaptation to acid, aluminum toxic soils. *Communication in Soil Scence and Plant Anaysis*, **19**(7&12): 959–987.

Gahoonia, T. S. (1993). Influence of root-induced pH on the solubility of aluminium in the rhizosphere. *Plant and Soil*, **149**(2): 289-291

Gahoonia, T. S. and Nilsen, N. E. (1992). The effects of root-induced pH changes on the depletion of inorganic and organic phosphorus in the rhizosphere. *Plant and soil*, **143**(2): 185-191.

Gardner W.K. Parbery D.G. and Barber D.A.(1982) The acquisition of phosphorus by *Lupinus albus* L. I. Some characterstics of the soil/root interface. *Plant and Soil*, **68:** 19-32.

Gardner, W.K., Barber, D.A. and Parbery, D.G. (1983). The acquisition of phosphorus by *Lupinus albus* L. III. The probable mechanism, by which phosphorus movement in the soil-root interface is enhanced. *Plant and Soil*, **70**(1): 107-114.

George, S.J., Kumar, B.M., Wahid, P.A. and Kamalam, N.V. (1996). Root competition for phosphorus between the tree and herbaceous components of silvopastoral systems in Kerala, India. *Plant and Soil*, **179**(2): 189-196.

George, P. J. and Panikkar, A.O.N.(2000). Rubber Yielding Plants. In: *Natural Rubber: Agromanagement and Crop Processing* (Eds: P. J. George and C. Kuruvilla Jacob). Rubber Research Institute of India, Kottayam, pp: 20-28.

George, P.J. and Jacob, C.K. (2000). *Natural Rubber: Agromanagement and Crop Processing*, Rubber Research Institute of India, Kottayam.648p.

George, T.S., Gregory, P. J., Robinson, J. S., and Buresh, R. J. (2002). Changes in phosphorus concentrations and pH in the rhizosphere of some agroforestry and crop species. *Plant and Soil*, **246**(1): 65-73.

Gerendás, J. and Schurr, U. (1999). Physicochemical aspects of ion relations and pH regulation in plants - a quantitative approach. *Journal of Experimental Botany*, **50**(336): 1101–1114.

Gerke, J., Romer, W. and Jungk, A. (1994). The excretion of citric and malic acid by proteiod roots of *Lupinus albus*. L. Effects of soil solution concentrations of phosphate, iron and aluminium in the proteioied rhizosphere sample of an oxisol and a luvisol. *Journal of Plant Nutrition and Soil Science*, **157**(4): 289-294.

Gobran, G. R. and Clegg, S. (1996). A conceptual model for nutrient availability in the mineral soil-root system. *Canadian Journal of Soil Science*, **76**(2): 125131.

Gracia, C., Roldan, A. and Hernandez, T. (2005). Ability of different plant species to promote microbiological processes in semiarid soil. *Geoderma*, **124**(1&2): 193202.

Grayston, S. J., Vaughan, D., and Jones, D. (1997). Rhizosphere carbon flow in trees, in comparison with annual plants: the importance of root exudation and its impact on microbial activity and nutrient availability. *Applied soil ecology*, **5**(1): 29-56.

Hamza, S., Srinivasan, V. and Dinesh, R. (2013). Management of acid soils under major spice crops. *Indian Journal of Arecanut, Spices and Medicinal Plants*. **15**(3): 3-6.

Hartmann, A., Rothballer, M. and Schmid, M. (2008). Lorenz Hiltner, a pioneer in rhizosphere microbial ecology and soil bacteriology research. *Plant and Soil*, **312**(1&2): 7-14.

Haynes, R. J. (1980). Ion exchange properties of roots and ionic interaction within the root apoplasam: their role in ion accumulation by plants. *The Botanical Rview*, **46**(1): 75-99.

Haynes, R. J. (1990). Active ion uptake and maintanace of cation-anion balance: A critical examination of their role in regulating rhizospere pH. *Plant and Soil* **126**(2): 247-264.

Hermann, D. J., Johnson, K. K. and Jaeger C. H. III, Schwartz E. and Firestone M. K. (2006). Root influence on nitrogen mineralization and nitrification in *Avena barbata* rhizosphere soil. *Soil Biology and Biochemistry*, **70**(5): 1504–1511.

Hiltner, L. (1904). Über neuere Erfahrungen und Probleme auf dem Gebiete der Bodenbakteriologie unter besonderer Berücksichtigung der Gründüngung und Brache. Arbeiten der Deutschen Landwirtschaftlichen Gesellschaft **98**: 59–78.

Hinsinger, P. (2001a). Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant and Soil,* **237**(2): 173-195.

Hinsinger, P. (2001b) Bioavailability of trace elements as related to root-induced chemical changes in the rhizosphere. In: *Trace elements in the rhizosphere.* Chapter 2. (Eds. Gobran, G. R., Wenzel, W. W. and Lombi, E. (2001), CRC press, Boca Raton, Florida. pp. 25-41.

Hinsinger, P, Bengough, A. G., Vetterlein, D. and Young, I. M. (2009) Rhizosphere: biophysics, biogeochemistry and ecological relevance. *Plant and Soil*, **321**(1&2): 117–152.

Hinsinger, P., Plassard, C., Tang, C. X. and Jaillard, B. (2003) Origins of rootmediated pH changes in the rhizosphere and their responses to environmental constraints: a review. *Plant and Soil,* **248**(1&2): 43–59.

