SOIL CHARACTERISATION OF RUBBER ECOSYSTEMS WITH SPECIAL REFERENCE TO SOIL ORGANIC MATTER

THESIS

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By
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DEDICATED TO MY PARENTS

DECLARATION

I, ANNIE PHILIP hereby declare that the thesis entitled **"Soil characterisation of Rubber** .ubber **ecosystems with special reference to soil organic matter"** is a bonafide record of the research work carried out by me at Rubber Research Institute of India, Kottayam under the supervision of Dr. Joshua Abraham, Senior Scientist, Agronomy/Soils Division, RRII. I further declare that the thesis has not been previously formed the basis for the award of any degree, diploma or fellowship.

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CERTIFICATE

This is to certify that the thesis entitled **"Soil characterisation of Rubber ecosystems with special reference to soil organic matter"** is an authentic record of research work carried out by Smt. Annie Philip, Senior Scientist, Agronomy/Soils Division , RRII, Kottayam under my supervision and guidance in partial fulfilment of the requirements for the award of the degree of **Doctor of Philosophy** in Chemistry under the Faculty of Science of the Mahatma Gandhi University, Kottayam. The work presented in this thesis has not been submitted for any other degree or diploma earlier.

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ABSTRACT

Soil quality or health, is important in determining the agricultural sustainability. Soil quality is mainly governed by soil organic matter (SOM). The quantity and quality of SOM may vary in arable systems depending on the crops and management practices. The present investigation was carried out to characterize soil properties and to quantify different SOM pools in the major land use patterns in rubber plantation in three locations where rubber cultivation is concentrated.

Leaf litter of *Hevea brasiliensis* (rubber), *Mucuna bracteata* and *Pueraria phaseoloides* being the major organic matter inputs in rubber growing soils, were chemically characterized and their decomposition was studied through litter bag technique. The study revealed that the three litter species *viz.*, *Hevea*, *Pueraria* and *Mucuna* varied in quality, decomposition process and nutrient release. Among the three species studied, *Pueraria* litter having more cellulose and less lignin and polyphenols decomposed at a higher rate whereas rubber litter having more lignin and polyphenols decomposed at a lower rate. The rate of release of N, P, K, Ca and Mg from the three litter species also varied and it could be seen that the release of nutrients were higher from the *Pueraria* litter followed by *Mucuna* and *Hevea*.

During the early stages (immature phase) of rubber plantation, intercropping with banana or pineapple or cover cropping with *Mucuna* or *Pueraria* is the common practice. Soils under mature as well as immature rubber systems were examined for soil quality at three locations *viz.*, Amayannoor, Mundakayam and Erumely in Kerala. The four systems studied at Amayannoor were mature rubber, rubber-*Pueraria,* rubber-banana and rubber-pineapple. At Mundakayam

mature rubber, rubber-*Mucuna,* rubber-banana and rubber-pineapple systems were examined. Mature rubber, rubber-*Pueraria* and rubber-*Mucuna* systems were studied at Erumely.

Soil parameters studied were physical (bulk density, particle density, porosity and water stable aggregates) and chemical (OC, TN, CEC, available nutrients and pH) properties and labile carbon fractions in surface soil of these systems. Spectroscopic characterization of soil organic matter was also carried out. It was observed that different vegetation and management practices in rubber plantation had influenced the soil properties and organic matter quantity and quality. At location Amayannoor, soils under rubber-*Pueraria* and rubber–banana systems showed better physical properties (porosity and water stable aggregates) compared to the other two systems. Organic carbon and labile pools of SOM, water soluble carbon (WSC) and hot water extractable carbon (HWEC) were also significantly higher in rubber-*Pueraria* and rubber-banana systems than the other two systems. At location Mundakayam, porosity and water stable aggregates were higher in rubber-banana and rubber-*Mucuna* systems. Even though OC status was significantly higher, in rubber-*Mucuna* system, labile carbon pools (HWEC and POSC) were comparable with that of other systems at Mundakayam. Here also rubber-banana system showed significantly higher WSC compared to other systems. At both locations rubber-banana system was less acidic than other systems. Even though carbon status was higher in mature rubber at Erumely, WSC and HWEC were more in rubber-*Pueraria* system compared to other two systems. Mature rubber and rubber-*Pueraria* systems were comparable in water stable aggregates at this location.

In all the three locations, irrespective of the system, carbon content increased with decrease in soil particle size. It was observed that more than 70% of the total soil carbon was associated with the smallest size fraction, *viz.*, silt-clay sized fraction which has very little

contribution to short-term plant nutrition. UV-Vis and FTIR spectroscopic characterizations indicated more humification in mature rubber system compared to the immature systems at all locations. Spectroscopic characterizations also showed better SOM quality- more carbohydrates and polyssacharides and less aromaticity- in rubber–*Pueraria* system than the other systems in the immature phase, both at Amayannoor and Erumely. At Mundakayam, rubber- banana system showed better SOM quality compared to rubber-pineapple and rubber–*Mucuna* systems. The relatively much higher contents of labile C pool can contribute significantly towards nutrient release, especially in the growing phase of rubber.

Incubation study conducted to understand the carbon mineralization in different rubber based systems indicated that SOM decomposition was influenced by organic matter quality. The rate of carbon mineralization of the various systems at Amayannoor, was in the order rubber–*Pueraria* > rubber–banana = rubber- pineapple > mature rubber. Since carbon mineralization was highly correlated with WSC, HWEC, POSC and carbon content in macro sized fraction these labile C fractions can be used as soil quality indices in rubber growing soils.

The study revealed that during the growing phase of rubber, *Pueraria* is more beneficial in improving soil quality than *Mucuna* as a cover crop. Banana is a better intercrop than pineapple in improving soil quality in rubber based system. Pineapple cultivation in rubber system had adversely affected the soil quality. The SOM under mature rubber system had undergone more condensation and may remain in the system for longer periods which would be environmentally beneficial.

Key words: Carbon mineralization, Characterization, Litter, Rubber based systems, Soil organic matter, Soil quality.

PREFACE

Soil organic matter (SOM) is a critical component of the soil-plant ecosystem and has been considered as a key indicator of soil quality. The quantity and quality of SOM may vary in arable systems depending on the crops and management practices.

Most of the rubber plantations in Kerala are at the end of the second or in third cycle. The rubber growing soils are highly weathered and declining in SOM content. Though the SOM decline is reported, detailed investigation on SOM quality or on different SOM pools is lacking, necessitating a study to characterize soil properties and different SOM pools in major land use patterns in rubber cultivation in three locations where rubber cultivation is concentrated.

The details of the study conducted along with data generated and conclusions arrived have been presented in five chapters. The first chapter introduces the topic and describes the main objectives of the study. A review of different aspects of the study is presented in the second chapter. The experimental details and methodology followed in the study are explained in third chapter. In fourth chapter the results obtained and discussion of the results are presented. Summary and conclusions are given in fifth chapter, while the bibliography of references cited in the study are included at the end of this thesis.

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Abbreviations

Al^{+3}	Aluminium ion
ANOVA	Analysis of variance
et al.,	And others
$BaCl_2$	Barium chloride
Ca	Calcium
C	Carbon
CO_2	Carbon dioxide
CEC	Cation exchange capacity
$cmol(+)kg^{-1}$	Centimol per kilogram
Cu	Copper
CD	Critical difference
^0C	Degree centigrade
FTIR	Fourier transform infra red
g	Gram
$g\ kg^{-1}$	Gram per kilogram
HWEC	Hot water extractable carbon
HCl	Hydrochloric acid
Fe	Iron
kg	Kilogram
Mg	Magnesium
Mn	Manganese
$Mg\ m^{-3}$	Mega gram per cubic meter
mM	Milli molar

Continued….

Abbreviations

mg	Milligram
N	Nitrogen
NS	Non significant
OC	Organic carbon
POC	Particulate organic carbon
POM	Particulate organic matter
%	Per cent
POSC	Permanganate oxidisable soil carbon
P	Phosphorus
K	Potassium
KBr	Potassium bromide
$NaHCO_3$	Sodium bicarbonate
NaOH	Sodium hydroxide
SOM	Soil organic matter
SE	standard error
TN	Total nitrogen
UV-Vis	Ultra violet- visible
viz.,	Namely
WSC	Water soluble carbon
WSA	Water stable aggregate
Zn	Zinc

INTRODUCTION

Chapter 1

INTRODUCTION

1.1. Soil - the natural resource

Soil forms the skin of unconsolidated mineral and organic matter on the earths' surface and maintains the ecosystem upon which all life activities depend. Soil is a dynamic living resource whose condition is vital in crop productivity. Sustainability of life on earth is totally dependent on soil.

1.2. Soil quality and soil health

The quality and health of soil determine the agricultural sustainability and environmental quality and as a consequence, plant, animal and human health. In a broader perspective, soil quality or health can be defined as the capacity of a soil to perform its functions, as a vital living system, within the ecosystem and land use boundaries that determines sustained biological productivity, maintenance of the quality of air and water and promotion of plant, animal and human health. Soil health is commonly used to describe those aspects of soil quality that reflects the conditions of soil as expressed by management sensitive operations (Islam and Weil, 2000). The concept of soil quality refers to the suitability and capability of a soil to perform specific ecosystem functions (Doran and Parkin, 1994; Bezdicek *et al.*, 1996; Karlen *et al.*, 1997; Karlen *et al.*, 2001). In an agriculture ecosystem the major ecosystem processes mediated through soil can be grouped into four fundamental, though somewhat overlapping functions *viz.*, 1) promotion of plant growth; 2) biogeochemical .cycling of elements especially carbon and mineral nutrient elements; 3) provision of habitat for soil organisms; and 4) partitioning, storage, translocation and decontamination of water (Weil and Magdoff, 2004). The only soil component which directly or indirectly influences all these soil functions is soil organic matter (SOM).

1.3. Agriculture and soil health

The health of soil is changing over time, due to human use and management. The vertical rise in population demands for more food and fiber, which has led to intense farming activities in the past few decades. Worldwide, concern for sustainable global development and preservation of soil resources is reflected in the theme of numerous international conferences (Janzen *et al.*, 1992; Doran *et al.*, 1994; Doran and Zeiss, 2000). Cultivation is disturbing the natural system, which may bring changes in soil properties. Proper management of the soil resources is of extreme importance in sustaining crop and land productivity. Also monitoring the changes in soil properties is essential for proper assessment of the impact of cultivation on soil properties and to evolve suitable agro-ecological management policies.

1.4. Soil organic matter (SOM)

SOM is a component that regulates the physical, chemical and biological properties of a soil which in turn largely determines the soil fertility, agricultural productivity and sustainability. It consists of a mixture of plant and animal residues at various stages of decomposition, of substances synthesized chemically and biologically from the break down products and of microorganisms and small animals and their decomposing remains. The precise structure or composition of SOM is not well understood. SOM comprises hundreds of organic compounds that are chemically and structurally different. These compounds vary in quantity in different soils under various crops and management practices. As the extent of influence of these different compounds on soil physical, chemical or biological properties can differ, soils with varying SOM composition may function differently. SOM is probably the most complex and least understood soil component (Weil and Magdoff, 2004). It is difficult and cumbersome to isolate each and every organic compound in soil and to study their specific influence on various soil properties. However, several pools of organic compounds are defined by their turnover rates and availability to microbial processes.

1.5. Soil organic matter pools

To sustain the health of agricultural lands, it is essential to properly manage SOM in arable soils. Conventionally, humus has been equated with inherent soil fertility and can be efficiently extracted from mineral soils in alkali. The resulting humic or fulvic acid fractions of SOM had been extensively studied. However, recent developments in organic matter research had proved that these fractions are 'procedural artifacts' existing only in laboratory and have not proven to be useful guides to adaptive management or contribute significantly in understanding the SOM dynamics or soil quality (Wander, 2004). However, upon renewed interest in soil organic matter research in the past few decades, many had come out with measurable SOM fractions that impart fundamental characteristics to soil (Wander, 2004). SOM can be broadly categorized to labile and recalcitrant pools depending on their decomposition or turnover rates (Six *et al.*, 2002). Labile fraction mainly consists of easily oxidizable components such as carbohydrates, sugars, cellulose *etc.*, which are palatable to microbes whereas lignin and tannin type materials fall under the recalcitrant group, which are resistant to decay. Labile or active pool of SOM is reported to be responsible for building soil aggregate structure, micronutrient chelation and nutrient mineralization and is very sensitive to changes in management practices or cultural operations (Tisdall and Oades, 1982; Gunapala and Scow, 1998; Blair and Crocker, 2000). According to Loveland and Webb (2003), active fraction or labile pool of SOM is more important factor in controlling changes in soil properties than the total SOM. In contrast, the passive pool, with half-life period measured in centuries, is composed of recalcitrant compounds that are resistant to decay and tends to accumulate in soil over time (Weil and Magdoff, 2004).

1.6. SOM – Significance of labile pool

Knowledge about the nature and turnover of SOM is a prerequisite for understanding the structure, chemical reactivity and inherent fertility of soils and for predicting the fate of mineral fertilizers, animal manures and crop residues added to the soil. SOM is highly sensitive and susceptible to changes depending on the land use pattern and associated management practices (Wander, 2004). Changes in total organic matter content in response to changes in land use or soil management practices that occur over relatively short periods are difficult to detect because of high background carbon content and natural soil variability (Haynes and Beare, 1996). Identifying and quantifying the suitable indicators that are sensitive enough to reflect the changes in SOM quality and quantity is very important to develop suitable nutrient management strategies for a sustainable nutrient management system. The labile fractions of organic matter such as particulate organic matter, soluble organic matter or microbial biomass can respond more quickly to land use or soil management changes and are suggested as early indicators of SOM changes (Gregorich *et al.*, 1994).

It has been reported that higher quantity of organic matter need not necessarily maintain or increase crop yield (Ladha *et al.*, 2003). According to Brinson *et al.*, (1998) the nutrient availability in a system is more influenced by the size of the labile or active SOM fraction rather than the total quantity of SOM. Parton and Rasmussen (1994) also reported that the labile component of SOM plays the most important role in the short-term turnover of nutrients.

1.7. Plant litter and crop residues as SOM sources

Major sources of organic matter in natural as well as many of the cultivated soil systems such as that of plantation crops are plant litter and crop residues (Chadwick *et al.*, 1998; Fioretto *et al.*, 2001; Santa Regina and Tarazona, 2001; Kogel-Knabner, 2002). The decomposition and nutrient release patterns of organic materials are determined by the resource quality, decomposing organisms and environmental conditions (Berg *et al.*, 2000). Since litter quality influences the decomposition process of soil organic matter, the quality of SOM vary in different land use systems (Giller and Cadisch, 1997; Pankhurst *et al.*, 1997; Krull *et al.*, 2003).

1.8. SOM quality and decomposition

Chan *et al.*, (2001) observed that different organic carbon fractions vary in their decomposition pattern. Mineralization of soil organic matter has a key role in the availability of nutrients. With changes in the quality and quantity of SOM, the potential of a soil to supply or sequester carbon and nutrients is altered through changes in mineralization–immobilization rates (Janssen and Persson, 1982). Decomposition of organic matter in a soil is mainly governed by soil microbes. However, the decomposition rate varies with the quality and physical availability of substrate, which are the energy sources to soil microbes (Raich and Tulekcioglu, 2000). Thus the organic matter decomposition or organic carbon mineralization pattern may vary with the land use type and soil management. Understanding the decomposition kinetics of soil organic matter under different land use systems or management practices can provide useful information on the carbon stabilization potential of the systems as well.

1.9. Rubber based land use systems

Rubber (*Hevea brasiliensis*), the prime source of natural rubber, has been commercially cultivated in India since, 1902. Major portion of the rubber area in India is confined to the west coast of the country extending from Kanyakumari district of Tamilnadu in the south to Coorg district of Karnataka in the north. Most of the rubber plantations in the traditional rubber growing tract in India are now in the second or third planting cycle (Krishnakumar and Potty, 1992; Karthikakuttyamma, 1997) and majority of these are to be replanted again. Because of the tropical climate of the traditional belt with heavy rainfall and high temperature, the soil in these regions are highly weathered and mostly laterite and lateritic types. In general, organic carbon (OC) content of traditional rubber growing soils is medium to high (NBSS & LUP, 1999). However, a decline in OC status occurs with replanting (Karthikakuttyamma *et al.*, 2000).

The rubber tree, a native of the Amazon river basin has a defoliation cycle by which large quantities of litter is added to the soil. In mature rubber plantation about 5 t $ha^{-1}year^{-1}$ of litter is added through annual leaf fall (Philip *et al.*, 2003) which is the main source of organic matter.

Establishment of leguminous cover crop in immature phase of rubber is a recommended and commonly followed agro-management practice. The leguminous cover crops, *Pueraria phaseoloides* or *Mucuna bracteata* is usually established in the immature rubber fields. Huge turnover of organic matter (5 to 7 t ha^{-1}) additions are reported from these cover crops (Kothandaraman *et al.*, 1989; Philip *et al.*, 2005).

Since rubber has a long gestation period of about seven years, intercropping with banana or pineapple is also a common practice in the initial years of immature phase of rubber. The quantity and quality of crop residues generated and incorporated in these systems are different and since the plant residues are the primary source of SOM, the relative size and composition of SOM pools in these rubber based systems may vary. The management practices such as tillage operation, fertilizer and organic matter input etc., are also different in these rubber based systems which may also contribute to varying organic matter composition and soil quality.

Objectives

Though many reports are available on the effect of cover crop and intercrop on soil properties in rubber growing soils, information on litter quality, labile fractions of organic carbon and soil carbon mineralization in different rubber based systems is limited. Hence the present investigation was carried out with the following objectives;

1. To determine the quality and decomposition pattern of the three major litter species *viz.*, *Hevea*, *Pueraria* and *Mucuna* in rubber plantations
2. To characterize soil organic matter and soil properties in different rubber based systems and
3. To study the carbon mineralization in soils under different rubber based systems

REVIEW OF LITERATURE

Chapter 2

REVIEW OF LITERATURE

This review aims to provide a comprehensive assessment of the current state of knowledge of the soil quality assessment. The changes in soil quality associated with management operations are also described. The rationale for separating SOM into discrete organic pools by particle size separation is also discussed. Also it is highlighted that total SOC is often not a good indicator for assessing soil quality. The relevance of studying these pools separately and in conjunction with a specific function to understand the key impacts of a SOC pool are reported based on recent publications.

2.1. Soil quality indicators

Soil quality indicator is a soil physical, chemical or biological property that is sensitive to disturbance and represents performance of an ecosystem function in the soil under investigation. Indicators are not static, but dynamic soil properties. As soil functions cannot be directly measured, soil quality indicators are used to evaluate different functional properties (Doran and Parkin, 1996). Three major group of indicators *viz.*, physical, chemical and biological are often determined to assess soil quality. Chemical indicators represent nutrient cycling, water relations and buffering properties while physical indicators are related to physical stability and support, water relations and habitat and biological indicators mainly point to biodiversity and nutrient cycling (NRCS, 2011). Widely used chemical indicators are pH, total nitrogen (TN) etc. and physical indicators are water holding capacity, aggregation stability, porosity etc., and biological indicators are particulate organic carbon (POC), organic carbon (OC), soil respiration and minerlizable N.

2.2. Soil organic carbon (SOC)

The most widely accepted and followed indicator of soil quality is SOM (Gregorich *et al.*, 1994; Wander and Drinkwater, 2000). Since SOM has no precise chemical composition, the dominant elemental constituent of SOM, soil organic carbon (SOC), is more commonly measured and reported in scientific literature. Small changes in SOC resulting from changes in soil management are often difficult to measure, but can have pronounced effects on soil behavior and microbial processes (Weil *et al.*, 2003). Measurable differences in SOC may occur only on continuous cultivation for decades (Sikora *et al.*, 1996). The soil type, climate, management, mineral composition, topography, soil biota and the interactions between each of these are modifying factors that will affect SOC content. Any changes made to the natural status of the soil systems such as conversion of forest to agriculture or plantation will result in different conditions under which SOC enters and exits the system (Baldock and Skjemstad, 1999). Thus in rubber plantation system, different land use types exist and changes in SOM as well as SOC status is expected which may change the functional behavior of these soil systems.