Hinsinger, P and Jailland, B. (1993). Root-induced release of interlayer potassium and vermiculitization of phlogopite as related to potassium depletion in the rhizosphere of ryegrass. *Journal of Soil Science*, **44**(3):535-545.

Hinsinger, P. (1998). How do plant roots acquire mineral nutrients? Chemical processes involved in the rhizosphere. *Advances in Agronomy*. **64:** 225–265.

Hinsinger, P., Plassard, C. and Jaillard, B. (2006). Rhizosphere: A new frontier for soil biogeochemistry. *Geochemical Explorations*, **88**(1&3): 210-213.

Huang, Q., Wang, Z., Wang, C., Wang, S., and Jin, X. (2005). Phosphorus release in response to pH variation in the lake sediments with different ratios of ironbound P to calcium-bound P. *Chemical Speciation and Bioavailability*, **17**(2): 55-61.

Irshad, M., Honna, T., Yamamoto, S., Eneji, A.E and Yamasakes, N.(2005). Nitrogen mineralization under saline conditions. *Communications in Soil Science and Plant Analysis*, **36**(11&12): 168-189.

Jackson, M. L. (1958). Soil Chemical analysis. Prentice Hall of India, New Jersey, 498p.

Jacob, J., Joseph, J. and Siju, T. (2018). A road map for attaining self-reliance in natural rubber production in India by 2030. *Rubber Science*, **31**(2): 83-91.

Jilling, A., Keiluweit, M., Contosta, A.R., Frey, S., Schimel, J., Schnecker, J and Grandy, A.S. (2018). Minerals in the rhizosphere: overlooked mediators of soil nitrogen availability to plants and microbes. *Biogeochemistry*, **139(2)**: 103-122.

Jones, D. L., Dennis, P. G., Owen, A.G and Van Hees, P.A.W. (2003). Organic acid behaviour in Soils: misconceptions and knowledge gaps. *Plant and Soil*, **248**(1&2): 31-41.

Jones, D. L., Hodge. and Kuzgakkov, Y. (2004). Plant and mycorrhizal regulation of rhizo deposition. *New phytologist*, **163**: 459-480.

Jones, D.L. (1998). Organic acids in the rhizophere- a critical review. *Plant and soil*, **205**(1): 25-44.

Joseph, M. (2016). Rubber growing soils of India: An overview. *Rubber Science*, **29**(2): 119-139.

Joseph, M. (2012) .Rubber growing soils of South India and response of rubber to liming. Compendium of Abstracts. *Eighth International Symposium on plant –soil Interaction at low pH.* 18-22. October, 2012, Bangalore, India, pp. 254-255

Joseph, M., Syamala, V.K., Punnoose, K. I. (2009). Effect of liming on the availability of nutrients and growth of young rubber. *Natural Rubber Research*, **22**(1&2): 55-63.

Jungk, A. and Claassen, N. (1986). Availability of phosphate and potassium as the result of interaction between root and soil in the rhizosphere. *Zeitschriftfur. Pflabnzenemahrung und Bodenkunde*. **149**(4): 411-427.

Jungk, A. Seeling, B. and Gerke, J. (1993). Mobilization of different phosphate fractions in the rhizosphere, *Plant and Soil,* **155/156**: 91-94.

Jungk, A. (1991). Dynamics of nutrient movement at the soil-root interface. In: *Plant Roots: The Hidden Half* (Eds. Y. Waisel A. Eshel U. Kafkafi), New York, NY: Marcel Dekker, pp. 455-481.

Jungk, A. (2001). Root hairs and acquisition of plant nutrients from soil. *Journal of Plant Nutrition and Soil Science*, **164**(2): 121-129.

Kahn, A. A., Jilani, G., Akhter, M.S., Naqvi, S.M.S. and Rasheed, M. (2009). Phosphorus solubilizing bacteria: occurance, mechanism and their role in crop production. *Journal of Agricultural Biological sciences*, **1**(1):48-58.

Kamprath, E. J. (1970). Exchangeable aluminium as criterion for liming leached mineral soil. *Soil Science Society of America Proceedings*, **24**: 252-254.

Karthikakuttyamma, M., Joseph, M and Nair, A.N.S. (2000). Soils and Nutrition. In: *Natural Rubber: Agromanagement and Crop Processing* (Eds: P. J. George and C. Kuruvilla Jacob). Rubber Research Institute of India, Kottayam. pp: 170-198.

Kidd, P. S. and Proctor, J. (2000). Effects of aluminium on the growth and mineral composition of *Betula pendula* Roth. *Journal of Experimental Botany*, **51**(347): 1057-1066.

Kiflu, A., Beyene, S and Jeff, S. (2017). Fractionation and availability of phosphorous in acid soils of Hagereselam, Southern Ethiopia under different rates of lime. *Chemical and Biological Tecnologies in Agriculture,* **4**(1): 1-7

Kirk, G.J.D. and Levan Du. (1997). Changes in rice root architecture, porosity and oxygen and proton release under phosphorus deficiency. *New Phytologist*, **135**(2): 191-200.

Kirlew, P. W. and Bouldon, D.R. (1987). Chemical properties in the rhizosphere in an acid sub soil. *Soil Science Society of America Journal*, **51**(1): 128-132.

Kochian, L.V., Hoekenga, O. A. and Pineros, M.A. (2004). How do crop plants tolerate acid soils? Mechanisms of aluminum tolerance and phosphorous efficiency. *Annual Review of Plant Biology,* **55**: 459-493.

Kreutzer, K. (1995). Effects of forest liming on soil processes. *Plant and Soil*, **168169**: 447-470.

Krishnan, B. (2015). Growth assessment of popular clones of natural rubber (*Hevea brasiliensis*) under warm, dry climatic conditions of Chhattisgarh state, Central India. *Journal of Experimental Biology and Agricultural Science*, **3**(2): 157-161.

Krishnan, P., Venugopal, K.R. and Sehgal, J (1996). *Soils of Kerala: their kinds, distribution, characterization and interpretations for optimising land use.* NBSS Publication 48, Soils of India Series. *National Bureau of Soil Survey and Land Use Planning*, Nagpur, India. 60p.

Kuchenbuch, R. and Jungk, A. (1982). A method for determining concentration profiles at the soil-root interface by thin slicing of rhizosphere soil. *Plant and Soil*, **68**(3): 391-394.

Lambers, H., Mougel, C. and Jaillard, B. (2009). Plant-microbe-soil interactions in the rhizosphere: an evolutionary perspective. *Plant and Soil*, **321**(1&2): 83-115.

Le Bot J., Alloush, G.A., Kirkby, E.A. and Sanders, F. E. (1990). Mineral nutrition of chickpea plants supplied with NO_3^- N or NH_4-N. II. Ionic balance in relation to phosphorus stress. *Journal of Plant Nutrition*, **13**(12): 1591-1605.

Lindsay, W. L.(1979). *Chemical Equilibria in Soils*. John Wiley and Sons, New York, 449p.

Little, D.A., Welch, S. A. and Field, J.B. (2004). The life and times of tree roots: preliminary results for root mediated weathering in the rhizosphere. In: *Regolith*, **2004**: 1-20.

Liu, R., Xiao N., Wei, S., Zhao, L. and An, J. (2014). Rhizosphere effects of PAH contaminated soil phytoremediation using a special plant named Fire Phoenix. *Science of the total environment*, **473**: 350-358.

Lombi, E, Wenzel, W.W., Gobran, G.R. and Adirano, D.C. (2001). Depedency of phytoavailability of metals on indigenous and induced-rhizosphere processes: a review. In: *Trace Element in the Rhizosphere* (Eds. G. R. Gobran, W. W. Wenzel and E. Lombi). CRC Press, Boca Raton, pp. 3-24

Lynch, J.M. and Whipps, J.M. (1990). Substrate flow in the rhizosphere. *Plant and Soil*, **129**(1): 1-10.

Magdoff, F. and Bartlett, R.J. (1980). Effect of liming acid soils on potassium availability. *Soil Science*, **129** (1): 12-14.

Maier, N.A., McLaughlin, M.J., Heap, M., Butt, M and Smart, M.K. (2002). Effect of current season application of calcite lime and phosphorus fertilization on soil pH, potato growth, yield, dry matter content and cadmium concentration. *Communication in Soil Science and Plant Analysis*, **33**(13&14): 2145-2165.

Malavolta E. (2006). *Manual of mineral plant nutrition.* Sao Paulo: Editora Agronomicaceres Ltd, 631p.

Mansell, G. P., Pringle, R.M., Edmeades, D.C. and Shannon, P.W.(1984). Effect of lime on pasture production on soils in the North Island of New Zealand. 3. Interaction of lime with phosphorus. *New Zealand Journal of Agricultural of Agricultural Research*, **27**(3): 363-369

Marcet, P. Sr., Souto, J. C., Gonzalez, S., and Baamonde, D. (2006). Influence of different tree species on the chemical properties in rhizosphere and bulk soils. In: *Proceedings of the 18th World Congress of Soil Science.* July, 5-9, Philadelphia, PA,. pp. 9-15.

Marshner, H., Hussilng, M. and George, E. (1991). Ammonium and nitrate uptake rates and rhizosphere pH in non-mycorrhizal roots of Norway spurce (*Picea Abies* L.) [*Karst*].) *Trees*, **5**(1):14-21.

Marshner, H, Kirkby, E.A. and Cakmak, I. (1996). Effect of mineral nutritional status on shoot-root partitioning of photoassimilates and cycling of mineral nutrients. *Journal of Experimental Botany*, **47**: 1255-1263.

Marshner, H., Romheld, V. and Kissel, M. (1986). Different strategies in higher plants in mobilization and uptake of iron. *Journal of Plant Nutrition*, **9**(3&7): 695713.

Marshner, H. (1995a). Rhizosphere pH effects on phosphorus nutrition. In: (Eds. Johansen C, Lee K K, Sharma K K, Subbaro G V, Kueneman E A.) Genetic Manipulation of Crop Plants to Enhance Integrated Nutrient Management in Cropping System. I. Phosphorus. Proceedings of an FAO/ICRISAT Expert Consultary Workshop, ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) Asia Center, India. Patancheru, Andhra Pradesh, India. pp. 107-115.

Marshner H. (1998). Soil-root interface: Biological and biochemical processes. *Soil Chemistry and Ecosystem Health,* 52: 191-231.

Marshner, H. (1991). Mechanisms of adaptation of plants to acid soils. *Plant and Soil*, **134**(1): 1-20.

Marshner, H., Romheld, V. and Kissel. M. (1987). Localization of phytosiderophore release and of iron uptake along intact barley roots. *Physiological Plantarum*, **71**(2): 157-162.