It has been widely reported that SOC plays a key role in soil physical, chemical and biological properties of soil. SOM is the source of energy for microbes and is essentially regulating whole of the biological processes in soil and acts as the reservoir of nutrients such as N, P and S. Stabilization of soil structure, buffering the pH changes and controlling microbial activity are properties influenced by SOC. These properties and SOC and total nitrogen (TN) are considered as critical indicators for soil health and quality assessment (Lal, 1993). Considering wide variety of performance indicators, Karlen *et al.*, (2003) and Norfleet *et al.*, (2003) pointed out that soil quality needs to be assessed with regard to what the soil is used for, as a particular soil may be of high quality for one function and may perform poorly for another. Reeves (1997) also reported that SOC is a good soil quality indicator. Elliott (1997) indicated that SOM was a key indicator of soil health but further suggested that particulate organic matter (POM) could be used as an indirect measure of soil health because of its short turnover time. Swift and Woomer (1993) regarded POM as the 'organic fertilizer' property of SOM.

2.3. Sources of SOM

Plant residues are the primary source of organic matter in soil. Its composition influences the nature of SOM. The organic compounds in plant tissue consist of sugars, starches, proteins, cellulose, hemicellulose, fats, waxes, polyphenols and lignin. Carbohydrates, which range in complexity from simple sugars and starches to cellulose are the main organic component (50%) of plant tissue. They are comparatively faster in decomposition. Lignin, a component of cell wall, is a complex compound consisting of hundreds of interlinked phenolic ring units. Lignin and polyphenols are highly resistant to decomposition. Seed and leaf coatings contain fats, waxes and oils, which are more complex than carbohydrates but less than lignins. Animals are secondary sources of organic matter. As they eat the original plant tissues, they contribute waste products, and they leave their own bodies when they die. Earthworms, termites, ants, and dung beetles also play an important role in the incorporation and translocation of organic residues. The decomposition of plant litter is the primary mechanism by which organic matter and nutrients are returned to the soil. The decomposition of organic materials is influenced by the resource quality, decomposing organisms and environmental conditions (Berg *et al.*, 1993). Chemical composition of plant litter is species specific. Carbon to Nitrogen ratio was considered as a general index of plant litter quality as early as 1920's (Waksman, 1924; Waksman and Tenney, 1928). However, in the last few decades, many papers have questioned its reliability to predict C and N mineralization in soil (Herman *et al.*, 1977; Heal *et al.*, 1997). The different carbon compounds present in litter are varying in nature and structure, and cannot be treated as a single entity – total-C, especially when their interactions with decomposer organisms widely differ. For example, decomposition rate is positively correlated with polysaccharides, hemicelluloses and pectin (Swift *et al.*, 1979) while negatively correlated with lignins and tannins in litter (Hammel, 1997; Dighton, 1978; Rayner and Boddy, 1988; Slapokas and Granhall, 1991). The carbon content of plant residues ranges from 40 to 58% while nitrogen content varies from 1 to 6% (Brady and Weil, 1999). As the quality and quantity of organic matter source in cultivated or natural systems are different, their rate of decomposition can also be different, which in turn will reflect subsequently on nutrient release.

2.4. SOM- physical fractionation

Particle size fractionation is based on the concept that SOM fractions associated with particles of different size (and therefore also of different mineralogical composition) differ in structure and function and therefore play different roles in SOM turnover. Particle size fractionation allows the separation of soil organic matter according to its origin and degree of transformation. Organic matter of recent plant origin is believed to be preferentially recovered in the sand-size fraction (2.00 – 0.053 mm) whereas more microbially processed material can be found in the silt and clay-size (< 0.053 mm) fractions (Cheshire and Mundie, 1981). The coarser fraction can be further partitioned to macro size (2.00 – 0.25 mm) and micro size (0.250 – 0.053 mm) fractions.

The lability of SOM is the ease and speed with which it is decomposed by microbes and depends on both chemical recalcitrance and physical protection from microbes. The association of SOM with clay and silt particles is a dominant mechanism of physical protection from decomposition. The chemically linked SOM particles on the clay minerals are seldom attacked by microbes and remains in the soil for longer periods. Chemical recalcitrance is conferred by higher molecular weight, irregular structure and/or aromatic structures (Krull *et al.,* 2003). In addition to exchangeable cations, the passive pool (< 0.053 mm) contains nutrients that are tightly locked into complex organic-mineral assemblages (Stevenson, 1986). Gregorich *et al.*, (1994) reported that more than 75% of SOM exists as compounds that are only slowly decomposable and the remainder is readily decomposable compounds. Particle size fractionation showed that the C to N ratio declines with decreasing particle size and that SOM in the sand or coarser fractions consist of relatively unaltered planting material. Jagadamma and Lal, 2010 also have reported that physical fractionation of soil is a useful approach to quantify functional pools of SOM. Saha *et al.*, (2010) reported more carbon storage in the < 0.053 mm fraction under tropical tree based land-use systems.

The relative size of the various SOM pools is determined by the nature of vegetation, soil, environmental factors and agricultural practices (Anderson *et al.*, 1974; Lal and Khang, 1982). The amount of organic carbon in a particular soil is a function of the balance between the rate of deposition of plant residues in or on soil and the rate of mineralization of the residue C by soil biota (Baldock and Nelson, 2000). Particle size fractionation is based on the observation that carbon in the sand fraction is generally more labile than C in silt and clay size fractions (Tiessen and Stewart, 1983). The labile pool is composed of relatively recent plant residues, root exudates and the microbial biomass (Tisdall and Oades, 1982).

The quantities of labile pools are sensitive to land management, especially agriculture. The soil organic carbon and its fractions are good indicators of soil quality and environmental stability. The labile or active fraction of soil organic matter consists of materials with relatively high C to N ratios (about 15-30) and short half-lives. This fraction includes the living biomass, some of the fine particulate detritus (coarse and fine POM) and most of the polysaccharides.

The sand sized fraction (2.00-0.25 mm) is also referred as active fraction since, it provides most of the readily accessible food for the soil organisms and mineralizable nitrogen. It is responsible for most of the beneficial effects on structural stability that lead to enhanced infiltration of water. The active fraction accounts for 10-20% of the organic matter in good agricultural soils. The silt-clay sized fraction (< 0.053 mm) which is also referred as passive fraction of soil organic matter consists of various stable materials remaining in the soil for hundreds or even thousands of years. This fraction includes most of the humus physically protected in clay-humus complexes, most of the humin and much of the humic acids. The passive fraction is most closely associated with the colloidal properties of soil humus, and it is responsible for most of the CEC and water-holding property of soil. The medium sized fraction (0.250–0.053 mm) referred also as the slow fraction of soil organic matter is intermediate in properties between the active and passive fraction. The half-lives of such materials are in decades. The slow fraction is an important source of mineralisable nitrogen and other plant nutrients, and it provides the food source for the microbes.

Particulate organic carbon, microbial biomass carbon, dissolved organic carbon, hot water extractable carbon and permanganate oxidisable carbon have been recognized as good indicators of labile soil organic carbon pools (Cambardella and Elliot,1992; Blair *et al.*, 1995; Haynes and Beare, 1996; Ghani *et al.*, 2003).

Separation of SOC into different sized pools can be useful in identifying and understanding differences in structure, function and bioavailability. More POM in soil indicates that carbon and other nutrients are stored in the intermediately available pool and not subjected to losses and available upon demand (NRCS, 2011). Certain management practices such as no-till, cover crops and organic manure additions enhances the POM content in soil (Carter *et al*, 2003; Fronning *et al.*, 2008). There are many laboratory methods reported for estimation of POM, of which the method suggested by Cambardella and Elliot (1992) is widely followed.

2.5. Carbon Mineralization – Soil respiration

When organic compounds decompose aerobically, carbon dioxide (CO_2) is released. The CO_2 released from the soil surface is referred as soil respiration. Mostly the CO_2 released from soil surface results from the aerobic microbial decomposition of soil organic matter (SOM) to obtain energy for their growth and functioning (microbial respiration). Plant roots and faunal respiration, may also contribute to the CO_2 efflux from soil. Soil respiration or measure of soil CO_2 efflux is one measure of biological activity and decomposition. During the decomposition of SOM, organic nutrients contained in organic matter (eg. organic phosphorus, nitrogen, and sulfur) are converted to inorganic forms that are available for plant uptake. This conversion is known as mineralization. Soil respiration reflects the capacity of a soil to support soil life including crops, soil animals, and microorganisms. It describes the level of microbial activity, SOM content and its decomposition. Soil respiration can be used to estimate soil microbial biomass and make some inference about nutrient cycling in the soil. Soil respiration also provides an indication of the soil's ability to sustain plant growth (Parkin *et al.*, 1996).

Tillage often results in excessive respiration and SOM decomposition as the destruction of soil aggregates takes place and physically protected SOM becomes exposed to microbial attack. Tillage also increases soil aeration, which enhances carbon mineralization. Soil respiration may lower when SOM decline takes place, especially when the soluble and labile fractions decline. Reduced soil respiration rates indicate that there is little or no SOM or aerobic microbial activity in the soil. Apart from resource quality, physical factors such as soil temperature, moisture, aeration and available N also influence SOM decomposition or soil respiration. A reduction in soil respiration indicates lower nutrient turn over in soil. Also there are reports that soil respiration under favorable temperature and moisture conditions is generally limited by the supply of SOM. Certain agricultural practices such as conservation tillage, organic manure addition, incorporation of crop residues and cover crops usually enhance soil respiration (Parkin *et al.*, 1996; NRCS, 2011). Mineralizable C can provide an assessment of soil organic matter changes induced by tillage or other management practices (Carter and Rennie, 1982).

2.6. Aggregate stability

Soil aggregates are groups of soil particles that bind to each other more strongly than to adjacent particles. Disruptive forces associated with tillage or wind or water erosion are resisted by strong aggregation in soil. The wet aggregate stability suggests, how well a soil can resist raindrop impact and water erosion, while size distribution of dry aggregates can be used to predict resistance to abrasion and wind erosion. Changes in aggregate stability may serve as early indicators of recovery or degradation of soils. Aggregate stability is also reported to be an indicator of organic matter content, biological activity, and nutrient cycling in soil (NRCS, 2011). Generally, the particles in small aggregates (< 0.25 mm) are bound by older and more stable forms of organic matter. Microbial decomposition of fresh organic matter releases products (that are less stable) that bind small aggregates into large aggregates (> 2-5 mm). These large aggregates are more sensitive to management effects on organic matter, serving as a better indicator of changes in soil quality. Greater amounts of stable aggregates suggest better soil quality. When the proportion of large to small aggregates increases, soil quality generally increases. Stable aggregates also increases pore space which favors easy water and air movement and enhances nutrient availability and root penetration. Management operations such as tillage, removal of organic matter sources such as crop residues etc., may disrupt soil aggregates. The aggregate stability is reported to be enhanced by addition of SOM (Arshad *et al.,* 1996; Kemper and Resenau, 1986).

2.7. Bulk density

Soil compaction is indicated by bulk density and is calculated as the dry weight of soil divided by its volume. This volume includes the volume of soil particles and the volume of pores among soil particles. It is reported that bulk density reflects the soil's ability to function for structural support, water and solute movement and soil aeration (NRCS, 2011). Bulk densities above thresholds indicate impaired function. Bulk density is also used to convert between weight and volume of soil. It is used to express soil physical, chemical and biological measurements on a volumetric basis for soil quality assessment and comparisons between management systems. This increases the validity of comparisons by removing error associated with differences in soil density at time of sampling. High bulk density is an indicator of low soil porosity and soil compaction, which may restrict root growth and poor movement of air and water through the soil which can affect plant growth. Also soil compaction restricts water infiltration. It is important to note that, tillage operation may temporarily decrease bulk density and disturbs compacted soil layers, but subsequent rainfall events may re-compact the soil (NRCS, 2011; Arshad *et al.*, 1996)

2.8. Soil pH

Soil pH generally refers to the degree of soil acidity or alkalinity. Since the pH scale is in logarithmic units, even a small change can induce significant changes in the chemical environment and affects sensitive biological processes. Soil pH influences the physical, chemical, and biological properties and processes in soil and consequently affects plant growth. Sources of H^+ ions in soil solution include carbonic acid produced when carbon dioxide (CO_2) from decomposing organic matter, root respiration and the soil atmosphere is dissolved in soil water (Tisdale *et al.*, 1985) Other sources of H^+ ions are root release, reaction of aluminum ions (Al^{+3}) with water, nitrification of ammonium from fertilizers and organic matter mineralization, reaction of sulfur compounds, rain water and acid rain (Khonje *et al.*, 1989; Parfitt *et al.*, 1997)). Generally in acid soils, cations such as calcium and magnesium are deficient whereas aluminum and manganese are abundant. Also there are reports that bacterial populations and activity decline at low pH levels, whereas fungi adapt to a large variation in pH (Blagodatskaya and Anderson, 1998; Rousk *et al.*, 2009) SOM mineralization is reported to be reduced in acidic soils because of the lower microbial activity linked to lower bacterial populations. The effects of soil pH on cation availability influence aggregate stability since multivalent cations, such as calcium ions act as bridges between organic colloids and clays. Leguminous cover crops are reported to be increasing soil pH (Tang *et al.*, 1999) whereas Horst *et al.*, 2001 reported an increase in soil acidity by legume cover crops. The enrichment of SOM content in soil improves its buffering capacity (Smith and Doran, 1996).

2.9. Water soluble carbon

Water soluble carbon (WSC) is considered as the most active component of soil organic matter (McGill *et al.*, 1986). WSC contributes to the soil nutrient cycle and is the main energy and substrate source of soil microorganisms, although it accounts for a small part of SOM (Qualls *et al.*, 1991). It has been found to be sensitive to soil management (Haynes, 2005). The WSC is composed of an array of molecules generally reflecting the composition of total soil organic matter since the soluble phase tends to be in equilibrium with the solid phase of soil organic matter. Land use and management practices may significantly influence the amount and the composition of WSC in soil. There are contrary reports on the effect of tillage on WSC. Linn and Doran (1984) reported that compared to no-till plots WSC content was lower in conventionally tilled soils. Gregorich *et al.*, (2000) found more WSC when corn residues were incorporated and suggested that by loosening the soil and mixing with corn residues, tillage would stimulate microbial degradation of the residues, thereby increasing WSC production. So also, Leinweber *et al.* (2001) found that an increase in tillage intensity improved soil WSC content as the tillage intensity enhanced oxidative microbial activity. There are reports that WSC was different under different vegetation (Smolander and Kitunen, 2002; Kiikkilä *et al.*, 2005). Moreover, the extent of decline in WSC appears to be more pronounced as the number of years under arable cropping increases (Gregorich *et al.*, 2000; Haynes, 2000), apparently due to a gradual depletion in the whole soil organic matter (Saviozzi *et al.*, 1994). In crop rotations including annual and perennial crops, soil WSC content tends to increase with the number of years under perennial crops (Campbell *et al.*, 1999; Haynes, 2000). Inorganic fertilizers may influence WSC content in soil. It is reported that urea-based and ammonium-based fertilizers temporarily solubilize soil organic matter and can induce a marked increase in WSC content (Myers and Thien, 1988; Liu *et al.*, 1995; Hartikainen and Yli-Halla, 1996).

2.10. Hot water extractable carbon

Hot-water extraction methods for quantifying the labile SOM have also been suggested in arable soils. Hot-water extractable carbon (HWEC) is strongly correlated with microbial biomass C, total organic C in arable soils (Liang *et al.*, 1998; Haynes, 2000; Ghani *et al.*, 2003). It is reported that, the impact of different land uses on the amounts of HWEC in the same soil type was far greater than that was observed for the total soil OC (Ghani *et al.*, 2003). Sparling (1992) and Ghani *et al.*, (2003) reported that HWEC could be used as an integrated measure of soil quality. The HWEC, being a component of the labile pool of soil organic carbon and also being closely related to soil microbial biomass and aggregation, it could be used as one of the soil quality indicators in soil-plant ecosystems (Ghani *et al.*, 2003). HWEC accounts for about 1-5% of total organic C (Chan and Heenan, 1999; Sparling *et al.*, 1998). Hot water extracted organic matter is largely composed of carbohydrates and N-containing compounds, amino N species and amides in particular. Hazarika and Parkinson (2011) found HWEC as a suitable indicator in detecting the changes in an agricultural ecosystem. It has been reported that there exists difference in molecular-chemical composition of cold and hot water–extracted OM (Landgraf *et al.*, 2006). The mass spectra of the hot water–extracted organic matter revealed more intensive signals of carbohydrates, phenols, and lignin monomers. Ghani *et al.*, (2003) reported that HWEC is influenced by mineral nitrogen fertilizer application adversely. Also they have reported that

HWEC was positively correlated with soil microbial biomass-C, microbial nitrogen, mineralisable N, and total carbohydrates. Also the HWEC was positively correlated with WSC and total organic C (Wang and Wang, 2011). Ghani *et al.*, (2000) observed that about 40–50 percent of the C in the HWEC extract was carbohydrates.

2.11. Permanganate oxidizable soil carbon

Permanganate oxidizable C (POSC) is a relatively new method that can quantify labile soil C rapidly and inexpensively. Permanganate oxidizable soil carbon (POSC) is a fraction of the SOM pool that is oxidizable in the presence of potassium permanganate in solution. It was reported that carbon compounds oxidized by this process includes the C most readily degradable by microorganisms and also include partially C that are bound to soil minerals. As POSC contains C from the mineral fraction also, it is rather treated as a chemical indicator, not as a biological indicator. However, there are reports that POSC is significantly related to particulate organic carbon, soil microbial biomass carbon and soil organic carbon (Culman, 2012). The residence time of POSC is estimated to be 2 to 5 years, in contrast to recalcitrant C that has a turnover time of several hundred to thousands of years. POSC originates from various fractions of SOM such as fresh organic material, soil microbial biomass, particulate organic matter and other easily metabolized organic compounds, such as carbohydrates (sugars) and proteins (amino acids), as well as C loosely bound to soil minerals. Because of its relatively short turnover time, POSC is more sensitive to management changes affecting soil C in agro-ecosystems than total organic carbon. POSC may be used as an indicator of change produced by cropping and soil management practices that manipulate SOM content (Weil *et al.*, 2003; Andrews *et al.*, 2004; Reddy, 2010; Culman, 2012; Lucas and Weil, 2012).

2.12. Rubber based land use systems

Rubber, a tree native of the Amazon forests was introduced to India about a century ago. It is now very widely planted and occupies about 16 percent of the total cultivated area in the Kerala State of India. Most of the initial rubber plantations were on forest cleared areas. Rubber plantations are cycled by new trees in about 30 years and many of the plantations in Kerala have entered the third replanting cycle (Karthikakuttyamma *et al.*, 2000). In rubber plantations during the initial four to five years of cultivation the fields are usually planted with leguminous cover crops such as, *Mucuna* or *Pueraria* and the litter turnover is estimated to be 3-6 tonnes (Mathew *et al.*, 1989; Krishnakumar and Potty, 1992). Subsequently rubber leaf litter itself becomes the principal organic matter source in rubber plantations and its turnover is estimated to be about 6 t ha^{-1} yr^{-1} (Krishnakumar and Potty, 1992).

Not only that quantity of organic matter input differs in these systems, quality also widely varies. Abraham and Chudek (2008) reported that relative abundance of different C compounds present in litter samples of *Hevea*, *Pueraria* and *Mucuna* were different. Also the litter associated microbial activity varied among different systems. Microbial activity was higher in legume litters in terms of respiration rate. *Hevea* litters were found to have lower litter associated microbial activity.