Marshner, H. and Romheld, V. (1994). Strategies of plants for acquisition of iron. *Plant and Soil*, **165**: 261-274.

Marshner, H., Romheld, V., Horst, W.J. and Martin, P. (1986). Root induced changes in the rhizosphere: Importance for the mineral nutrition of plants. *Zeitschriftfur Pflanzenernahrung und Bodenkunde*, **149(4):** 441-456.

Marshner, H. (1995). *Mineral Nutrtion of Higher Plants, Ed.2.* Academic Press, London, 889p.

Marshner, P., Solaiman, Z., Rengel, Z. (2006). Rhizosphere properties of Poaceae genotypes under P-limiting conditions. *Plant and Soil*, **283**(**1-2**): 11-24

Marshner P, Crowley, D.E, Higashi, R.M. (1997). Root exudation and physiological status of a root-colonizing fluorescent pseudomonad in mycorrhizal and non-mycorrhizal pepper (*capsicum annuum* L.). *Plant and Soil*, **189**(1): 11-20.

Marshner, P., Fu, Q. and Rengel, Z. (2003). Manganese availability and microbial populations in the rhizosphere of wheat genotypes differing in tolerance to Mn deficiency. *Journal of Plant Nutrition and Soil Science*, **166**(6), 712-718.

Massaccesi, L., Benucci. G., Gigliotti, G.M.N., Cocco, S., Corti, G and Agnelli, A. (2015). Rhizosphere effect of three plant species of environment under periglacial conditions (Majella Massif, Central Italy). *Soil Biology and Biotechnology*, **89**: 184-195.

McNear Jr, D. H. (2013). The rhizosphere – Roots, soil and everything in between. *Nature Education* Knowledge, **4**(3): 1.

Mc Lean, A. J. (1956). Influence of addition of lime to soils on the availability of potassium and other cations for Alfalfa. *Canadian Journal of Agricultural Sciences,* **36** (3): 213-220.

Mc Lean, E. O. (1965). Aluminium. In: *Methods of soil Analysis. Part II.* Chemicaland Microbiological Properties (Ed.C.A.Black *et al.*,).American Society of Agronomy, Madison, Wisconsin, USA, pp. 978-998.

Mehta, P., Walia, A., Kulshrestha, S., Chauhan, A. and Shirkot, C.K. (2015). Efficiency of plant growth -promoting P-solubilizing *Bacillus Circulans* CB7 for enhancement of tomato growth under nethouse conditions. *Journal of Basic Microbiology*, **55**(1): 33-44.

Michaud, A.M, Bravin, M.N, Galleguillos, M. and. Hisinger, P. (2007). Copper uptake and phytotoxicity as assessed in situ for durum wheat (*Triticum turgidum durum* L.) cultivated in Cu-contaminated, former vineyard soils. *Plant and Soil*, **298**: 99-111.

Murfy J. and Riley J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta,* **27:** 31-36.

Myers, J.A., McLean, E.O. and Bigham, J.M. (1988). Reductions in exchangeable magnesium with liming acid Ohio soils. *Soil Science Society of America Journal*, **52**(1): 131-136.

Naik, D. Smith, E. and Cumming, J. R. (2009). Rhizosphere carbon deposition, oxidative stress and nutritional changes in two poplar species exposed to aluminium. *Tree Physiology*, **29**(3): 423-436.

NBSS and LUP (1999). *Resource Soil Survey and Mapping of Rubber Growing Soils of Kerala and Tamil Nadu*: National Bureau of Soil Survey and Land Use Planning, ICAR, Nagpur, 295p.

Neumann G. and Maasonneau, E., Langlade, N., Dinkellaker, B., Hengeler, C., Romeheld, C. and. Mardinoia, E. (2000). Physiological aspects of cluster root function and development in phosphorus-deficient white lupin (*Lupinus albus* L.) *Annals of Botany*, **85:** 909-919.

Neumann, G., Massonneau, A., Martinoia, E. and Romheld, V. (1999). Physiological adaptations to phosphorus deficiency during proteoid root development in white lupin. *Planta*, **208:** 373-382.

Neumann, G. and Romheld, V. (2002). Root induced changes in the availability of nutrients in the rhizosphere. In: *Plant roots, The hidden half.* (Eds. Y. Waisel, A. Eshel and U. Kafkafi). Ed3, Marcel Dekker, Inc, New York, pp 617-649.

Neumann, G. and Romheld, V. (2000). The release of root exudates as affected by the plant's physiological status. In: *The Rhizophere: Biochemistry and organic substance in the soil- plant interface* (Eds. R. Pinton, Z, Varanini and P. Nannipieri). Marcel Dekker, New York, NY, USA, pp. 41-93.

Niebes, J. F., Dufey, J. E., Jaillard, B., and Hinsinger, P. (1993). Release of non-exchangeable potassium from different size fractions of two highly Kfertilized soils in the rhizosphere of rape (*Brassica napus cv Drakkar*). *Plant and Soil*, **155**(1): 403-406.

Nowtony, I., Dahne, J., Klingelhofer, D. and Rothe, G.M. (1998). Effects of artificial soil acidification and liming on growth and nutrient status of mycorrhizal roots of Norway Spruce (*Picea abies* [L]. Krast). *Plant and Soil*, **199**(1): 29-40.

Noodin, W.D. (2017). Rubber plantation: soil management and nutritional requirements. Serdang: University Putra, Malasian Press, Serdang, pp. 90-111

Ohwaki, Y. and Sugahara, K. (1997). Active extrution of protons and exudation of carboxylic acid in response to iron deficiency by roots of chick pea (*Cicer arietinum* L.). *Plant and Soil*, **189**(1): 49-55.

Onthong, J. and Osaki, M. (2006). Adaptations of tropical plants to acid soils. *Tropics*, **15**(4): 337-347.

Orwin K. H., Buckland S. M., Johnson D., Turner B. L., Smart S., Oakley S. and Bardgett, R. D. (2010) Linkages of plant traits to soil properties and the functioning of temperate grassland. *Journal of Ecology*, **98**: 1074–1083

Paardekooper, E. C. (1989). Exploitation of the rubber tree. In *Rubber* (Eds. C.C. Webster, C.C and W.J. Baulkwill). Longman Scientific and Technical. England. pp. 349-414.

Page, A. L., Miller, R.H. and Keeney, D.R. (1982). *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*. American Society of Agronomy, Soil Science Society of America, Madison, Wisconsin, USA, pp. 159-165.

Pan, W.L., Hopkins A. G and Jackson W.A. (1989). Aluminium inhibition of shoot lateral branches of *Glycine max* and reversal by exogeneous cytokinin. *Plant and Soil,* **120**(1): 1-9.

Pandey, A. and Palni, L.M.S. (2007). The rhizosphere effect in trees of the Indian Central Himalaya with special reference to altitude. *Applied Ecology and Environmental Research*, **5**(1): 93-102

Pang, P. C., Hedlin, R. A. and Cho, C. M. (1973). Transformation and movement of band-applied urea, ammonium sulphate and ammonium hydroxide during incubation in several Manitoba soils. *Canadian Journal of Soil Science*. **53**(3): 331-341.

Pattanayak, S.K. and Sarkar, A.K. (2016). Sustainable management of acid soilstechnologies and their transfer. *Indian Journal of Fertilisers,* **12**(7): 16-24 & 35.

Perrott, K.M. and Mansell, G.P. (1989). Effect of fertilizer phosphorous and liming on inorganic and organic soil phosphorous fractions. *New Zealand Journal of Agricultural Research*, **32**(1): 63-70.

Phillips, R. P. and Fahey, T. J. (2006). Tree species and mycorrhizal associations influence the magnitude of rhizosphere effect. *Ecology*, **87**(5): 1302-1313.

Piper C. S. (1966), Soil and Plant analysis, Bomby, India: Hans publishers. Bombay. Hans, India. 368p.

Prashar. P., Kapoor, N. and Sachdeva. S. (2014). Rhizosphere: its structure, bacterial diversity and significance. *Review in Environmental Science and Biotechnology*, **13**: 63-77.

Priha, O. and Smolander, A. (2003). Short term uptake of $^{15}NH_4^+$ into soil microbes and seedlings of pine, spruce and birch in potted soils. Biology and fertility of Soils, **37**(5): 324-327.

Quin, B. F., Condron, L.M., Rickard, D.S and Goh, K. M. (1984). Changes in soil organic phosphorous following liming. *Proceedings of a workshop on lime in Agriculture.* MAF Workshop, Ruakura. pp: 43-46.

Rahmanian, M., Hosseinpour, A.R and Manouchehri, N. (2016). Effec of chemical and natural chelators on zinc fractionation in the rhizosphere of maize (Hybrid (KSC. 704) in a sandy contaminated soil. *In proceedings of the IRES 26th International conference*, Paris, France, 30th January, 2016, ISBN: 978-9385973-07-9.

Raynal, D. J., Joslin, J. D., Thornton, F.C., Schaedle, M and Henderson, G.S. (1990). Sensitivity of tree seedlings to aluminium: III. Red spruce and loblolly pine. *Journal of Environment Quality*, **19**(2): 18-187.

Rengel, Z. (2002). Genetic control of root exudation. *Plant and Soil*, 245(**1**): 59-70.

Richardson, A. E., Barea, J. M., McNeill, A. M and Prigent-Combaret, C. (2009). Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms, *Plant and Soil*, **321**(1&2): 305-339.

Richardson, A.E. (1994). Soil microorganisms and phosphorus availability. In: *Soil Biota: Management in sustanable Farming System* (Eds. C.E. Pankhurst B.M. Doube V.V.S.R. Gupta and P.R.Grace). CSIRO, Australia. pp. 50-62.

Riley, D. and Barber, S.A. (1969). Bicarbonate accumulation and pH changes at the soybean (*Glycine max* (L) Merr.) root-soil interface. Soil Science America Journal, **33**(6): 905-908.

Riley, D. and Barber, S. A. (1971). Effect of ammonium and nitrate fertilization on phosphorus uptake as related to root-induced pH changes at the root soil interface. *Soil Science Society of America Journal*, **35**(2): 301-306.

Robinson G. W. (1922). A new method for the mechanical analysis of soils and other dispersions. *The joural of Agricultural Science*, 12(3): 306-321.

Rodrigo, V.H.L., Iqbal, S.M.M. and Dharmakeerthi, R.S. (2011). Potential for rubber (*Hevea brasiliensis* Muell Arg) Cultivation in the Eastern province of Sri Lanka. *Journal of National Science Foundation of Sri Lanka*, 39(4): 403- 411.

Romheld, V. (1987). Different strategies for iron acquisition in higher plants. *Physiologia Plantarum*, **70**(2): 231-234.