It is reported by Abraham *et al.*, (2001) that SOC depletes by about 20% upon rubber cultivation. Organic carbon content in soils is getting depleted by continuous cultivation of plantation crops such as rubber or teak compared to nearby natural forests (Balagopalan and Jose,1993; Ulaganathan *et al.*, 2010). Vegetation types and soil nutrient levels are very much related. Abraham and Chudek (2008) reported that litter associated microbial activity was higher in *Pueraria* and *Mucuna* than rubber in terms of respiration rate. An increase in microbial respiration rate was noted as the alkyl-C to O-alkyl-C ratio in litter decreased.

2.13. Soil characterization by spectroscopic methods

The use of spectroscopic methods of analysis is important in the characterization of SOM. Spectroscopic techniques such as ultraviolet- visible (UV-Vis) and fourier-transform infrared (FTIR) are used for both qualitative and quantitative characterisation of SOM (Rivero *et al.*, 1998; Barancikova *et al.*, 1997). SOM generally show strong absorbance in the UV-Vis range (190-800nm), particularly in the UV region, because of the presence of aromatic chromophores and / or other organic compounds (Schnitzer and Khan, 1972). The ratio of absorbance at 465 and 665 nm (E_4/E_6) is often used for the characterisation of SOM.

The magnitude of E_4/E_6 ratio is related to the degree of condensation of aromatic carbon network with a low ratio indicative of a relatively high degree of condensation of aromatic humic constituents. A high E_4/E_6 ratio reflects the presence of relatively large proportions of aliphatic structures (Chen *et al.*, 1977; Chin *et al.*, 1997). The studies conducted in Czech soils indicated that UV-Vis spectroscopy is a useful tool for the evaluation of SOM maturity and quality (Fasurova and Pospisilova, 2010). Purmalis *et al.*, (2013) also reported that different UV ratios can be successfully used for describing humification of organic matter.

FTIR spectroscopy can provide insight into SOM quality as it enables identification of the chemical building blocks that make up SOM, including labile carbon pools relevant to nutrient mineralization. Absorbance intensity in mid – infrared region (4000-400 cm^{-1}) can be used to finger print SOM composition. Specific spectral features offer a means to monitor compositional changes induced by management practices and land uses. Using FTIR spectra, Ellerbrock *et al.*, (1999a, 1999b, 2001a, 2001b) and Gerzabek *et al.*, (2001, 2006) had identified distinct compositional features of SOM under different types of land use and agricultural soil management practices. Solomon *et al.*, (2005) demonstrated the long term impact of land use on different organic C functional forms present in the size separates of Ethiopian soils through FTIR spectroscopic studies.

2.14. Soil Carbon – environmental concern

In terms of agronomical aspects litter quality refers to the relative easiness of decomposition by decomposing organisms and associated mineralization of nutrients (Hopkins *et al.*, 2000; Paustian *et al.*, 1997). On the other hand retardation in the rate of decomposition favors more resident period for the input C and this environmental aspect of litter quality is gaining importance in the soil C sequestration efforts to minimize the CO_2 build up in atmosphere (Janzen, 2006). Soil has a higher potential to store C compared to vegetation and atmosphere (Bellamy *et al.*, 2005). Agriculture leads to some environmental problems especially related to soil erosion, green house effect and water contamination (Davidson and Ackewrmann, 1993). CO_2 emissions result from biomass and SOC losses. Land-use changes are the second largest source of human-induced greenhouse gas emission, mainly due to deforestation in the tropics and subtropics. The highest SOC losses were caused by conversion of primary forest into cropland (−25%) and perennial crops (−30%) (Don *et al.*, 2011). Changes in land use contribute about 15% global green house gas emission (Berndes *et al.*, 2011).

2.15. SOM in rubber based systems

In general organic carbon (OC) content of traditional rubber growing soils is medium to high (NBSS&LUP, 1999). However, a decline in OC status was observed by continous rubber cultivation (Ulaganathan *et al.*, 2013). Karthikakuttyamma (1997) and Ulaganathan *et al* (2010) reported depletion of organic carbon by continuous cultivation of rubber compared to nearby natural forest. Effect of growing cover crops and intercrops during the immature phase of rubber on soil physico-chemical properties is well documented (Jessy *et al.*, 1998; Philip *et al.*, 2005; Jayasree *et al.*, 2006; George *et al.*, 2012). However information on various organic matter pools in different rubber based systems is very limited.

MATERIALS AND METHODS

Chapter 3

MATERIALS AND METHODS

3.1. Litter quality and decomposition

The decomposition pattern of three major litter species in rubber plantation *viz.*, *Hevea, Pueraria* and *Mucuna* were studied through litter bag technique (Bocock *et al.*, 1960) at Travancore Rubber Estate, Erumely, near Kottayam in Kerala.

3.1.1 Collection of litter

Freshly fallen litter of *Hevea*, *Pueraria* and *Mucuna* in an area of one square meter from a 12 year-old rubber plantation, 3 year old rubber plantation with cover crop, *Pueraria* and 3 year old rubber plantation with cover crop, *Mucuna* respectively were collected randomly from 12 different points from each field. These samples were oven dried at 70°C and recorded the weight. The average input of these litter species in one square meter was computed for fixing the quantities of litter to be taken in the litter bags.

3.1.2. Litter decomposition

In each situation (mature rubber / rubber-*Mucuna* / rubber-*Pueraria* systems), 120 nylon litter bags of size 30 cm x 30 cm with a mesh size of 2 mm were used. Litter bags containing 40 g of *Hevea* litter or 35 g *Pueraria* or 35 g *Mucuna* litter were placed randomly in contact with the surface soil in the respective fields and anchored to small pegs. Ten litter bags from each system were retrieved at monthly intervals for a period of one year and brought to the laboratory. The bags were gently rinsed over a fine soil sieve to remove soil and other extraneous material and the residual litter was removed from the bags, oven dried at 70^0C to constant weight and weighed. The decay rate coefficient and percentage of nutrients remaining in residual litter were worked out.

3.1.3. Chemical analysis of litter

Oven-dried (70^0C) samples of the fresh litter of the three species and those retrieved at monthly intervals through the litter bags were finely ground and nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) contents were estimated following standard procedures (Piper, 1966). N content of litter was determined by micro kjeldhal method using nitrogen analyzer (Kjeltec 2300- FOSS Tecator, Sweden). P, K, Ca and Mg contents in litter samples were estimated by dry ashing followed by digestion with 1:1HCl. P content was estimated by vanadomolybdate method using auto analyzer (Auto Analyzer 3. Bran Luebbe, Germany). K content was estimated flame photometrically using auto analyzer. Ca and Mg contents were determined using atomic absorption spectrophotometer.

Biochemical parameters *viz.*, cellulose, lignin and polyphenols of the fresh litter were estimated as described by Anderson and Ingram (1993). Cellulose and lignin were determined by refluxing the samples in acid detergent solution, with the resulting fibrous residue treated with concentrated H_2SO_4 followed by ashing (Van Soest method, 1963). Polyphenols in litter samples were extracted in 50% aqueous methanol and estimated colorimetrically using Folin-Denis reagent. All parameters were estimated using 10 replicates of each litter species.

3.1.4. Decay constant

The decay rate coefficient was calculated using the equation $X/X_o = e^{-kt}$ (Olson, 1963) where X is the dry weight remaining at time t, X_o is the original dry weight of the litter and k is the decay rate coefficient.

The time required for 50% and 95% loss was estimated using the equations $t_{0.5} = 0.693/k$ and $t_{0.95} = 3/k$.

3.1.5. Nutrients remaining in the residual litter

Nutrients remaining in the residual litter were estimated by the equation

Nutrient (%) remaining= $(C/C_o) \times (DM/DM_o) \times 100$ (Bockhelm *et al.*, 1991)

Where 'C' is the concentration of the nutrient at time t, 'C_0' is the initial concentration of the nutrient, 'DM' is the dry weight of the litter after time t, 'DM_0' is the initial dry weight of the litter.

3.2. Characterization of soil organic matter and soil properties in different rubber based systems

The study was conducted at three locations in Central Kerala. Two locations were selected from the estate sector and one from the small holding sector. The fields in the estate sector were in Harrisons Malayalam Limited, Mundakayam (9^0 31' N, 76^0 52' E) and Travancore Rubber Estate, Erumely, (9^0 27' N, 76^0 52' E). The small holding was at Amayannoor, Kottayam (9^0 37' N, $76^0$36' E).

3.2.1. Site description and management practices

The systems and associated management practices in each location are briefed in Table 1.

Table 1. Management practices followed in different rubber based systems

Location	Systems	Planting cycle	Age (years)	Organic Manure	Tillage/Pitting
Amayannoor	Mature Rubber	Second	23	Rubber : FYM* 12 kg during planting	Pitting at the time of planting rubber
	Rubber-*Pueraria*	Third	3	Rubber : FYM 12 kg during planting	Pitting at the time of planting rubber
	Rubber-banana	Third	2	Rubber : FYM 12 kg during planting Banana : FYM – 10 kg per plant	Pitting at the time of planting rubber Manual tillage of inter row area of rubber plants for planting banana.
	Rubber-pineapple	Third	2	Rubber : FYM 12 kg during planting Pineapple : FYM 25 t ha^{-1} basal dose	Pitting at the time of planting rubber Mechanical tillage of the entire area before planting pineapple
Mundakayam	Mature Rubber	Second	20	Rubber : FYM 12 kg during planting	Pitting at the time of planting rubber
	Rubber-*Mucuna*	Third	3	Rubber : FYM 12 kg during planting	Pitting at the time of planting rubber
	Rubber-banana	Third	2	Rubber : FYM 12 kg during planting Banana : FYM – 10 kg per plant	Pitting at the time of planting rubber Manual tillage of inter row area of rubber plants for planting banana.
	Rubber-pineapple	Third	2	Rubber : FYM 12 kg during planting Pineapple : FYM 25 t ha^{-1} basal dose	Pitting at the time of planting rubber Mechanical tillage of the entire area before planting pineapple

Erumely	Mature Rubber	Third	12	Rubber : FYM 12 kg during planting	Pitting at the time of planting rubber
	Rubber-*Pueraria*	Third	3	Rubber : FYM 12 kg during planting	Pitting at the time of planting rubber
	Rubber-*Mucuna*	Third	3	Rubber : FYM 12 kg during planting	Pitting at the time of planting rubber

* FYM- Farm Yard Manure

- NPK fertilizer application in mature rubber
- NPKMg fertilizer application in immature fields
- Separate application of NPK to inter crops

Cu fungicide application at locations Mundakayam and Erumely only

In all locations, the selected fields were located in close vicinity. The soils at Amayannoor and Mundakayam were sandy-clay loam in texture where as it is sandy clay in texture at Erumely. All soils were acidic in nature.

3.2.2. Collection of soil samples

Soil samples (0-10 cm) were collected on a random basis from all the systems in each location. Five sites in each system in locations 1 and 2 *viz.*, at Amayannoor and at Mundakayam and ten sites at location 3, *viz.*, Erumely were identified and soil samples were collected from each site. Three samples were collected from each sampling site and composited.

The field moist samples were brought to the laboratory and a portion was sieved through a 2mm sieve and used for the estimation of water soluble carbon (WSC) and hot water extractable carbon (HWEC). The remaining portions were air dried, sieved (2mm) and used for other analyses.

3.2.3. Soil analysis

Following soil properties were estimated in each soil sample.

A) Soil physical properties

Particle size analysis

Texture of the soil was determined by international pipette method (Jackson, 1973)

Bulk density

Bulk density was determined by core sampling method (Black, 1965). Samples were taken with core sampler of diameter 5.2 cm and height 8.2 cm. The samples were dried in a hot air oven at 105^{0}C.

Particle density

Particle density was estimated by displacement method (Black, 1965)

Porosity

Porosity was calculated using the formula St = 100(1-Db/P) Where 'St' is the total porosity, 'P' is the particle density and 'Db' is the bulk density.

Water stable aggregates (WSA)

Water stable aggregates were determined by following the method as described by

Kemper and Koch (1966).

4 g of 1-2mm air dried aggregates were sieved through 60 mesh sieve in water for 3 or 3 minutes and then in 0.2% NaOH for 8 minutes. WSA was estimated based on the oven dry weight of the soil collected in water and NaOH solution.

Soil chemical properties

Soil reaction (pH)

Soil was equilibrated with water (1:2.5 soil solvent ratio). The pH of the suspension was determined electrometrically on a direct reading pH meter with combined calomel – glass electrode.

Cation exchange capacity

Cation exchange capacity (CEC) was estimated using neutral normal ammonium acetate (Black, 1965).

Total carbon and nitrogen

Total carbon and nitrogen were estimated by dry combustion method using an automated elemental analyser (Leco Truspec CN). The total carbon estimated in 2 mm soil was organic carbon (OC) as the soils were acidic in nature and no inorganic forms of carbon was present in any of the soil studied.

Available phosphorus

Available phosphorus extracted using Bray II extractant and estimated by chloromolybdic stannous chloride reduction method (Jackson, 1973).

Available potassium, calcium and magnesium

Soil samples were extracted with neutral normal ammonium acetate solution. Potassium was estimated by flame photometry and calcium and magnesium by atomic absorption spectrophotometry.

Available iron, manganese, copper and zinc

Soil samples were extracted with 0.1N HCl ((Martens and Chesters, 1967) and estimated by atomic absorption spectrophotometry.

3.2.4. Characterization of soil organic matter

3.2.4.1. Physical fractionation

Particle size fractionation of soil was carried out by dispersion followed by wet sieving and sedimentation (Cambardella and Elliot, 1992,). Soil (10 g) was dispersed in 30 ml 0.5% sodium hexa metaphosphate by shaking for 15 hours on a reciprocal shaker. After dispersion, the suspension was sieved to separate the 2.00- 0.250 mm, 0.250 - 0.053 mm and < 0.053 mm fractions. All the fractions were dried at 65^{0}C. Carbon in the size separates was estimated by dry combustion method using an automated elemental analyser (Leco Truspec CN).

3.2.4.2. Chemical fractionation

3.2.4.2.a. Water soluble carbon (WSC)

Field moist soil samples (2 mm) were extracted with distilled water in the ratio 1:3 for 30 minutes on an end-over –end shaker and centrifuged for 20 minutes at 8000 rpm. The supernatant was filtered and the extract was estimated for water soluble carbon by dichromate oxidation method (Ghani *et al.*, 2003).

3.2.4.2.b. Hot water extractable carbon (HWEC)

10 g field moist, sieved (2mm) soil was mixed with 30 ml distilled water in n polypropylene centrifuge tube and shaken on a horizontal shaker for 30 minutes. Then the tubes were capped and left in an 80°C hot-water bath for 16 hours. Shaken for 10 minutes on a horizontal shaker and subsequently centrifuged at 8000 rpm for 20 minutes and supernatant used to determine HWEC by dichromate oxidation method (Ghani *et al.*, 2003).

3.2.4.2.c. Permanganate oxidizable soil carbon POSC)

Air dried soil samples were used to determine POSC by following the method as described by Blair *et al.*, (1995) with minor modifications as suggested by, Weil *et al.*, (2003), Reddy (2010) and Abraham (2014). In brief, soil samples (3 g) were weighed in to a 50 ml centrifuge tube and 30 ml of 20 m*M* $KMnO_4$ solution added and shaken for 30 minutes. The contents were centrifuged for 5 minutes at 2000 rpm. 2 ml of the aliquot made up to 50 ml and the absorbance measured at 560 nm using a spectrophotometer. POSC was calculated based on the assumption that 1 mM of MnO_4 is consumed in the oxidation of 0.75 mM of organic carbon (Blair *et al.*, 1995).

3.2.4.3.a. Spectroscopic characterisation- UV/Vis spectroscopy

Organic compounds were extracted from the soil with 0.05M $NaHCO_3$ and the absorbance was measured at 254 (E_2), 365 (E_3), 465 (E_4) and 665 (E_6) nm using a UV-Vis spectrophotometer (UV-1601, Shimadzu). E_2/E_3 and E_4/E_6 ratios were worked out (Schnitzer, M. 1982).

3.2.4.3.b. Spectrosopic characterisation - FTIR spectroscopy

2 mm sieved soil samples were powdered in an agate mill. Two mg of the homogenized agate milled 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°C for two hours prior to analysis to minimize interference from absorbed water. FTIR spectra recorded with a spectrometer (Varian 660-IR FTIR). The resolution was 4 $cm^{-1}$and 20 scans (Ellerbrock *et al.,* 1999a). All spectra were corrected to reduce the effect of mineral contents, using the subtraction method (Bio Rad, 1996).

3.3. Soil carbon mineralisation – Soil respiration (Incubation experiment)

Carbon mineralisation of soil samples collected from different systems from Amayannoor were studied by quantifying the CO_2 evolution from soils incubated for different time intervals, as described by Ladd *et al.* (1995). Soil samples (20 g, 2 mm) were moistened to 60 % field capacity and incubated at 28°C in air -tight plastic containers for 60 days in five replications. Evolved CO_2 was allowed to get absorbed in 10 ml of 1N NaOH kept in a beaker placed inside the container. The beakers were taken out at regular intervals *viz.,* 7, 15, 30, 45, 60 days and titrated with 0.5 N HCl after precipitating the carbonate with

15% $BaCl_2$ solution in the presence of phenolphthalein. The containers were opened for ten minutes every third day to allow gas exchange. The amount of CO_2-C evolved was calculated using the formula, CO_2-C evolved ($mg100^{-1}$ g soil) = (A-B) x N x 6 where A and B are the volume of HCl consumed for titrating 10 ml of NaOH in control and sample respectively and N is the normality of HCl .

3.4. Statistical Analysis

One-way ANOVA was carried out for all data of litter and soil. Pearson linear correlations between parameters were conducted. All the analyses were done in SPSS version 10.0.

RESULTS AND DISCUSSION

Chapter 4

RESULTS AND DISCUSSION

4.1. Litter decomposition

The table 2 and 3 show the nutrient contents and biochemical parameters of fresh fallen litter of the three species *viz., Hevea* (rubber), *Mucuna* and *Pueraria.* The different nutrient contents vary in the three litter species. N, P and K were significantly higher in litter samples of both legume species, *Mucuna* and *Pueraria* than in rubber litter. Among the legume litters, *Mucuna* had higher N content and *Pueraria* had higher P content while K content was not differing. The biochemical parameters were also varying among the litter species (Table 3). The cellulose content was distinctly more in legumes however, *Pueraria* had the highest content.

Table 2. Nutrient content in different litter species

Litter Species	N	P	K	Ca	Mg	C
	(%)					
Hevea	1.14	0.05	0.46	1.56	0.33	36.58
Pueraria	2.44	0.12	0.56	1.21	0.39	34.10
Mucuna	2.71	0.08	0.54	1.74	0.31	38.44
SE	0.01	0.003	0.005	0.01	0.007	0.42
CD (P=0.05)	0.03	0.008	0.02	0.03	0.02	1.23

Table 3. Lignin, Polyphenol and Cellulose contents in different litter species

Litter Species	Cellulose	Lignin	Polyphenols	C/N
	(%)			
Hevea	26.0	37.0	1.04	32.09
Pueraria	32.0	21.1	0.42	13.98
Mucuna	23.0	22.6	0.53	14.18
SE	0.28	0.34	0.01	0.26
CD (P=0.05)	0.81	0.98	0.03	0.77

The recalcitrant compounds *viz.*, lignin and polyphenols were significantly higher in rubber litter than in legume litters. Though lignin contents were comparable in the two legume litter species, polyphenols was more in *Mucuna* litter. The C to N ratio was not varying among the legume species however, was significantly lower compared to rubber litter (Table 3).

The litter weight-loss pattern in the three species agreed to exponential model (Fig. 1). There was a rapid weight loss during the first month for all the three species and then followed a slow rate in the subsequent periods. In the first month 42%, 38% and 32% weight-loss were recorded for *Pueraria, Mucuna* and *Hevea* litter respectively. The initial rapid disintegration may be due to the leaching of inorganic as well as soluble organic compounds from the litter (Swift *et al.*, 1979). The slow rate of decomposition in the later phase may be due to the accumulation of resistant compounds like lignin and polyphenols. The litter decomposition rates of the three species studied were not significantly different. After one year 3.36% *Pueraria*, 7% *Mucuna* and 8.95% *Hevea* litter remained in the bag.

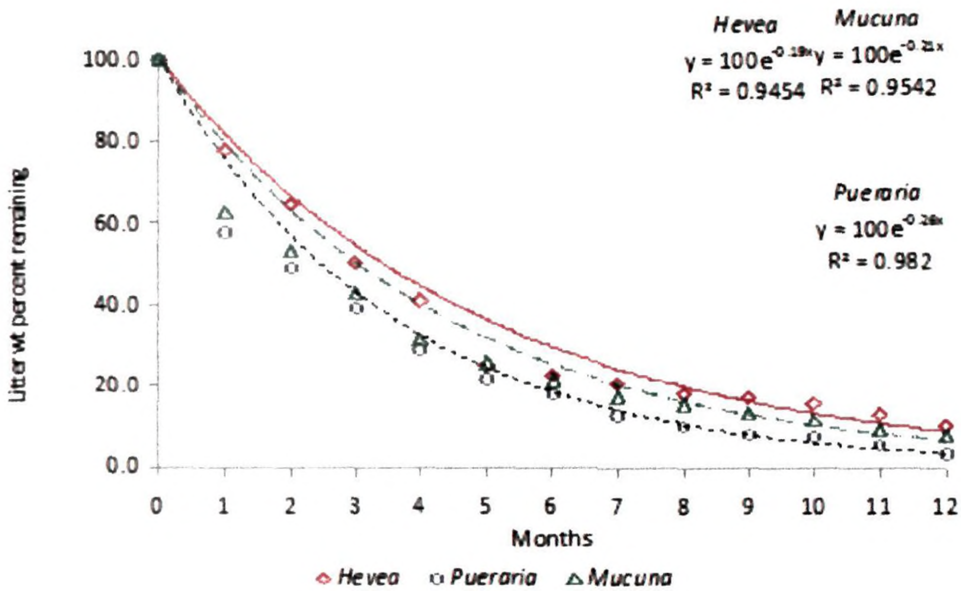


Fig. 1. Litter decomposition pattern

The decay rate coefficient (k) and time required for 50% and 95% decay are presented in table 4.

Table 4. Decay constants and time required for 50% and 95%decay

Litter Species	Decay constant (k)	$t_{50\%}$ (months)	$t_{95\%}$ (months)
Hevea	0.19	3.6	15.8
Pueraria	0.26	2.7	11.5
Mucuna	0.21	3.3	14.3

Pueraria litter recorded the highest decay rate constant (0.26) followed by *Mucuna* (0.21) and *Hevea* litter recorded the lowest decay rate constant (0.19). Among the three litter species studied the half-life period for decomposition was lowest in *Pueraria* (2.7 months), highest in *Hevea* (3.6 months) and intermediate in *Mucuna* (3.3 months). For 95 per cent decay also *Pueraria* took less time (11.5 months) than *Mucuna* (14.3 months) and *Hevea* (15.8months) litter. Similar results were reported for *Hevea* litter by Deka *et al.*, (1998).

The influence of initial contents of biochemical parameters and nutrient contents on disintegration rate was given in table 5. It could be noted that the initial N, P, K, Mg contents in litter showed significant and positive correlation with the cumulative weight loss. However, Ca content was negatively correlated to the cumulative weight loss of litter. It is important to note that as expected, the lignin and polyphenol contents were negatively correlated to the weight loss. The cellulose content was positively correlated to the weight loss. There were many similar reports that the decomposition is influenced by nutrients as well as cellulose content (Meentemeyer, 1978; Taylor *et al.*, 1991).

Table 5. Correlation between initial chemical composition of litter and cumulative weight loss

Initial chemical composition of litter	Cumulative weight loss of litter
N	0.43*
P	0.84**
K	0.67**
Ca	-0.77**
Mg	0.81**
Cellulose	0.77**
Lignin	-0.59**
Polyphenols	-0.65**

** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

High initial N and P contents can accelerate decomposition as these nutrients enhance microbial activities (Taylor *et al.*, 1989). Relative contents of organic substances are also important in determining rate of decomposition. Cellulose serves as an immediate source of energy for microorganisms and promotes break down of litter whereas phenolic compounds inhibit growth and activity of soil decomposers. Lignin itself is resistant to decay, also slows down the decay of other cell constituents (Chesson, 1997; Issac and Nair, 2005). The relatively faster decomposition of litter of *Pueraria* than *Mucuna* may be due to its higher cellulose and lower polyphenol contents. The lower decomposition rate of *Hevea* litter may be due to its higher lignin and polyphenol and lower N and P contents. These results are in agreement with the study of Abraham and Chudek (2008).

Table 6. Nutrient content in the *Hevea* litter remaining at different months

Months	N	P	K	Ca	Mg
	(%)				
Initial	1.14	0.05	0.46	1.56	0.33
1	1.47	0.07	0.33	2.13	0.31
2	1.61	0.08	0.26	2.13	0.29
3	2.07	0.08	0.21	1.92	0.29
4	1.77	0.09	0.19	2.86	0.24
5	1.96	0.10	0.19	1.75	0.24
6	1.98	0.10	0.21	2.00	0.23
7	2.15	0.10	0.20	1.78	0.24
8	2.07	0.10	0.21	1.05	0.24
9	2.09	0.11	0.21	1.16	0.27
10	1.88	0.11	0.20	1.00	0.24
11	1.71	0.11	0.20	1.27	0.24
12	1.69	0.11	0.18	1.34	0.24
SE	0.04	0.003	0.008	0.09	0.01
CD (P=0.05)	0.12	0.01	0.02	0.25	0.03

Nutrients concentration (%) in the residual litter of the three species at different time intervals is given in table 6, 7 and 8. There was significant variation in the concentration of N, P, K, Ca and Mg in the remaining litter at different time intervals.

All the three species showed an increase in N content in the initial phase of decomposition and a decline in the later phase. Accumulation of N in residual litter during decomposition has been reported by Melillo *et al.*, (1982) and Schlesinger (1985).

Table 7. Nutrient content in the *Pueraria* litter remaining at different months

Months	N	P	K	Ca	Mg
	(%)				
Initial	2.44	0.12	0.56	1.21	0.39
1	2.49	0.10	0.20	1.78	0.29
2	2.46	0.10	0.20	1.73	0.28
3	2.78	0.12	0.19	1.87	0.26
4	2.52	0.12	0.19	1.72	0.23
5	2.64	0.11	0.18	1.29	0.23
6	2.76	0.11	0.18	1.16	0.20
7	2.83	0.12	0.19	0.77	0.24
8	2.68	0.12	0.19	1.01	0.25
9	2.62	0.12	0.18	1.04	0.26
10	2.44	0.13	0.17	1.13	0.21
11	2.16	0.12	0.16	0.85	0.22
12	1.75	0.11	0.16	0.86	0.22
SE	0.10	0.00	0.01	0.07	0.01
CD (P=0.05)	0.28	0.01	0.03	0.20	0.03

Phosphorus content in residual litter showed variable trends in the three species. In the residual *Hevea* litter it increased as decomposition proceeds. In the case of *Pueraria* litter no definite trend was observed. In *Mucuna* litter initially there was an increase in P content and during the later phase a decrease was noticed. The reason for faster release during the initial phase could be due to the leaching out of inorganic N and P compounds from the litter and more N and P enriched organic forms release at a lower rate.

Table 8. Nutrient content in the *Mucuna* litter remaining at different months

Months	N	P	K	Ca	Mg
	(%)				
Initial	2.71	0.08	0.54	1.74	0.31
1	3.16	0.10	0.20	1.71	0.24
2	3.00	0.10	0.20	1.69	0.25
3	3.59	0.11	0.19	1.8	0.22
4	3.49	0.12	0.19	1.34	0.21
5	3.17	0.11	0.18	1.12	0.21
6	3.40	0.10	0.19	1.10	0.20
7	3.51	0.11	0.19	1.16	0.19
8	3.38	0.11	0.19	1.12	0.18
9	3.32	0.11	0.20	0.81	0.17
10	3.33	0.11	0.19	1.08	0.16
11	3.45	0.10	0.18	0.94	0.16
12	3.08	0.08	0.18	0.92	0.16
SE	0.08	0.003	0.008	0.07	0.009
CD (P=0.05)	0.22	0.01	0.02	0.19	0.03

Unlike N and P, K and Mg contents in litter decreased continuously as decomposition progressed. For K, the decrease was rapid in early stages and gradual in later stages of decomposition. This could be due to the highly mobile nature as well as soluble character of K and Mg compounds in litter. In general, Ca in all the three species showed an increase in the initial phase of decomposition and then a declining trend. This may be due to the relatively immobile nature of Ca in the cell wall. Calcium is firmly bound as calcium pectate in the cell walls and protected by lignin till last stages of decomposition.

Studies on forest litter decomposition have shown that in the early stages of decay, concentrations of N and P tend to accumulate while K declined (Berg *et al.*, 1992). Nutrient dynamics is influenced by the litter quality especially the palatability of the compounds by microorganisms and to their solubility. Also it is influenced by the nature of chemical bonds which attach the element to the organic matter. Since K is not a structural component of litter, its rapid decline could be due to leaching. As Mg is partly occurring as a constituent of complex molecules like chlorophyll and pectin, its decline is relatively slower than K.

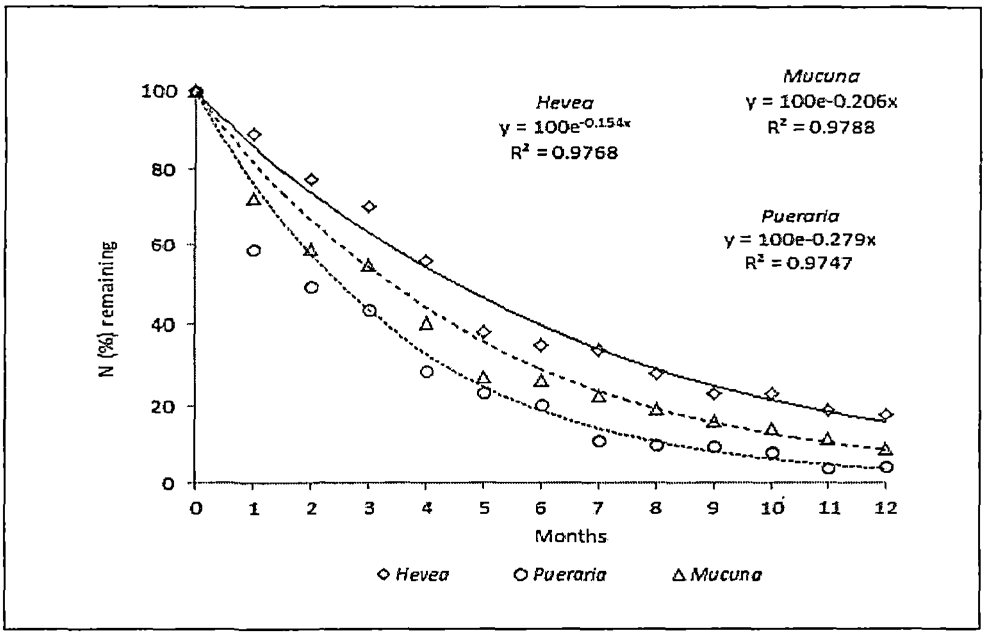


Fig. 2. Percentage of initial N content remaining in litter samples at different time intervals

The N content in the residual portion of litter at different time intervals, as percentage of the initial N content is shown in Fig. 2. It could be seen that the N decay rate from *Hevea* litter was at the rate of 15.40% per month while from *Mucuna* litter was at 20.60%and from *Pueraria* was at 27.90%.

The P content in the residual portion of litter at different time intervals, as percentage of the initial P content is shown in Fig. 3. It could be seen that the P decay rate from rubber litter was at the rate of 13% per month while from *Mucuna* litter was at 20% and from *Pueraria* was at 28.9%.

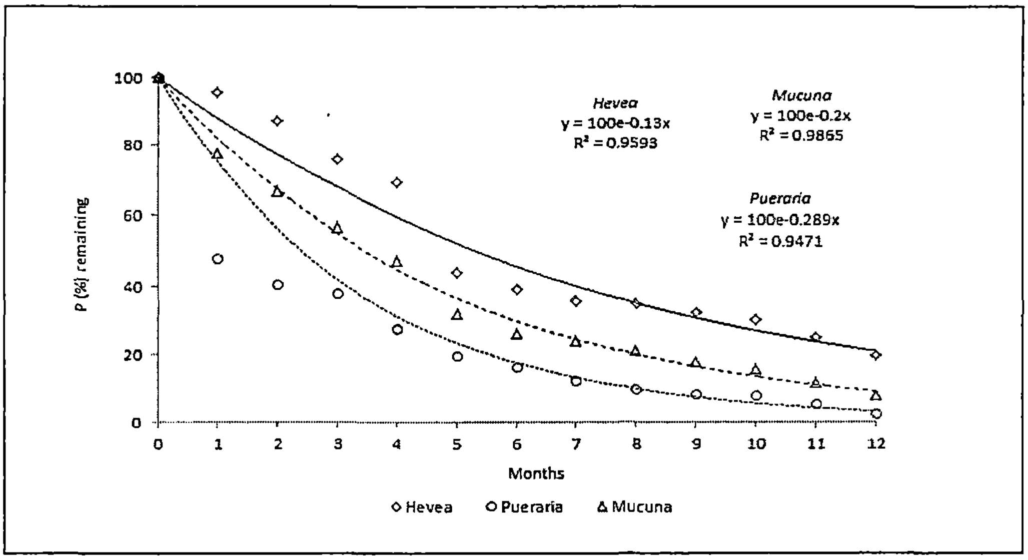


Fig. 3. Percentage of initial P content remaining in litter samples at different time intervals

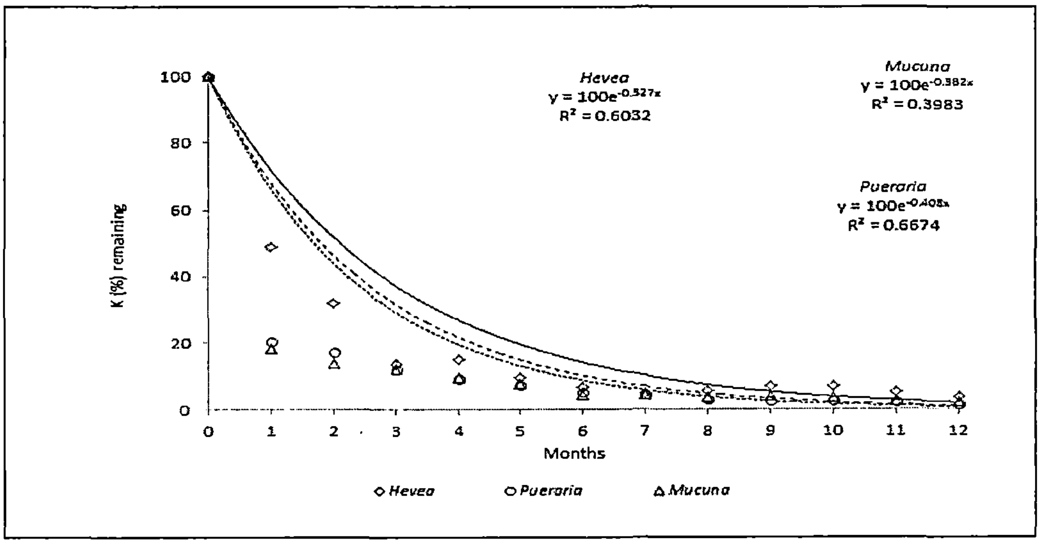


Fig. 4. Percentage of initial K content remaining in litter samples at different time intervals

The K content in the residual portion of litter at different time intervals, as percentage of the initial K content is shown in Fig. 4. It could be seen that the K decay rate was at a higher level of N or P and from *Hevea* litter was at the rate of 32.7% per month while from *Mucuna* litter was at 38.2% and from *Pueraria* was at 40.8%. Since in all the litter species K release was at a higher rate, it must be because of the nature of K compounds in the litter. As mentioned earlier, the K was not present in litter as a structural component; it was not remaining for longer period in all the litter species.

The Ca content in the residual portion of litter at different time intervals, as percentage of the initial Ca content is shown in Fig. 5. It could be seen that the Ca decay rate from *Hevea* litter was at the rate of 22.10% per month while from *Mucuna* litter was at 28.90% and from *Pueraria* was at 30.90%.

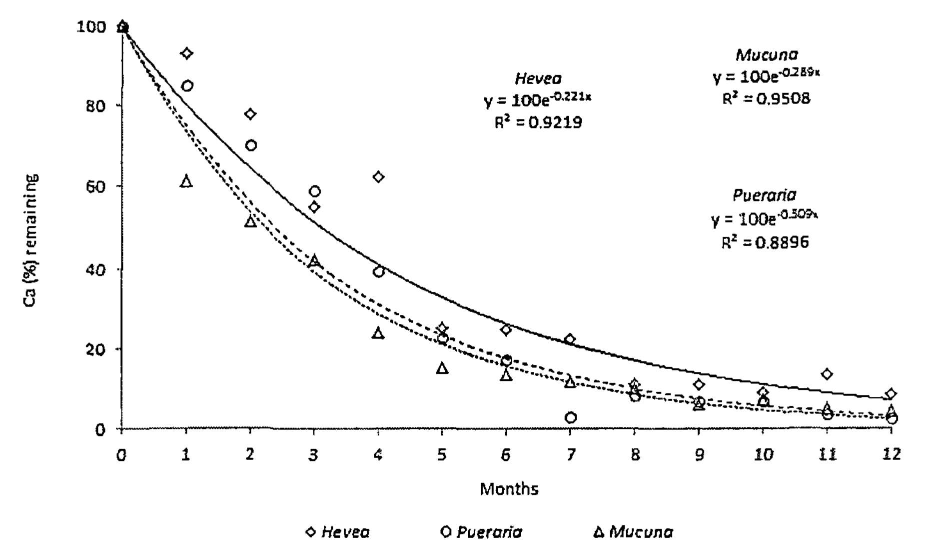


Fig. 5. Percentage of initial Ca content remaining in litter samples at different time intervals

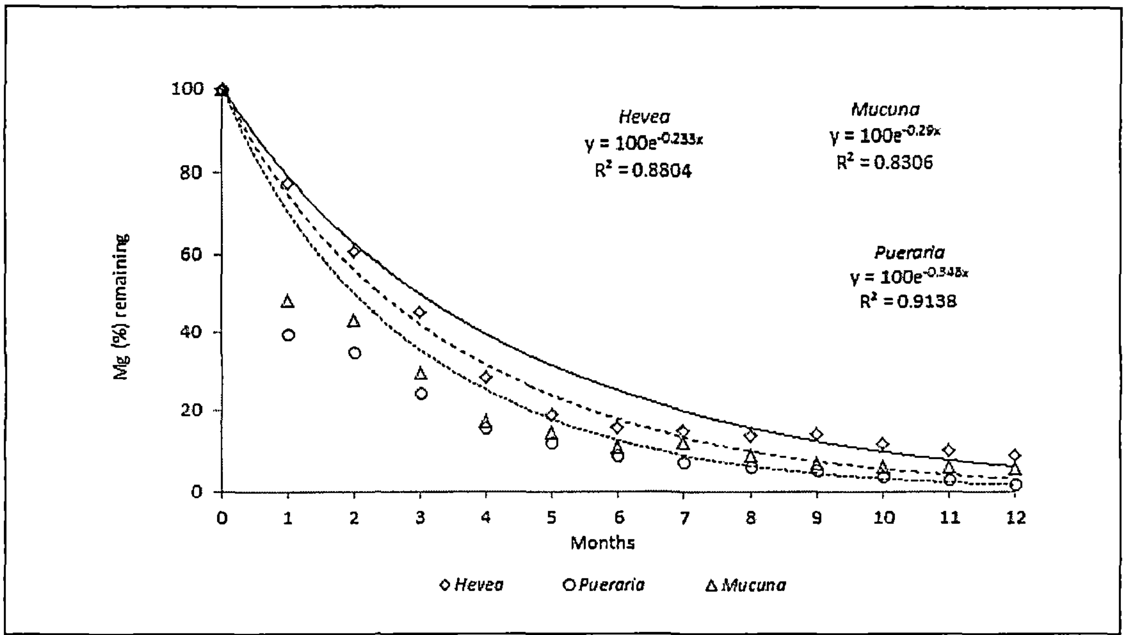


Fig. 6. Percentage of initial Mg content remaining in litter samples at different time intervals

The Mg content in the residual portion of litter at different time intervals, as percentage of the initial Mg content is shown in Fig.6. It could be seen that the Mg decay rate from *Hevea* litter was at the rate of 23.3% per month while from *Mucuna* litter was at 29% and from *Pueraria* was at 34.8%.