Ruan, J., zhang, F and Wang, M.H. (2000). Effects of nitrogen form and phosphorus source on growth, nutrient uptake and rhizosphere property of *Camellia sinensis* L. *Plant and Soil*, **223**(1&2): 65-73.

Rufty, T.W., MacKown, C.T., Lazof, D. B. and Carter, T.E. (1995). Effects of aluminium on nitrate uptake and assimilation. *Plant, Cell and Environment*, **18**(11): 325-1331.

Ryan, P.R., Delhaize, E. and Randall, P.J. (1995). Characterization of Al- stimulated malate efflux from the root apices of Al-tolerant genotypes of wheat. *Planta*, **196**: 103110.

Ryan, R. P., Ditomaso, M. J and Kochian, V. L. (1993). Aluminium toxicity in roots: An investigation of spacial sensitivity and the role of the root cap. *Journal of Experimental Botany*, **44**(2): 437-446.

Sadana, U.S., Lata, K. and Claassen, N. (2002). Manganese efficiency of wheat cultivars as related to root growth and internal manganese requirement. *Journal of Plant Nutrition*, **25**(12): 2677-2688

Sarkar, A.K., Mahapatra, P. and Kumar, A. (2007). Management of macronutrients in acid soils. In: *Nutrient management in acid soils* (Ed. R.K.Rattan). *Bulletin of the Indian Society of Soil Science*, **25:**10-26.

Sarker, A., Kashem, M.A. and Osman, K.T (2014). Phosphorous availability, uptake and dry matter yield of Indian Spinach (*Basella alba* L.) to lime and phosphorous fertilization in an acidic soil. *Open Journal of Soil Science*. **4**(1): 42-46.

Saunders, W.H.M. (1958). Effect of phosphate top dressing on a soil from Andesitic volcanic ash: II. Effect on distribution of phosphorus and on related chemical properties. *New Zealand Journal of Agricultural Research*, **2**(3): 445- 462

Saunders, W.H.M. and Williams, E.G. (1955). Observations on the determination of total organic phosphorus in soils. *Journal of Soil Science*, **6**(2): 254-267.

Schottelndreier. M. and Grerup, F. U. (1999). Plant induced alteration in the rhizosphere and the utilization of soil heterogeneity. *Plant and Soil*, **209**(2): 297-309.

Seguin, V. Gagnon, C. and Courchesne, F. (2004). Changes in water extractable metals, pH and organic carbon Concentrations at the soil-root interface of forested soils. *Plants and Soil*, **260**(1&2): 1-17.

Sethuraj, M. R. and George, M. J. (1980). Tapping. In: *Handbook of Natural Rubber Production in India* (Ed. P.N.R. Pillai), Rubber Research Institute of India, Rubber Board, Kottayam, India, pp. 209-229.

Sethuraj, M.R. (1985). Physiology, growth and yield in *Hevea brasiliensis*: In: *Proceedings of the International Rubber Conference* (Eds. Rajarao, J.C. and Amin, L.L.). 21-25 October 1985, Kula Lumpur, Malaysia, pp. 3-20.

Shamshuddin, J. and Fauziah, C. I. (2010). Ferilizer requirement and management. Weathered tropical soils: The Ultisols and Oxisols. *Universiti Putra Malaysia Press*, pp. 9-13.

Sharaf, J. M., Noordin, W. D., Zulkefly, S., Shamshuddin, J. and Hanafi, M. M. (2017). Soil chemical properties and growth performance of *Hevea brasiliensis* through basalt application. *Proceedings of International Rubber Conference,* 18-22 October, Cleveland, Ohio, USA, pp.308-320.

Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W. and Zhang, F. (2011). Phosphorus dynamics: from soil to plant. *Plant Physiology*, **156**(3): 997-1004

Shi, S., Callaghan, M.O., Jones, E.E., Richardson, A.E., Walter, C., Stewart, A, Condron, L. (2012). Investigation of organic anions in tree root exudates and rhizosphere microbial communities using in situ and destructive sampling techniques. *Plant and Soil*, **359**(1&2): 149-163.

Shortle, W. C. and Smith, K. T. (1988). Aluminium induced calcium deficiency syndrome in declining red spruce. *Science,* **240**(4855): 1017-1018.

Shuman, L. M. (1977). Adsorption of Zn by Fe and Al hydrous oxides as influenced by aging and pH. *Soil Science Society of America Journal*, **41**(4): 703-706.

Smith, S.E., Facelli, E., Pope, S. and Smith, F.A. (2010) Plant performance in stressful environments: interpreting new and established knowledge of the roles of arbuscular mycorrhizas. *Plant and Soil*, **326**(1&2): 3-20.

Smith, F.W. (2001). Plant responses to nutritional stresses. In: *Molecular analysis of plant adaptations to the environment* (Eds. M.J. Hawkesford and P. Buchner), Sprinkler, Kluwer Academic Publishers, Dardrecht. pp: 249-269.

Snedecor, G.W. and Cochran, W.G. (1967). *Statistical Methods*, Sixth Edition, Oxford and IBH Publishing, New Delhi, 465p.

Soil Survey Manual (1993). *Selected chemical properties.* Soil Conservation Service, U.S. Department of Agriculture, Handbook 18. Chapter 3. Retrieved 2011-03-12.