The study revealed that the three litter species *viz*., *Hevea*, *Pueraria* and *Mucuna* vary in quality, decomposition process and nutrient release. Among the three species studied, *Pueraria* litter having more cellulose and less lignin and polyphenols decomposed at a higher rate whereas *Hevea* litter having more lignin and polyphenols decomposed at lower rate. Though the C to N ratio of *Mucuna* and *Pueraria* was not varying much, their polyphenol contents differed significantly which might have contributed to the variation in different decay rates of these litters. The decay rates or nutrient release pattern was more depending on the different C species rather than mere total C and N contents. The release of rates of N, P, K, Ca and Mg from the three litter species also varied and it could be seen that the release of nutrients were invariably higher from the *Pueraria* litter followed by *Mucuna* and *Hevea*. The results clearly pointed out that during the growing phase of rubber, when higher demands of nutrients exist, legume cover crops are beneficial. The nutrient release followed in the order *Pueraria* > *Mucuna* > *Hevea*. The biochemical species such as lignin and polyphenols inhibited the decomposition while cellulose enhanced the rate.

4.2. Characterization of SOM and soil properties

The SOM characterization and soil properties of the three locations are detailed below.

4.2.1. Location 1. Amayannoor

The four studied systems were mature rubber, rubber-*Pueraria,* rubber-banana and rubber-pineapple.

Physical properties

The physical properties *viz*., bulk density, particle density, porosity and water stable aggregates (WSA) of the different systems at Amayannoor are given in table 9. The bulk density of the different systems didn't vary much. It ranged narrowly from 0.98 Mg m^{-3} to 1.04 Mg m^{-3}. The particle density of the rubber-pineapple system was distinct and significantly lower than the other three systems. The other systems *viz*., rubber-*Pueraria*, the rubber-banana and mature rubber were comparable in particle density. Similarly porosity of the rubber-*Pueraria* system was distinct and was significantly higher than the other three systems which were comparable. The WSA in the four systems were varying from each other, however, the rubber-banana and rubber- *Pueraria* systems were significantly higher than mature rubber and rubber-pineapple systems.

Table 9. Physical properties of soil in different rubber based systems at Amayannoor

Systems	Bulk density	Particle density	Porosity	Water stable aggregates
	($Mg\ m^{-3}$)	($Mg\ m^{-3}$)	(%)	(%)
Mature Rubber	1.01	2.16	53.20	35.55
Rubber-*Pueraria*	0.98	2.16	55.00	43.25
Rubber- banana	1.04	2.18	52.60	46.29
Rubber- pineapple	1.02	2.09	52.00	38.06
SE	0.02	0.01	0.59	0.57
CD (P=0.05)	NS	0.03	1.77	1.70

Chemical properties

The chemical properties of the soils of different systems are presented in table 10. Organic carbon (OC) status of the four systems showed significant variation. Significantly higher OC status recorded in rubber-*Pueraria* system. The OC status decreased in the order rubber-*Pueraria* > rubber–banana > rubber-pineapple > Mature Rubber. Similar trend was noted for total nitrogen (TN) also. There was significant difference in cation exchange capacity (CEC) of different systems. CEC varied from 7.28 to 8.26 cmol(+) kg^{-1}. Rubber-*Pueraria* system recorded significantly higher CEC followed by rubber-banana system. CEC of rubber-pineapple and mature rubber systems were lower and comparable.

Table 10. Chemical properties of soil in different rubber based systems at Amayannoor

Systems	OC	CEC	TN	Av. P	Av.K	Av.Ca	Av.Mg	pH
	g kg^{-1}	cmol(+) kg^{-1}	g kg^{-1}	mg kg^{-1}				
Mature Rubber	20.55	7.28	2.08	32.2	54.14	104.71	38.64	4.88
Rubber-*Pueraria*	23.40	8.26	2.40	47.8	40.96	115.12	45.81	4.91
Rubber-banana	21.63	7.91	2.12	80.28	67.82	240.48	63.60	5.06
Rubber-pineapple	19.36	7.31	2.02	70.80	73.04	191.11	65.24	4.79
SE	0.54	0.09	0.01	4.53	3.26	12.65	4.34	0.03
CD (P=0.05)	1.62	0.26	0.03	13.60	9.76	37.94	13.02	0.08

Av. - Available

The available nutrients (P, K, Ca, Mg) status also showed marked difference between the systems. It was noticed that in general rubber-banana and rubber-pineapple systems recorded significantly higher available nutrient status than the other two systems. Though the soils of all the systems were acidic in reaction, there was significant difference in pH among the systems. The rubber-banana system recorded the highest pH and the lowest in rubber-pineapple system.

It was noticed that available Ca status was significantly higher in rubber-banana and rubber-pineapple systems than the rubber-*Pueraria* and mature rubber systems. Wide variations in available Mg status could be noticed between the mature and immature rubber systems. The mature rubber system was significantly lower than the intercropped systems. The available micronutrient status also showed variation among the systems studied (table 11).

Table 11. Micronutrient (mg kg^{-1}) status of the different rubber based systems at Amayannoor

Systems	Fe	Mn	Cu	Zn
Mature Rubber	25.06	17.56	1.71	1.24
Rubber-*Pueraria*	28.26	14.84	2.72	0.85
Rubber- banana	21.20	14.59	1.52	0.95
Rubber- pineapple	24.48	19.14	3.47	1.08
SE	1.07	1.60	0.06	0.17
CD (P=0.05)	3.21	4.80	0.19	NS

Micro nutrients, Fe, Mn and Cu status varied significantly among the systems while the Zn was not varying much. Available Fe ranged from 21.20 to 28.26 mg kg^{-1} among the four systems. Rubber-*Pueraria* showed a significantly higher available Fe status than the other systems. Available Mn was higher in the rubber-pineapple and mature rubber systems than the other two systems, which were comparable. Available Cu status was significantly higher in rubber-pineapple system followed by rubber-*Pueraria* system.

Characterization of SOM

Physical fractions

The distribution of soil particles in different size fractions are shown in table 12. The particle size distribution of soil in different systems varied. In mature rubber and rubber-pineapple systems macro sized fraction (2.00 - 0.25 mm) was more than the other two fractions whereas in rubber-*Pueraria* and rubber-banana systems silt-clay sized (< 0.053 mm) fraction was more than the other two larger sized fractions.

Table 12. Weight (g kg^{-1}) of different physical fractions in the different land use systems at Amayannoor

Systems	Size fractions		
	Macro size	Micro size	Silt-clay size
Mature Rubber	461.40	142.40	390.80
Rubber-*Pueraria*	368.60	165.80	467.00
Rubber- banana	414.20	120.20	460.00
Rubber- pineapple	464.80	104.20	429.20
SE	7.17	5.03	5.36
CD (P=0.05)	21.10	14.81	15.78

In all the four systems, the micro-sized (0.250 – 0.053 mm) fractions were lowest than the other two size fractions. Both rubber-pineapple and mature rubber systems recorded significantly higher amount of macro-sized fraction. It was lowest in rubber-*Pueraria* system. The silt-clay sized fraction was significantly higher in rubber-*Pueraria* and rubber-banana systems compared to other two systems.

Carbon in different size fractions

It was observed that in all the systems, carbon content in the soil particle size fractions increased with decreasing size (Table 13). On an average carbon content in the silt clay sized fraction was 36.94 g kg^{-1} and in micro sized fraction is 14.41 g kg^{-1} whereas only 6.9 g kg^{-1} carbon was associated with macro sized fraction. The C content of each size fraction varied significantly among the different systems. It was also noticed that there was wider variation in carbon content of the macro sized fraction than that in other size fractions. In other size fractions C content variations were only marginal. In the macro sized fraction, carbon content decreased in the order rubber- *Pueraria* > rubber-pineapple > mature rubber > rubber-banana.

Table 13. Carbon content (g kg^{-1}) in different size fractions in different systems at Amayannoor

Systems	Size fractions		
	Macro size	Micro size	Silt-clay size
Mature Rubber	6.02	15.90	39.68
Rubber-*Pueraria*	9.68	15.26	37.38
Rubber- banana	5.52	13.34	37.62
Rubber- pineapple	6.44	13.16	33.06
SE	0.13	0.59	0.98
CD (P=0.05)	0.38	1.76	2.93

Carbon content in the micro sized fraction ranged between 13.16 - 15.90 g kg^{-1} in different systems. Mature rubber and rubber-*Pueraria* systems were not varying much in carbon content of this size fraction. However, the other two systems rubber-banana and rubber-pineapple systems were comparable and significantly lower in C content in micro size fraction. In the silt-clay sized fraction, carbon content in rubber-pineapple system was significantly lower than all other three systems which were having comparable carbon.

Percentage of total carbon in different size fractions of mature rubber is shown in figure 7. It could be observed that 75% of the total carbon is associated with the silt-clay sized fraction in the system. Only 14 and 11% of the total carbon is associated with macro sized and micro sized fractions respectively. Similarly the percentage of total C in different size fractions of rubber-*Pueraria*, rubber-banana and rubber-pineapple systems are given in figure 8, 9 and 10 respectively. In all the systems the silt-clay sized fraction had highest allocation of the total C.

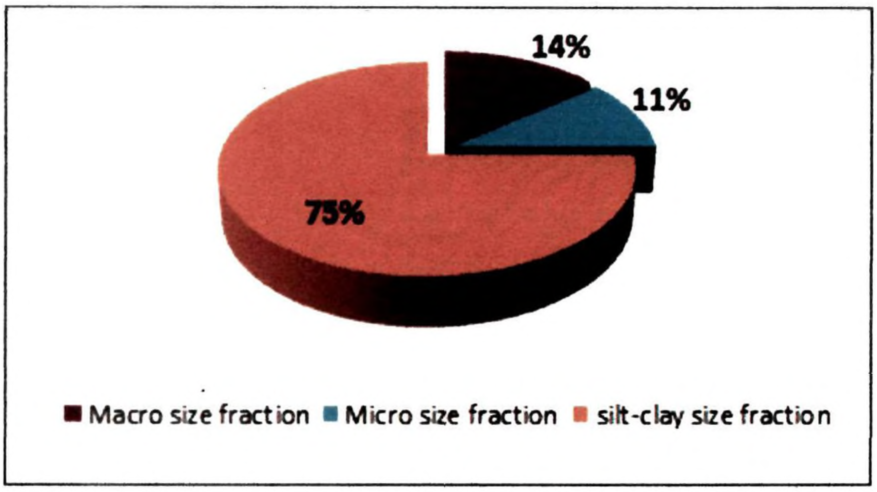


Fig. 7. Percentage of total C associated with different size fractions in mature rubber system at Amayannoor

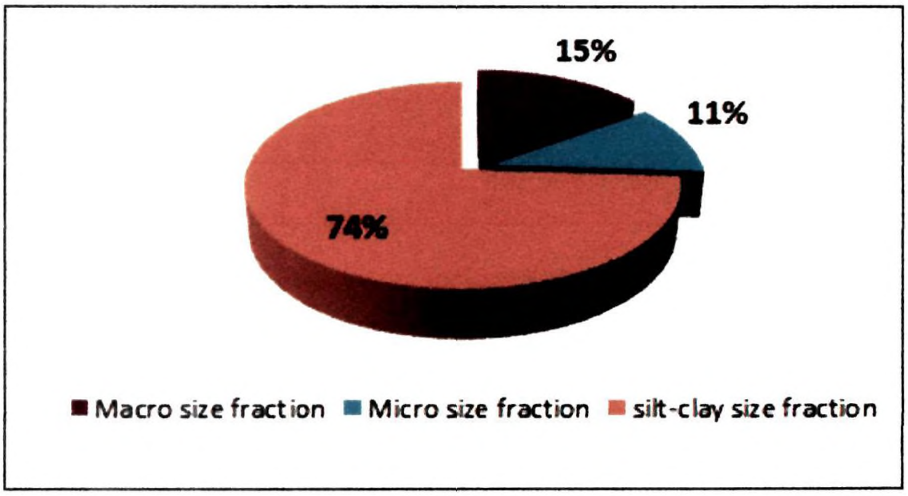


Fig. 8. Percentage of total C associated with different size fractions in rubber-*Pueraria* system at Amayannoor

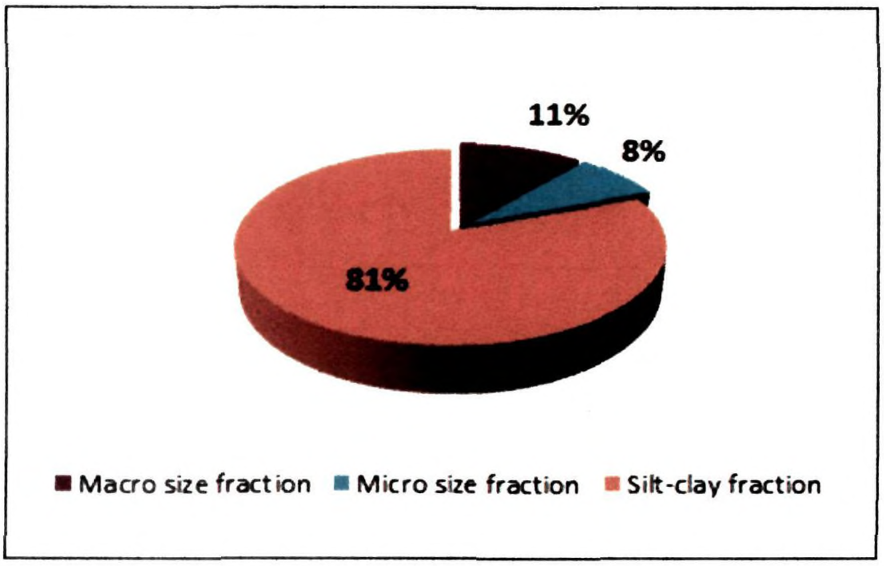


Fig. 9. Percentage of total C associated with different size fractions in rubber-banana system at Amayannoor

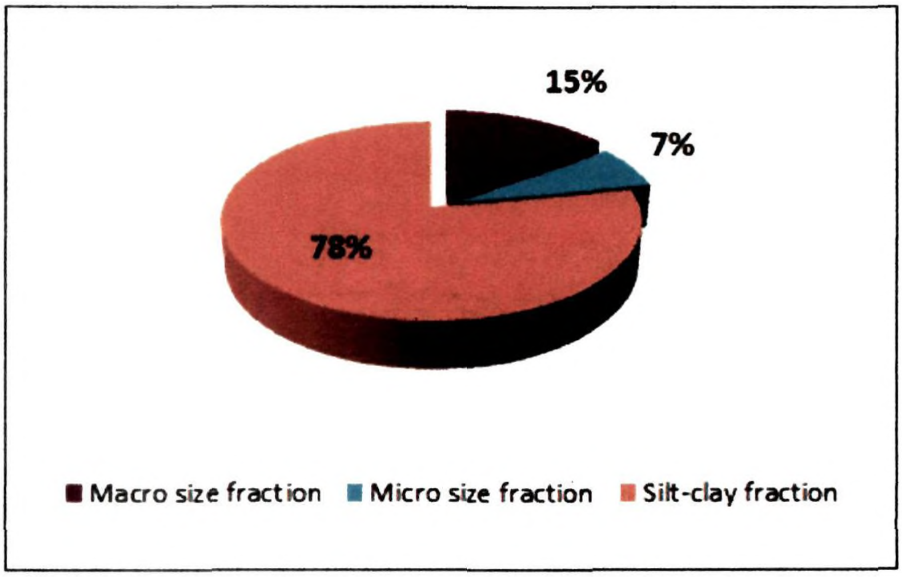


Fig. 10. Percentage of total C associated with different size fractions in rubber-pineapple system at Amayannoor

Labile Carbon Pools

Water soluble carbon (WSC), Hot water extractable carbon (HWEC) and Permanganate oxidizable soil carbon (POSC)

The data on WSC, HWEC, and POSC indicated that the studied systems were widely varying in organic matter quality (table 14).

Table 14. Labile carbons (WSC, HWEC and POSC) in different systems at Amayannoor

Systems	WSC	HWEC	POSC
	mg kg^{-1}		
Mature Rubber	35	378	627
Rubber-*Pueraria*	58	556	759
Rubber- banana	56	592	546
Rubber- pineapple	37	398	594
SE	2.42	16.87	12.18
CD (P=0.05)	7.26	50.57	36.52

WSC in the different systems varied from 35 to 58 mg kg^{-1}. It accounted for 0.16 - 0.26% of total OC. WSC in rubber-*Pueraria* and rubber-banana systems were comparable and were significantly higher than the other two systems. Rubber-pineapple and mature rubber systems were comparable in WSC status. Similar trend was observed in HWEC also. It ranged from 378 to 592 mg kg^{-1} in different systems and comprised of 1.84 - 2.74% of the total C. Among the four systems studied, rubber-*Pueraria* system recorded significantly higher POSC. Rubber-banana system showed lowest POSC status, while the other two systems were comparable. It accounted for 2.52 - 3.22% of total C.

Discussion

The variations in physical properties of the systems are mainly contributed by the management operations such as tillage, organic manure additions, pesticide / herbicide / fertilizer additions and quantity and quality of different litter inputs. The organic matter content of the systems can also influence the physical properties.

Usually the tillage operations increase porosity in soil systems. The rubber-pineapple system which had undergone heavy tillage in the previous year and was expected to have more porosity. The reduction in porosity might be due to the filling up of pores by the rain after the tillage for two years. It is reported that tillage operation may temporarily decrease bulk density and increase porosity and disturbs compacted soil layers, but subsequent rainfall events may re-compact the soil (NRCS, 2011; Arshad *et al.*, 1996). Probably the heavy input of higher quality litter in the case *Pueraria* system might have contributed towards its higher WSA. Though not quantified, it is observed that the crop residue turnover in banana system was much higher compared to rubber-pineapple system and had reflected in the soil physical properties of the system. The banana system received substantially higher amount of organic manure compared to the *Pueraria* system and this could be the reason for its higher WSA. The pineapple system received many agrochemicals in the form of herbicides and pesticides and also the crop residue turnover in the system was negligibly small and this could have adversely affected the WSA as well as particle density. Similar reports are there in other crops by Blanco-Canqui and Lal, (2004).

Comparatively lesser OC in mature rubber system observed in this study is in agreement with that reported by Zhang *et al.*, (2007) and Ulaganathan *et al.*, (2013). The higher OC status in *Pueraria* system could be due to the heavy input of quality litter. The lower OC status of rubber-pineapple system was as expected due to two reasons. The heavy mechanical tillage during the planting time might have resulted in heavy decomposition and also due to the translocation of finer particles to the down layers through rain water. Also the negligible turnover of crop residues in the system affected the OC status adversely. Could be due to the same reasons, CEC of *Pueraria* system was recorded higher whereas pineapple system had lower values. George *et al.*, (2012) also reported higher OC in cover cropped and banana intercropped rubber fields than pineapple inter cropped fields. Total N was significantly higher in *Pueraria* system and the reason could be due to the higher litter turnover and N fixation property of the legumes. Comparison of available nutrients such as P, K and Mg is not of much relevance as varying levels of inputs were there in the different systems. Build up of available phosphorus in rubber plantations intercropped with banana and pineapple was reported by Jessy *et al.*, (1996); George *et al.*, (2012). In general Mg contents were more in all the immature rubber systems as these systems received Mg fertilizer. Important observation on pH is that banana system had higher pH since, heavy input of organic manure in the system might have generated higher buffering capacity. Also presence of more basic cations in plant materials contribute to an increase in pH (Pocknee and Sumner, 1997). The higher inputs of agro-chemicals might have resulted in lowering the pH of pineapple system.

The higher C concentration in lower soil size fractions in different systems was as expected, since many other similar reports are there in other soil types (Jenkinson, 1988; Gregorich *et al.,* 1994; Six *et al.,* 2002). The C in the lowest fraction might get linked to mineral components and this may retard the C decomposition rates. The variation in C associated with macro sized fraction termed as coarse particulate organic matter (POM), plays dominant role in the decomposition process. Among the studied systems, *Pueraria* system had the highest C association in the macro sized fraction.

The different systems showed variation in water soluble carbon. Chen et al., (2004) ; Wang and Wang, (2011) also reported that WSC was affected by vegetation type. The difference can be attributed to the difference in litter / crop residue quality as plant litter and root exudates are the primary source of WSC (Qualis *et al.*, 1991). The higher quality of *Pueraria* litter especially due to the higher cellulose content (table 3) might have contributed to the higher WSC and HWEC contents in the system. The recalcitrant C species such as lignin and polyphenols were much higher in *Hevea* litter and consequently WSC as well as HWEC contents were low in the system. The POSC was also more in *Pueraria* system as expected, however, its lower status in banana system was not as expected and the reason is unknown.

Spectroscopic Characterization

UV-Vis Characterization

Absorbance of organic substances extracted by 0.05M $NaHCO_3$ were recorded at 254, 365, 465 and 665 nm. The absorbance ratio, E_2/E_3 (254 and 365 nm) and E_4/E_6 (465 and 665nm) are shown in table 15.

Table 15. UV-Vis absorbance ratios of organic substances in different systems at Amayannoor

Systems	Absorbance ratios	
	E_2/E_3	E_4/E_6
Mature Rubber	1.67	2.81
Rubber-*Pueraria*	3.66	4.52
Rubber- banana	2.87	4.22
Rubber- pineapple	2.52	3.26

It was found that mature rubber system recorded lowest E_2/E_3 value and rubber-*Pueraria* system the highest. The E_2/E_3 value decreased in the order rubber- *Pueraria* > rubber- banana > rubber- pineapple > mature rubber. E_4/E_6 values also showed a similar trend.

It has been reported that E_2/E_3 absorbance ratio is inversely correlated with molecular weight and aromaticity (Peuravuori and Pihlaja. 1997; Chen *et.al.,* 1994). The low E_2/E_3 ratio of mature rubber system indicated its higher aromaticity compared to other systems. The rubber-*Pueraria* system recorded the highest E_2/E_3 value which indicates the presence of relatively large quantities of aliphatic structures. The absorbance at higher wavelengths corresponds to more conjugation in the compounds, which reflects higher aromaticity or condensation.

Also, the E_4/E_6 ratio (absorbance measured at 465 and 665 nm) is related to the aromaticity and to the degree of condensation of the chain of aromatic carbons of the organic compounds and could be used as a humification index (Chen *et al.,* 1977). Low E_4/E_6 ratio also reflects a higher degree of condensation of aromatic structures while high ratio indicates presence of large quantities of aliphatic structures. E_4/E_6 is larger for non humified material by presence of proteins and carbohydrates, which increase the absorptivity in the UV region of the spectrum (Vieyra *et al.,* 2009).

The absorbance at 460 - 480 nm reflects the organic material at the beginning of humification and absorbance at 600 - 670 nm is indicative of strongly humified material with a higher degree of aromatic condensed groups (Albrecht, 2011).

IR characterization

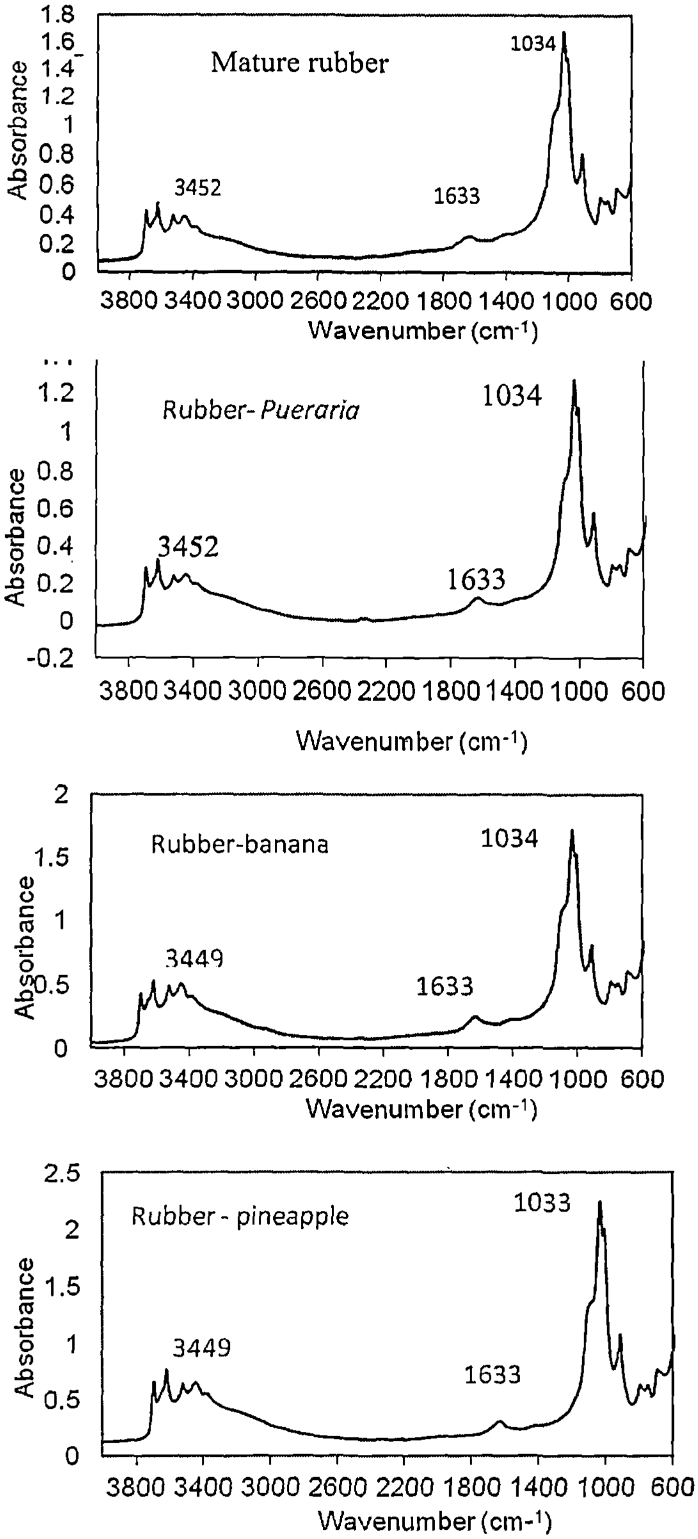


Fig: 11 FTIR Spectra of different rubber based systems at Amayannoor

The use of Fourier- Transformed Infrared (FTIR) spectroscopy is a useful tool for the analysis of SOM evolution in tropical soils (Haberhauer *et al.,* 2000). Figure 11 shows the FTIR spectra of bulk soils under rubber, rubber-*Pueraria*, rubber-banana and rubber-pineapple systems. The spectra shows same peak pattern for all the systems. Intense bands were recorded at about 3690 cm^{-1} (primary N-H stretch), 3400 cm^{-1} (stretching of bonded and non-bonded hydroxyl groups.), 1630 cm^{-1} (C=O vibrations of carboxylates and aromatic vibrations) and at 1034 cm^{-1} (C-O stretching vibrations of polysaccharides, carbohydrates) in all the systems.

In order to quantify the relative variations in the FTIR spectra and for spectral comparison, relative absorbance was calculated and is summarized in table 16.

Table 16. Relative IR absorbance of soils in different systems at Amayannoor

Systems	Relative absorbance at	
	1630 cm^{-1}	1034 cm^{-1}
Mature Rubber	18.31	81.68
Rubber-*Pueraria*	8.75	91.25
Rubber- banana	12.61	87.39
Rubber- pineapple	11.92	88.00

The relative absorption of the sharp band at 1034 cm^{-1} was the highest in rubber-*Pueraria* and the lowest in mature rubber system. The rubber-banana and rubber-pineapple systems showed comparable relative absorption and is intermediate to that of mature rubber and rubber-*Pueraria* system. The results indicate the presence of more carbohydrate and polysaccharides in rubber-*Pueraria* system than all the other systems. The relative absorption at 1630 cm^{-1} was highest in mature rubber and lowest in rubber-*Pueraria* system. The other two systems showed almost closer relative absorption.

The data revealed from the UV-Vis and IR spectra are complementary. Relatively more weathering or condensation had taken place in soils under mature rubber system. The strong IR absorption of mature rubber soils at 1630 cm^{-1} indicated more aromaticity in the rubber system. The higher aromaticity observed in the rubber-pineapple and rubber-banana systems than rubber-*Pueraria* might be due to the effect of associated management operations such as tillage. Tillage of soil leads to loss of more readily decomposable fraction, leading to an increase in the proportion of the more recalcitrant aromatic C forms in the SOM. Similar observations in other systems were reported by Golchin *et al.*, (1995) and Baldock *et al.*, (1997). It is also to be noted that the litter quality of rubber and *Pueraria* widely varied in terms of the presence of recalcitrant groups such as lignin and polyphenols and the labile species such as cellulose *etc.* (table 3). Also, Abraham and Chudek (2008) reported that based on ^{13}C NMR the *Pueraria* litter was having higher quality than rubber litter.

Based on the physical, chemical, organic matter quality parameters as well as UV-Vis and IR spectral evidences, it is rather clear that the SOM under mature rubber system had undergone more weathering and condensation and much of the total C in the system is associated with recalcitrant pool while the rubber-*Pueraria* system have relatively much higher content of labile C pool which can contribute significantly towards nutrient release especially in the growing phase of rubber. Among the intercrops, banana system is definitely superior in terms of SOM quality. The physical and chemical properties (table 9 and table 10) of rubber-banana system were superior to rubber-pineapple system. The soluble C contents also were more in rubber-banana system. However, for more confirmation, the results of C mineralization studies would be helpful.

4.2.2. Location 2. Mundakayam

The SOM characterization and soil properties of the four locations at Mundakayam are detailed below. The four studied systems were mature rubber, rubber-*Mucuna,* rubber-banana and rubber-pineapple.

Physical properties

The physical properties *viz.*, bulk density, particle density, porosity and WSA of the different systems at Mundakayam are given in table 17.

Table 17. Physical properties of soil in the different rubber based systems at Mundakayam

Systems	Bulk density	Particle density	Porosity	Water stable aggregates
	($Mg\ m^{-3}$)	($Mg\ m^{-3}$)	(%)	(%)
Mature Rubber	1.19	2.15	45.00	30.60
Rubber-*Mucuna*	1.06	2.16	52.60	38.60
Rubber- banana	1.07	2.19	51.20	44.20
Rubber- pineapple	1.18	2.16	45.60	28.60
SE	0.03	0.02	1.07	1.94
CD (P=0.05)	0.09	NS	3.20	5.81

Unlike the systems at the location, Amayannoor, the bulk density of the different systems were significantly varying at Mundakayam. The mature rubber and rubber-pineapple systems were having higher bulk density than the other two systems which were comparable. The particle density of the different systems did not vary much. Porosity of the rubber-*Mucuna* and rubber-banana systems were comparable and significantly higher than mature rubber and rubber-pineapple systems. The same trend was noted for WSA also.

Chemical properties

Table 18 and table 19 show the chemical properties of soils under different systems studied. There was significant difference in OC status of the various systems. It decreased among the systems in the order rubber-*Mucuna* > rubber- banana > rubber-pineapple > mature rubber. Similar trend was observed in CEC of the systems. Rubber-*Mucuna* recorded significantly higher CEC (9.76) and mature rubber (7.22) the lowest. Total nitrogen was also significantly higher in rubber-*Mucuna* system and it was lowest in mature rubber.

Table 18. Chemical properties of soil in the different rubber based systems at Mundakayam

Systems	OC	CEC	TN	Av. P	Av. K	Av.Ca	Av. Mg	pH
	g kg^{-1}	cmol(+) kg^{-1}	g kg^{-1}	mg kg^{-1}				
Mature rubber	19.13	7.22	1.63	15.64	56.98	64.70	22.66	4.44
Rubber-*Mucuna*	25.93	9.76	2.36	36.96	104.00	45.26	32.15	4.65
Rubber-banana	23.25	9.28	1.88	92.78	108.22	134.43	20.57	4.92
Rubber-pineapple	21.93	8.76	1.90	84.76	131.60	121.07	21.61	4.70
SE	0.44	0.07	0.01	3.39	11.89	12.44	2.32	0.04
CD(P=0.05)	1.32	0.22	0.03	10.18	35.66	37.29	6.95	0.11

Av. - Available

Available nutrients were also affected by the land use and management practices. Rubber-banana and rubber-pineapple systems recorded significantly higher available P than the other two systems. Rubber-*Mucuna*, rubber-pineapple and rubber-banana systems recorded comparable available K status, which was significantly higher than the mature rubber system. Available Ca was also significantly higher in rubber-banana and rubber-pineapple system than the rubber-*Mucuna* and mature rubber system. Rubber-*Mucuna* system recorded significantly higher available Mg status compared to other systems. Soil reaction in different systems showed significant variation. In general all the systems were strongly acidic in reaction. pH in the various systems decreased as follows rubber-banana > rubber-pineapple = rubber-*Mucuna* > mature rubber.

Among the different systems significant variation was observed in available micro nutrients Mn, Cu and Zn (table 19).

Table 19. Micronutrient (mg kg^{-1}) status of soil in the different rubber based systems at Mundakayam

Systems	Fe	Mn	Cu	Zn
Mature rubber	24.46	11.78	13.11	0.79
Rubber-*Mucuna*	33.96	10.70	28.16	5.55
Rubber- banana	27.65	28.74	27.40	2.51
Rubber- pineapple	26.02	12.75	29.45	0.91
SE	4.17	2.01	1.60	0.08
CD (P=0.05)	NS	6.05	4.80	0.24

Available Mn was significantly higher in rubber-banana system compared to other three systems. Higher available copper status was observed in all the systems, which ranged from 13.11 to 29.45 mg kg^{-1}. Rubber- *Mucuna* system recorded significantly higher Zn status followed by rubber-banana. Mature rubber and rubber- pineapple systems did not differ much in available Zn status, but lower than the other two systems. Available Fe status was not markedly influenced by the different land use/ management practices.

Characterization of SOM

Physical fractions

The distribution of soil particles in different size fractions are shown in table 20. It was noticed that different systems significantly varied in the particle size distribution.

Table 20. Weight (g kg^{-1}) of different size fractions in the different land use systems at Mundakayam

Systems	Size fractions		
	Macro size	Micro size	Silt- clay size
Mature Rubber	473.00	129.80	391.20
Rubber-*Mucuna*	371.80	199.60	422.60
Rubber- banana	377.00	192.20	427.80
Rubber- pineapple	414.40	140.80	441.20
SE	5.26	4.89	6.24
CD (P=0.05)	15.40	14.37	18.35

In mature rubber macro (2.00 - 0.250 mm) sized fraction was more than the silt-clay sized fraction whereas in the other three systems silt-clay sized fraction was more than the macro sized fraction. In all the systems, micro sized fraction was less than the other two size fractions. Among the four systems, macro sized fraction decreased in the order mature rubber > rubber–pineapple > rubber-banana = rubber-*Mucuna*. Rubber-*Mucuna* and rubber – pineapple systems recorded significantly higher amount of micro-sized fraction than the other two systems. Significantly lesser amount of silt-clay sized fraction was found in mature rubber than the other three systems which were comparable.

.Carbon in different size fractions

The data on carbon content in different particle size fractions of the different systems (Table 21) showed that it increased with decreasing size. In all the three size fractions, carbon content was more in rubber-*Mucuna* system. Major portion of soil carbon is associated with silt - clay sized fraction in all the systems.

Table 21. Carbon content (g kg^{-1}) in different size fractions in different systems at Mundakayam

Systems	Size fractions		
	Macro size	Micro size	Silt- clay size
Mature rubber	7.02	11.72	36.34
Rubber-*Mucuna*	9.66	20.84	43.00
Rubber- banana	7.50	12.22	42.84
Rubber- pineapple	8.06	12.74	38.22
SE	0.21	0.48	0.94
CD (P=0.05)	0.62	1.45	2.83

Percentage of total carbon in different size fractions of mature rubber is shown in Fig.12. It could be observed that 75% of the total carbon is associated with the silt-clay sized fraction.