Song, Y., Zhu, C., Raza, W., Wang, D., Huang, Q., Guo, S., Ling, N and Shen, Q. (2016). of the chemical niche and microbiome in the rhizosphere:

implications from watermelon grafting. *Frontiers of Agricultural Science and Engineering*, **33** (3): 249-262

Soong, J.L., Calderon, F.J., Betzen, J. and Soong, J. L., Calderón, F. J., Betzen, J., and Cotrufo, M. F. (2014). Quantification and FTIR characterization of dissolved organic carbon and total dissolved nitrogen leached from litter: a comparison of methods across litter types. *Plant and Soil*, **385**(1&2): 125-137

Spaccini, R., Piccolo, A., Haberhauer, G., Stemmer, M. and Grezabek, M.H. (2001). Decomposition of maize starw in three European Soils as revealed by DRIFT spectra of soil particle fractions. *Geoderma,* **99**(3-4): 245- 260.

Staaf, H., Persson, T and Bertills, U. (1996). In : Skogmarkskalking. Resultat och slutsatser fran Naturvardsverkets forsoksverksamhet. In: *Skogmarkskalkining* (Eds. H. Staaf., T. Persson and U. Bertills). *Naturvardsverkets rapport* 4559. Tryck Gotab, Stockholm, p. 290.

Stevanus, C. T., Hidayati, U., Wijaya, T. and Cahyo, A. (2017). Study of rubber growth under constraint of pyrite in muara sugihan Tidal Swampy area, *Journal of Wetlands Environmental Management*, **5**(2): 1-5.

Subbiah, B.V. and Asija, G.L. (1956). A rapid procedure for the estimation of available nitrogen in soils. *Current Science*, **25**(8): 259-260.

Sumner, M. E., Farina, P.M. W., Hurst, V.J. (1978). Magnesium fixation- a possible cause of negative yield responses to lime applications. *Communications in Soil Science and Plant Analysis*, **9**(10): 995-1007.

Suresh, P.R., Karthikakuttyamma, M., Punnoose, K.I. and Madhusoodhanan, P.K. (1996). Effect of lime and phosphogypsum on controlling exchangeable Al concentration in acid soils. *Proceedings of the eighth Kerala Science Cogress*, January 1996, Kochi, Kerala, India, pp. 218-219.

Syamala, V. K. (2006). *Characterization of acidity and its management in rubber growing soils.* Ph. D Thesis, Mahatma Gandhi University, Kottayam, India.106p.

Syamala, V.K. and Joseph, M. (2012). Forms of aluminium in the acid soils of South India under rubber cultivation. *Eighth International Symposium on plant – soil Interaction at low pH.* 18-22, October 2012, Bengaluru, India, *Abstracts*, pp. 226-227.

Syamala, V.K., Joseph, M and Punnoose, K. I. (2003). Effect of liming on soil properties and growth of young rubber seedlings. *Indian Journal of Natural Rubber Research*, **16** (1&2): 66-74.

Thankarajan, R., Bolan, N.S., Naidu, R. and Surapaneni, A. (2015). Effects of temperature and amendments on nitrogen mineralization in selected Australian Soils. Environmen Science Pollution Research, 22(12): 8843-8854. Doi:10.1007/s 11356-013-2191-y.

Tempeton, J.K. (1968). Growth studies in *Hevea brasiliensis.* L. Growth analysis up to seven years after budgrafting. *Journal of the Rubber Research Institute of Malaysia*, **20**(3): 136-146.

Tinti, A., Tugnoli, V., Bonora, S and Francioso, O. (2015). Recent applications of vibrational mid- infrared (IR) spectroscopy for studying soil components: a review. *Journal of Central European Agriculture*, 16(1): 1-22.

Toberman, H., Chen, C. and Xu, Z. (2011). Rhizosphere effects on soil nutrient dynamics and microbial activity in an Australian tropical lowland rain forest. *Soil Research*, **49**(7): 652-660.

Tuason, M.M.S and Arocena, J. M. (2018). Root organic acid exudates and properties of rhizosphere soils of white spruce (*Picea glauca*) and subalpine fir (*Abies lasiocarpa*). *Canadian Journal of Soil Science*, **89**(3): 287-300.

Turpault, M. P., Righi, D. and Literano, C. (2008). Clay minerals: Precise markers of the spatial and temporal variability of the biogeochemical soil environment. *Geoderma*, **147**(3&4): 490-496.

Ulaganathan, A., Satisha, G. C., Karthikakuttyamma, M., Ambily, K.K. and Nair, A.N.S. (2005). Phosphorus fractions and fixation of added phosphorus in rubber growing soils of Kerala. *Rubber Science*, **18**(1): 31-37.

Verhege, W. (2010). Growth and Production of rubber. In: *Land Use, Land Cover and Soil Sciences. Encyclopedia of Life Support Systems* (Ed. W. Verheye), UNESCO-EOLSS, Publishers, Oxford, UK.

Walkley, A. and Black, I. A. (1934). An examination of digestion method for determining organic matter and a proposed modification of the chromic acid titration method. *Soil Science*, **37**(1): 29-38.

Wang, X. P. and Zabowski, D. (1998). Nutrent composition of Douglas-Fir rhizosphere and bulk soil solutions. *Plant and soil*, **200**(1): 13-20.

Wang, Z.Y., Goottlein, A. and Bartonek, G. (2001). Effects of growing roots of Norway spruce (*Picea abies* (L.) [Karst] and European beech (*Fagus sylvartica* L.) on rhizosphere soil solution chemistry. *Journal of Plant Nutrition and Soil Science*, 164: 35-41

Watanabe, T. and Osaki, M. (2002). Mechanisms of adaptation to high aluminium condition in native plant species growing in acid soil: a review. *Communications in Soil Science and Plant Analysis*, **33**((7&8): 1247-1260.