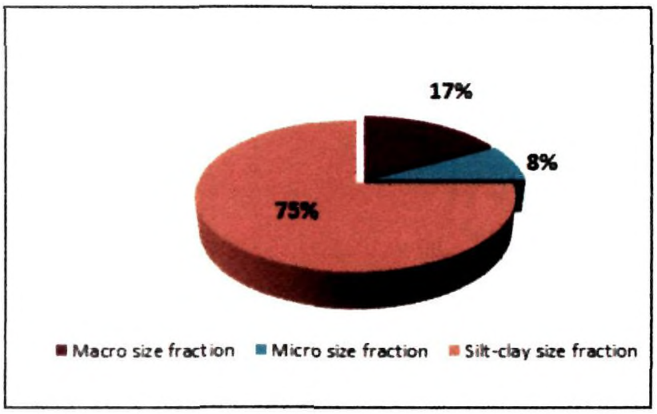


Fig. 12. Percentage of total C associated with different size fractions in mature rubber system

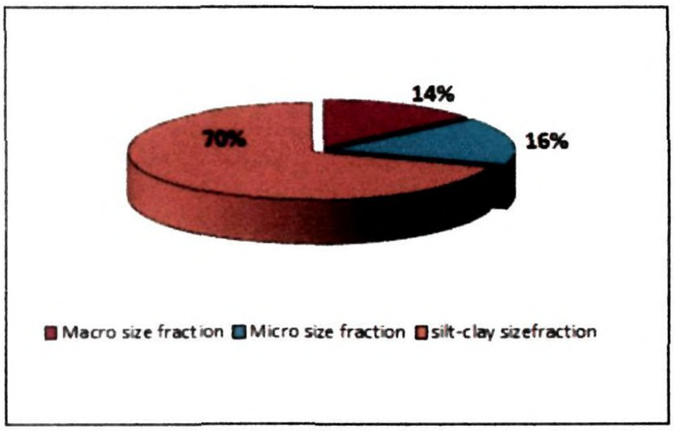
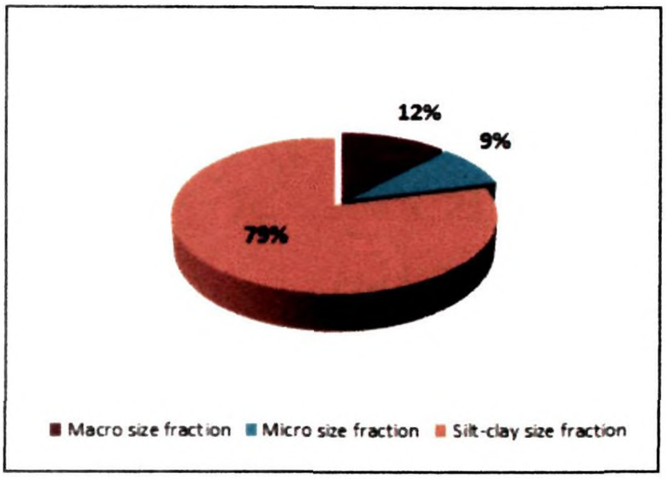
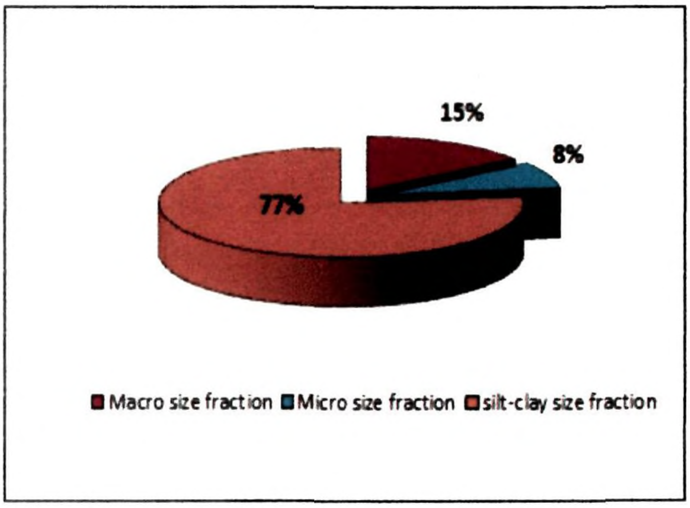


Fig. 13. Percentage of total C associated with different size fractions in rubber-*Mucuna* system at Mundakayam



;. 14. Percentage of total C associated with different size fractions in rubber-banana system at Mundakayam



5. Percentage of total C associated with different size fractions in rubber-pineapple system at Mundakayam

Similarly the percentage of total C in different size fractions of rubber-*Mucuna*, rubber-banana and rubber-pineapple systems are given in Fig. 13, 14 and 15 respectively. In all the systems the silt- clay sized fraction had highest allocation (70-79 %) of the total C.

Labile Carbon Pools

Water soluble carbon (WSC), Hot water extractable carbon (HWEC) and Permanganate oxidizable soil carbon (POSC)

Carbon in the labile pools are shown in table 22. The data on WSC, HWEC, and POSC indicated that the studied systems were widely varying in organic matter quality. It was observed that WSC widely varied among the systems and it holds on an average 0.18 - 0.22% of total carbon. Rubber-banana system recorded significantly higher WSC than the other three systems which were comparable. HWEC also varied among the systems and it accounted for 0.91 - 1.50% of total carbon. Among the four systems, rubber-pineapple system showed significantly lower HWEC and the other three were comparable. There was significant variation in POSC. It varied from 516 mg kg^{-1} (rubber-banana) to 716 mg kg^{-1} (rubber-*Mucuna).*

Table 22. Labile carbons (WSC, HWEC and POSC) in different systems at Mundakayam

Systems	WSC	HWEC	POSC
	mg kg^{-1}		
Mature Rubber	35	312	620
Rubber-*Mucuna*	39	389	716
Rubber- banana	52	313	516
Rubber- pineapple	38	200	660
SE	2.38	27.87	20.07
CD (P=0.05)	7.15	83.55	60.17

Discussion

It was observed that the four systems differed markedly in their soil physical and chemical properties. The management practices such as tillage, organic manure additions, and pesticide / herbicide / fertilizer additions affected soil physical properties. Quantity and *quality of litter inputs also might have influenced the soil* properties.

The higher litter input in *Mucuna* system might have contributed to the higher porosity and WSA. The crop residue additions in banana system were more than that in pineapple which might have lead to the better soil physical properties in rubber-banana system compared to rubber-pineapple system. Also to be noted, there were practically no residue turnover in pineapple system. The heavy tillage during the initial planting time and application of agro chemicals in pineapple system might have adversely affected the aggregate formation. The temporary advantageous effect of tillage on physical properties might have masked by subsequent rain fall factor as well as non repetition of tillage activities (NRCS, 2011; Arshad *et al.*, 1996). Comparatively higher organic manure addition in banana system might be the reason for its higher WSA. Whalen *et al.*, (2003) reported that application of organic manure enhances aggregate formation. The observations were similar to that in location, Amayannoor.

Comparatively lower OC in mature rubber system observed in this study also agreed with the findings of Ulaganathan *et al.*, (2013). The higher OC status in rubber-*Mucuna* system could be due to the heavy litter turnover. The lower OC status of rubber-pineapple system was might be due to the low residue input, more decomposition of organic matter as a result of tillage in the past and also due to the translocation of finer particles to the down layers through rain water. The higher organic carbon status in *Mucuna* and banana systems increased the CEC in these systems compared to the pineapple system. The high N content in *Mucuna* litter and N fixation capacity of the legume might have resulted in higher total N in this system. Comparison of available nutrients such as P, K and Mg was not of much relevance as varying levels of inputs were there in these systems. High pH in rubber-banana system and low pH in rubber-pineapple system observed was in agreement with that of George *et al.*, (2012). The heavy input of organic manure in banana fields might have contributed towards the higher buffering capacity. Probably higher inputs of agro-chemicals might have resulted in lowering the pH of pineapple system. Low pH in *Mucuna* established fields was also reported by many authors (Philip *et al.*, 2005; Jessy *et al.*, 2013).

The increase in C content with decrease in particle size observed in this study was in agreement with the findings of Solomon *et al.*, (2000) and Jagadamma *et al.*, (2010). Carbon in the silt-clay sized fraction might get linked to mineral components and this may retard the C decomposition rates.

The recalcitrant C species such as lignin and polyphenols were much higher in rubber litter and consequently the soluble forms *viz.,* WSC as well as HWEC contents were lower in this system. Though the *Mucuna* litter is not of much higher quality because of the presence of large amounts of tannins (Abraham and Chudek. 2008), the large quantity input in the system might have contributed to the higher HWEC in the rubber-*Mucuna* system.

Spectroscopic Characterization

The absorbance ratio E_2/E_3 (254 and 365 nm) and E_4/E_6 (465 and 665 nm) of organic substances are shown in table 23.

Table 23. UV-Vis absorbance ratios of organic substances in different systems at Mundakayam

Systems	Absorbance ratios	
	E_2/E_3	E_4/E_6
Mature rubber	1.50	2.73
Rubber-*Mucuna*	2.80	3.05
Rubber- banana	3.06	4.14
Rubber- pineapple	3.00	3.46

Rubber-banana and rubber-pineapple systems had the highest E_2/E_3 values. Mature rubber system showed the lowest E_2/E_3 value. Lower E_2/E_3 values of mature rubber system indicated that SOM in the system had higher degree of aromaticity and more condensation. E_4/E_6 ratio of the different systems increased in the order mature rubber < rubber- *Mucuna* < rubber-pineapple < rubber-banana. The result confirms the higher condensation of SOM in the mature rubber system. Comparatively higher E_4/E_6 value in immature systems indicates more aliphatic nature of organic compounds in these systems which might be due to the fresh additions of organic matter in the form of legume litter, crop residues and organic manure.

IR characterization

Figure 16, shows the FTIR spectra of soils under rubber, rubber-*Mucuna*, rubber-banana and rubber- pineapple systems at Mundakayam. All the spectra showed same peak pattern. Intense bands were recorded at about 3690 cm^{-1} (primary N-H stretch), 3400 cm^{-1} (stretching of bonded and non-bonded hydroxyl groups), 1630 cm^{-1} (C=O vibrations of carboxylates and aromatic vibrations) and at 1034 cm^{-1} (C-O stretching vibrations of polysaccharides, carbohydrates) in all the systems.

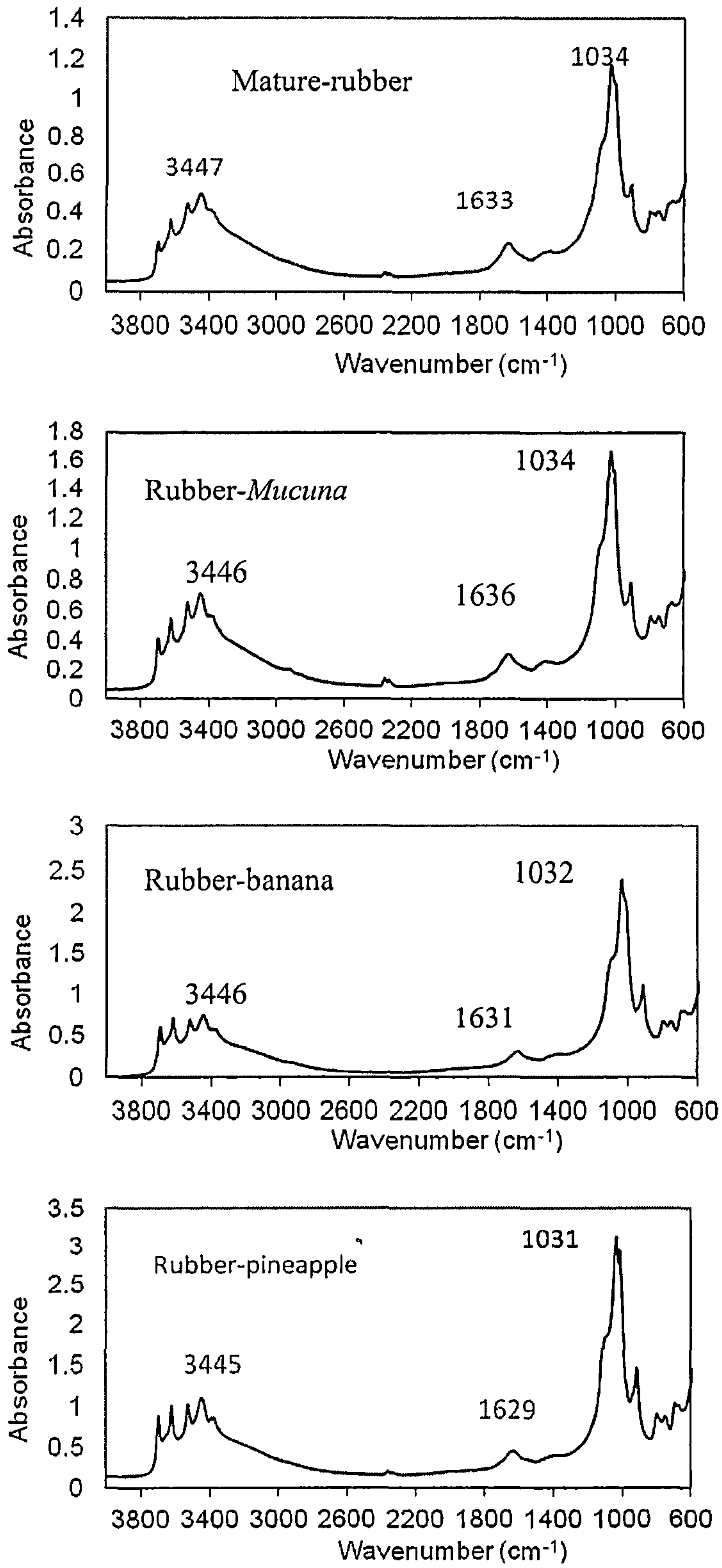


Fig: 16 FTIR Spectra of different rubber based systems at Mundakayam

Table 24. Relative IR absorbance of soils in different systems at Mundakayam

Systems	Relative absorbance at	
	1630 cm^{-1}	1034 cm^{-1}
Mature rubber	16.67	83.32
Rubber-*Mucuna*	15.80	84.20
Rubber- banana	11.08	88.85
Rubber- pineapple	12.71	87.29

For spectral comparison, relative absorbance was calculated and is summarized in table 24. The relative absorption at 1034 cm^{-1} was highest in rubber-banana system and lowest in mature rubber system. The relative absorptions of rubber-*Mucuna* and rubber-pineapple systems were intermediate to that of mature rubber and rubber-banana systems. Higher absorption at 1034 cm^{-1} indicates the presence of more carbohydrates and polysaccharides in rubber- banana system than all other systems. The relative absorption at 1630 cm^{-1} was highest in mature rubber and lowest in rubber-banana system. Relative absorptions were intermediate in the other two systems. The strong absorption of mature rubber at 1630 cm^{-1} indicates more aromaticity and hence more condensation in the SOM of rubber system.

The spectroscopic data revealed from the UV-Vis and IR results are complementary. Relatively more weathering or condensation had taken place in soils under mature rubber system as in the location, Amayannoor. The strong IR absorption of mature rubber soils at 1630 cm^{-1} indicated more aromaticity in the rubber system. Heavy mechanic tillage during the initial planting time in rubber-pineapple system and repeated manual tillage operations in rubber-banana system might have contributed for the higher aromaticity of the SOM in the systems. Tillage might have hastened the process of microbial activity which in turn had resulted in higher consumption of less aromatic less condensed forms of SOM. Also the tillage induced leaching might have triggered the loss of soluble and less aromatic species from the systems. These might have led to an increase in the proportion of the more recalcitrant aromatic C forms in the SOM in the tillage operated systems. Similar observations in other systems were already mentioned while the results of other location were discussed (Golchin *et al.*, 1995; Baldock *et al.*, 1997). It is also to be noted that the litter quality of *Hevea* and *Mucuna* was widely varying in terms of the presence of recalcitrant groups such as lignin and polyphenols and the labile species such as cellulose *etc.* (table 3).

Based on the physical, chemical, organic matter quality parameters as well as UV-Vis and IR spectral evidences, SOM under mature rubber system had undergone more weathering and condensation and much of the total C in the system was found to be associated with recalcitrant pool while the rubber-banana and rubber-*Mucuna* systems had relatively higher contents of labile C pool which can contribute significantly towards nutrient release especially in the growing phase of rubber. Among the intercrops, banana system is definitely superior in terms of SOM quality as in the case at location, Amayannoor. The physical and chemical properties (table 17 and table 18) of rubber-banana system were superior to rubber-pineapple system. The soluble C contents also were more in rubber-banana system.

4.2.3. Location 3. Erumely

The SOM characterization and soil properties of the three systems at location Erumely are detailed below. The three systems studied were mature rubber, rubber- *Mucuna,* rubber-*Pueraria.*

Physical properties

The physical properties *viz.*, bulk density, particle density, porosity and WSA of the different systems at Erumely are given in table 25. Bulk density was significantly higher in rubber-*Mucuna* system than the rubber-*Pueraria* and mature rubber systems. Particle density was not affected by the different systems. Mature rubber system recorded significantly higher porosity than the other two systems. Rubber-*Pueraria* and rubber-*Mucuna* systems were comparable in porosity. There was significant difference in water stable aggregates also. Mature rubber system showed higher aggregate stability, which was comparable with that of rubber-*Pueraria* system.

Table 25. Physical properties of soil in the different rubber based systems at Erumely

Systems	Bulk density	Particle density	Porosity	Water stable aggregates
	(Mg m^{-3})	(Mg m^{-3})	(%)	(%)
Mature Rubber	1.07	2.15	50.63	51.37
Rubber-*Pueraria*	1.11	2.12	45.60	46.91
Rubber-*Mucuna*	1.20	2.14	45.12	44.44
SE	0.03	0.01	1.28	1.53
CD (P=0.05)	0.08	NS	3.76	4.50

Chemical properties

There was significant variation in OC status of the three systems (Table 26). Higher OC status was noticed in mature rubber system followed by rubber-*Pueraria* and rubber-*Mucuna* systems. Available P status was significantly higher in rubber-*Pueraria* system. The other two systems were comparable in available P status.

Table 26. Chemical properties of soil in different rubber based systems at Erumely

Systems	OC	CEC	TN	Av. P	Av. K	Av.Ca	Av. Mg	pH
	g kg^{-1}	cmol(+) kg^{-1}	g kg^{-1}	mg kg^{-1}				
Mature Rubber	25.10	10.16	2.37	30.86	140.93	172.70	47.21	4.90
Rubber-*Pueraria*	21.86	9.69	2.28	43.00	108.44	74.80	19.26	4.82
Rubber-*Mucuna*	19.08	8.03	2.06	22.50	105.44	108.13	26.42	4.89
SE	0.56	0.13	0.06	3.48	6.13	8.51	1.69	0.05
CD (P=0.05)	1.69	0.38	0.18	10.45	18.41	25.52	5.09	NS

Av. - Available

Mature rubber system recorded significantly higher available K compared to other to systems which were on par. There was distinct variation in available Ca and Mg status also. Significantly higher Ca status was observed in mature rubber system followed by rubber-*Mucuna* system and rubber-*Pueraria* system. Similar trend was observed in available Mg status also. CEC was significantly higher in mature rubber systems followed rubber-*Pueraria* and rubber-*Mucuna* systems. Total nitrogen in mature rubber and rubber-*Pueraria* systems were comparable and significantly higher than rubber-*Mucuna* system. The soils in the three systems were strongly acidic in reaction.

Available micro-nutrient status also showed significant variation between the systems (table 27). Mature rubber and rubber-*Pueraria* systems had comparable Fe status and it was significantly higher than that of rubber-*Mucuna* system. Mn status was comparable in mature rubber and rubber-*Mucuna* systems. Rubber-*Pueraria* system had a significantly lower Mn status. The Cu status in three systems did not differ much. Mature rubber system showed a significantly higher Zn status. The other two systems were comparable in Zn status.

Table 27. Micronutrient (mg kg^{-1}) status of the different rubber based systems at Erumely

Systems	Fe	Mn	Cu	Zn
Mature Rubber	31.88	53.89	25.82	1.57
Rubber-*Pueraria*	32.48	42.81	27.89	0.90
Rubber-*Mucuna*	25.85	62.71	24.20	1.07
SE	1.45	3.15	1.89	0.08
CD (P=0.05)	4.36	9.46	NS	0.24

Characterization of SOM

Physical fractions

Table 28. Weight (g kg^{-1}) of different physical fractions in the different land use systems at Erumely

Systems	Size fractions		
	Macro size	Micro size	Silt-clay size
Mature Rubber	424.87	169.25	402.25
Rubber-*Pueraria*	358.00	129.50	500.37
Rubber-*Mucuna*	458.87	143.00	394.00
SE	7.61	5.13	7.87
CD (P=0.05)	22.40	15.08	23.16

The distribution of soil particle size fractions was different among the systems (Table 28). Among the three size fractions, macro sized fraction was more in mature rubber and rubber-*Mucuna* systems whereas in rubber-*Pueraria* system silt-clay sized fraction was more than the other two size fractions. In all the three systems the micro sized fraction was lowest.

There was a distinct variation in the carbon content in the various size fractions (table 29). As in the other two locations here also carbon content in the three size fractions increased in the order macro size fraction < micro size fraction < silt-clay size fraction.

Table 29. Carbon content (g kg^{-1}) in the different size fractions in the different land use systems at Erumely

Systems	Size fraction		
	Macro size	Micro size	Silt- clay size
Mature Rubber	10.11	18.22	46.75
Rubber-*Pueraria*	7.73	15.11	38.51
Rubber-*Mucuna*	6.70	9.10	36.62
SE	0.38	0.41	0.86
CD (P=0.05)	1.13	1.21	2.58

Carbon content between the systems also showed significant variation. Carbon content in the macro-size fraction decreased in the order mature rubber > rubber-*Pueraria*> rubber-*Mucuna*. Similar trend was observed in micro-size fraction also. In the silt-clay size fraction, significantly higher carbon content was noticed in mature system. The other two systems had a comparable, lower carbon content in the silt-clay size fraction. The proportion of C in size fractions of different systems are presented in the Fig.17, 18 and 19. It is observed that 12 – 16 % of total carbon was found in macro size fraction and 7 - 12 % was associated with micro size fraction. As in other two locations, major portion of carbon (72-80 %) was found in silt-clay size fraction of the three systems at Erumely also.