Watson, C. (1987). Factors affecting the efficiency of Urea for pot - grown ryegrass. *The Journal of Agricultural Science*, 109(3): 611-614.

Wear, J.I. and Sommer, A.L. (1948). Acid extractable zinc of soils in relation to the occurance of zinc deficiency symptoms of corn: a method of analysis. *Soil Science Society of America Journal*, **12**(c): 143-148

Whitney, D.A. (1988). Micronutrient soil tests for zinc, iron, manganese and copper. In: *Recommended chemical soil test proceedures for the north central region* (Ed. W.C. Dahuke.). North Dakota. Agricultural Experiment Station. Bulletin, Review, 499: 20-22

Yanai, R. D., Majdi, H., and Park, B. B. (2003). Measured and modelled differences in nutrient concentrations between rhizosphere and bulk soil in a Norway spruce stand. *Plant and Soil*, **257**(1): 133-142.

Youssef, R. A. and Chino, M. (1989). Root- induced changes in the rhizosphere of plants. II. Distribution of heavy metals across the rhizosphere soils. *Soil Science and Plant Nutrition*, **35**(4): 609-621.

Youssef, R. A. and Chino, M. (1987). Studies on the behaviour of nutrients in the rhizosphere: I. Establishment of a new rhizobox system to study nutrient status in the rhizosphere. *Journal of Plant Nutrition*, **10**(9-16): 1185-1195.

Yuossef, R.A. and Chino, M. (1988). Development of a new rhizobox system to study the nutrient status in the rhizosphere. *Soil Science and Plant Nutrition* **34**(3): 461-465.

Zak, D. R., Holmes, W. E., White, D. C., Peacock, A. D., and Tilman, D. (2003). Plant diversity, soil microbial communities, and ecosystem function: are there any links? *Ecology*, **84**(8): 2042-2050.

Zhang, F., Shen, J., Zhang, J., Zuo, Y. Li, L., Chen, X. (2010). Rhizosphere processes and management for improving nutrient use efficiency and crop productivity: Implications for China. *Advances in Agronomy*. 107: 1-32

Zhang J. L., George, E. (2009). Rhizosphere effect on ion concentration near different root zone of Norway spruce (*Picea abies* (L.) [Karst] and root types of Douglas- fir (*Pseudotsuga menziesii* L.) seedlings. *Plant and Soil*, **322**(1&2): 209-218.

Zhang, J. and George, E. (2002). Changes in the extractability of cations (Ca, Mg and K) in the rhizosphere soil of Norway spruce (*Picea abies*) roots. *Plant and Soil*, **243** (2): 209-217.

Zhao, F.J., Rooney, C.P., Zhang, H. and McGrath, S.P. (2006). Comparison of soil solution speciation and diffusive gradients in thin-films measurement as an indicator of copper bioavailability to plants. *Envrionmental Toxicology and Chemistry*, **25**(3): 733-742.

Zhao, Q., Zeng, D.H and Fan, Z.P. (2010). Nitrogen and phosphorus transformations in the rhizospheres of three tree species in a nutrient-poor sandy soil. *Applied Soil Ecology*, **46**(3): 341-346.

Zhiyong, L., Panfeng, D., Yanhui, W., Tao, L., Ashley, W.A., Yihao, W., Zhenhua, L., Kou, Z., Shi,T.G and Bingchao, Z. (2016). Effects of liming on health and growth of young *schima superba* trees under canopy of a *Pinus massoniana* stand damaged by soil acidification in Chongqing, China. *New Forests*, **47**(6): 801-813

Zoysa, A. K. N., Loganathan, P and Hedley, M. J. (1998). Effect of forms of nitrogen supply on mobilization of phosphorus from a phosphate rock and acidification in the rhizosphere of tea. *Australian Journal of Soil Research*, **36**(3): 373-387.

PUBLICATIONS

I. Papers in Research Journals

Ambily, K. K. and Joseph, M. (2018). Effect of soil pH and base status on the growth of young natural rubber plants. *Rubber Science*, 31(3): 232-242.

II. Presentation in Conference/Symposia/Seminars

1. Ambily, K. K. and Joseph, M. (2017). Effect of pH on the growth of natural rubber plants. Paper presented at the 82nd Annual Convention of the Indian Society of Soil Sciences and National Seminar on Developments in Soil Science, 11-14, December 2017, Calcutta, India.

2. Ambily, K. K. and Joseph, M. (2017). Liming for improving the nutrient availability and growth of rubber seedlings in the extremely acidic soil under rubber cultivation in South India. Paper presented at the 30th Kerala Science Congress, 28-30, January, 2018, Thalassery, Kerala, India.

3. Ambily, K.K and Joseph, M (2018). Rhizosphere adaptations of natural rubber (*Hevea brasiliensis*) plants for pH and nutrient availability. Abstracts of the International Rubber Conference, IRRDB Annual meeting, 22-26 October 2018, Cote d'Ivoire.

4. Ambily, K.K and Joseph, M. (2019). Rhizosphere adaptations of natural rubber (*Hevea brasiliensis)* plants for pH and nutrient availability. Abstracts of the 23rd Plantation Crops Symposium, 6-8 March 2019, Chikmangaluru, Karnataka, India.