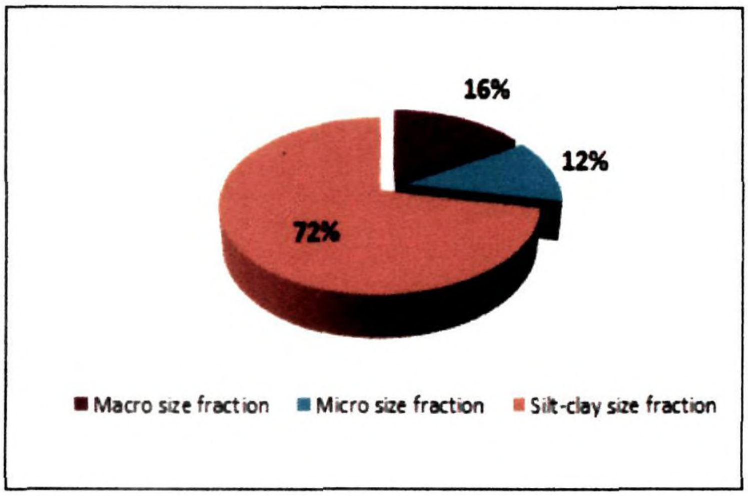


Fig. 17. Percentage of total C associated with different size fractions in mature rubber system at Erumely

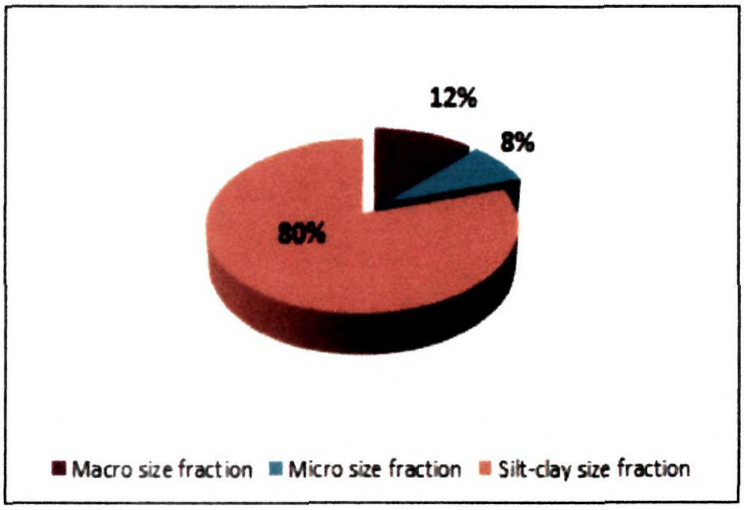


Fig. 18. Percentage of total C associated with different size fractions in rubber-*Pueraria* system at Erumely

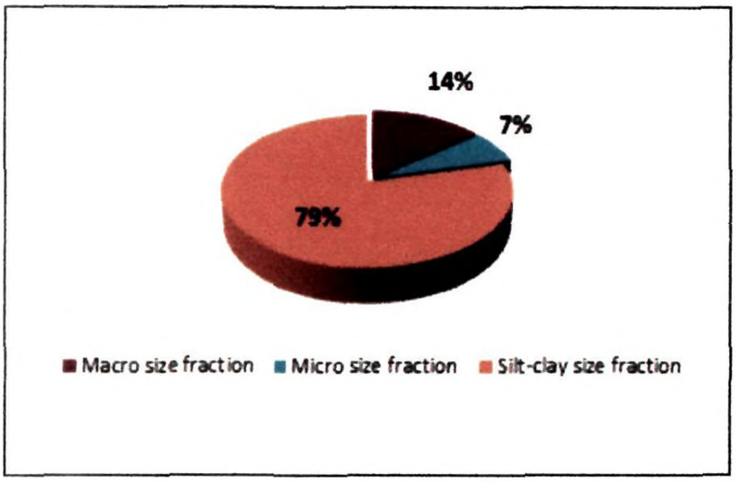


Fig.19. Percentage of total C associated with different size fractions in rubber-*Mucuna* system.

Labile Carbon Pools

Water soluble carbon (WSC), Hot water soluble carbon (HWEC) and Permanganate oxidizable soil carbon (POSC)

Table 30 presents the carbon in the labile pool. The data on WSC, HWEC and POSC indicated that the studied systems were widely varying in organic matter quality. WSC was significantly higher in legume species *viz.*, in rubber-*Pueraria* system and rubber-*Mucuna* system. Mature rubber system recorded lowest WSC. Rubber-*Pueraria* system recorded significantly higher HWEC also and it was comparable with that in the mature rubber. Rubber-*Mucuna* system was significantly lower in HWEC. POSC also showed significant variation between systems. It decreased among the systems as follows mature rubber > rubber-*Pueraria* > rubber –*Mucuna*.

Table 30. Labile carbons (WSC, HWEC and POSC) in different systems

Systems	WSC	HWEC	POSC
	mg kg^{-1}		
Mature Rubber	24	389	835
Rubber- *Pueraria*	28	401	783
Rubber-*Mucuna*	27	268	725
SE	0.64	20.98	16.32
CD (P=0.05)	1.92	62.99	48.98

Discussion

It was observed that the three systems differed in their soil physical and chemical properties. Unlike in other locations, the systems in Erumely did not have tillage or other soil disturbances since only legume cover crop situations are there. Probably because of the close proximity of the location to the existing forest environment, OC status remained higher in mature rubber compared to that in other locations. The higher OC status in mature rubber system in Erumely had contributed towards its better physical and chemical properties. Also to be noted the available nutrients and CEC also where markedly higher in mature rubber compared the immature rubber systems with legumes. It is important to note that the available Zn status also was more in mature rubber system probably again due to the higher OM status.

However, the labile C fractions represented by WSC and HWEC were more in rubber–*Pueraria* system. The higher cellulose content (table 3) in *Pueraria* litter compared to *Mucuna* and rubber litter might have contributed to the higher water and hot water soluble carbon contents in the system. The recalcitrant C species such as lignin and polyphenols were much higher in rubber litter and consequently soluble C contents were lower in the system.

Distribution of C in different size fractions followed the same trend in Erumely also as in other locations. The C concentration in lower soil size fractions in different systems were more than in the larger size fractions. The C in the silt-clay sized fraction might get linked to mineral components and this may retard the C decomposition rates. The C associated in the macro and micro sized fractions were more in mature rubber system probably due to its higher OC status.

Spectroscopic characterization

Among the three systems mature rubber system showed lower E_2/E_3 ratio of 1.65 whereas that in rubber-*Mucuna* and rubber-*Pueraria* systems were having the ratio as 3.04 and 3.65 respectively (table 31).

Table 31.UV-Vis absorbance ratios of organic substances in different systems at Erumely

Systems	Absorbance ratios	
	E_2/E_3	E_4/E_6
Mature Rubber	1.65	2.86
Rubber- *Pueraria*	3.65	5.15
Rubber-*Mucuna*	3.04	3.25

Since E_2/E_3 ratio is an indication of higher aromaticity, SOM in mature rubber system might have undergone more weathering and condensation as observed in other locations. Similarly rubber-*Pueraria* system as in other locations was having higher E_2/E_3 value probably because of the presence of more cellulose in the litter. E_4/E_6 ratio also showed similar trend. E_4/E_6 ratio decreased in the systems as follows; rubber-*Pueraria* >

rubber-*Mucuna* > mature rubber. The low E_4/E_6 value in mature system indicted its higher condensation than the immature systems.

IR characterization

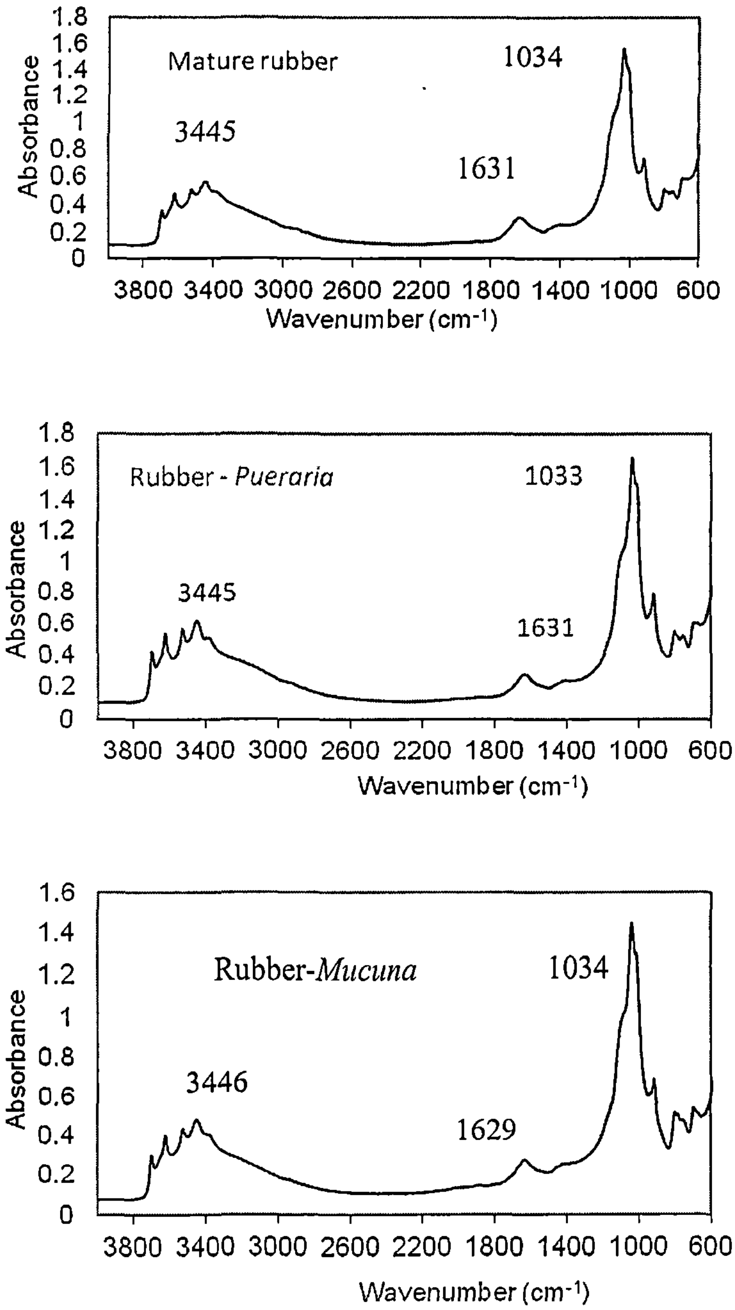


Fig. 20 FTIR Spectra of different rubber based systems at Erumely

Figure 20 shows the FTIR spectra of soils under mature rubber, rubber-*Pueraria* and rubber-*Mucuna* systems in Erumely. All the spectra showed same peak pattern. Intense bands were recorded at about 3690 cm^{-1}(primary N-H stretch), 3400 cm^{-1} (stretching of bonded and non-bonded hydroxyl groups.), 1630 cm^{-1}(C=O vibrations of carboxylates and aromatic vibrations) and at 1034 cm^{-1} (C-O stretching vibrations of polysaccharides, carbohydrates) in all the systems.

For spectral comparison, relative absorbance was calculated and is summarized in table 32. Relative absorbance at 1630 cm^{-1} was highest in mature rubber and lowest in rubber-*Pueraria* system. The relative absorbance of rubber-*Mucuna* was in between the other two systems. Stronger absorption of mature rubber system in aromatic region shows its more condensation and humification than the immature systems. The relative absorption at 1034 cm^{-1} was highest in rubber- *Pueraria* system and lowest in mature rubber system. Higher absorption at 1034 cm^{-1} indicated the presence of more carbohydrates and polysaccharides in rubber- *Pueraria* system than other systems.

Table 32. Relative IR absorbance of soils in different systems at Erumely

Systems	Relative absorbance at	
	1630 cm^{-1}	1034 cm^{-1}
Mature Rubber	16.35	83.65
Rubber- *Pueraria*	14.30	85.51
Rubber-*Mucuna*	16.19	83.81

The spectroscopic data revealed from the UV-Vis and IR results are complementary at Erumely also as in other locations. Relatively more weathering or condensation had taken place in soils under mature rubber system as in locations, Amayannoor and Mundakayam.

The strong IR absorption of mature rubber soils at 1630 cm^{-1} indicated more aromaticity in the rubber system. Litter quality of rubber, *Pueraria* and *Mucuna* were varying in terms of the presence of recalcitrant groups such as lignin and polyphenols and the labile species such as cellulose *etc.* (table 3) which had influenced the SOM characteristics as well. More recalcitrant groups might have remained in the soil for longer periods and might have undergone more decomposition or humification, thus more aromatic behavior for the SOM in mature soil.

Based on the physical, chemical, organic matter quality parameters as well as UV-Vis and IR spectral evidences, SOM under mature rubber system had undergone more weathering and condensation and much of the total C in the system was found to be associated with recalcitrant pool while the rubber-*Pueraria* system had relatively much higher contents of labile C pool which can contribute significantly towards nutrient release especially in the growing phase of rubber. However, the OC status of mature rubber was more and had influenced positively on many of the physical and chemical soil properties of the system. This observation was specific to this location and might be due to the close proximity of existing forest ecosystems.

4.3. Carbon mineralization – Location -Amayannoor

Carbon mineralization pattern of soils under different land use systems *viz.,* mature rubber, rubber-*Pueraria,* rubber-banana and rubber-pineapple at location, Amayannoor is shown in fig. 21.

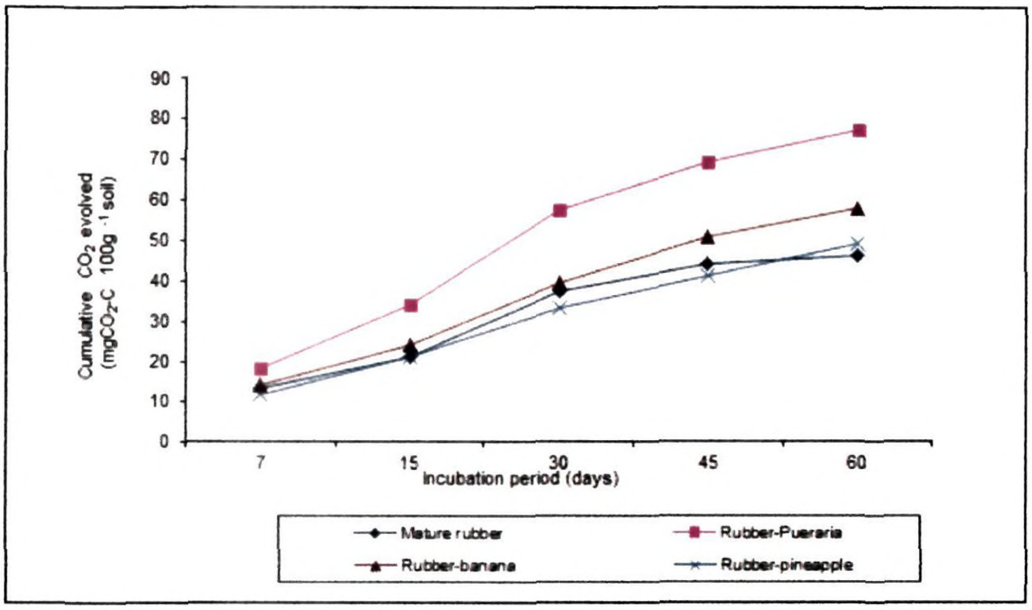


Fig. 21. Cumulative CO_2 evolution from soils under different systems at Amayannoor

There was a rapid release of CO_2 in the initial phase in all the systems studied which was followed by a slow phase. The cumulative CO_2 evolution during 60 days of incubation from soils of the four systems ranged from 46 to 77 mg CO_2-C *100* g^{-1} soil. Carbon dioxide evolution was highest in rubber-*Pueraria* system followed by rubber-banana system and the lowest in mature rubber system.

The decomposability of the organic matter in different systems was estimated by considering the amount of C mineralized per unit weight of OC in each system. It was found that, there was significant difference in total C mineralized (mg CO_2-C g^{-1}soil-C) during the incubation period of 60 days (Table 33). The C mineralization rate per day per unit soil-C was also worked and shown in table 33.

Table 33. Carbon mineralized from different systems at Amayannoor

Systems	C mineralized (mg CO_2-C g^{-1}soil-C	
	60 days	1 day
Mature rubber	22.42	0.37
Rubber- *Pueraria*	32.92	0.55
Rubber- banana	26.83	0.45
Rubber- pineapple	25.38	0.42
SE	0.87	0.01
CD (P=0.05)	2.60	0.04

Rubber-*Pueraria* system recorded highest cumulative CO_2-C evolution while the mature rubber system had the lowest. The rate of carbon mineralization (mg CO_2-C g^{-1} soil-C day^{-1}) was in the order rubber- *Pueraria* > rubber- banana = rubber-pineapple > mature rubber.

Correlations were worked out between C mineralization rate and different SOM quality parameters such as OC, WSC, HWEC, POSC and C in macro fraction of different systems and are shown in table 34. It could be observed that C mineralization rate was significantly and positively correlated to WSC, HWEC, POSC, OC and C in macro sized fraction. Correlation was the highest in the case of WSC and HWEC.

The reason for higher mineralization rate of *Pueraria* system was quite evident by the presence of more WSC, HWEC, POSC and C in the macro fraction. The mature rubber system had the lowest WSC, HWEC and C in macro fraction which had reflected in the lower C mineralization rate (table 13 and 14).

Table 34. Correlation between soil quality parameters and C mineralization

Soil quality	C Mineralization
WSC	0.80**
HWEC	0.72**
POSC	0.56*
OC	0.75**
Macro fraction-C	0.77**

** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

Micro-organisms play a dominant role in SOM mineralization (Tate, 2000). WSC is a favorable substrate for microorganism and a large portion of it is readily decomposable (Davidson *et al.,* 1987). Higher WSC might have enhanced the microbial activity, which in turn had reflected in higher C mineralization in rubber-*Pueraria* system. Kaur *et al.*, (2008) also reported that higher WSC enhanced C mineralization. Ahn *et al.*, (2009) also found high correlation between C mineralization rate and HWEC. The higher mineralization in rubber-*Pueraria* system indicated its higher nutrient supplying potential than the other two intercropped (banana and pineapple) systems. The lower mineralization in mature rubber plantation indicated its carbon sequestration potential.

SUMMARY AND CONCLUSIONS

Chapter 5

SUMMARY AND CONCLUSIONS

The study revealed that the nutrient content and biochemical constituents vary in *Pueraria, Mucuna* and *Hevea* litter. The decay rates of the three litter species also varied in rubber plantations. The decay rates of legume litter species *viz., Mucuna* and *Pueraria* was at a higher rate compared to that of rubber. During the growing phase of rubber, when higher nutrient demand exists, the cultivation of legumes, *Mucuna* and *Pueraria* are beneficial in improving soil quality. The biochemical constituents such as lignin and polyphenols were negatively correlated to decay rate. The rubber litter having higher lignin and polyphenols decompose slowly and the nutrient release also could be impaired. Though the C/N ratio of *Mucuna* and *Pueraria* litter was not varying much, their polyphenol contents differed significantly, which might have contributed to the variation in different decay rates of these litters. The decay rate or nutrient release pattern was more depending on the different C species rather than mere total C and N contents.

The four rubber based land use systems *viz.,* mature rubber, rubber-*Pueraria,* rubber -banana and rubber-pineapple were studied at location Amayannoor. It could be observed that the management operations such as tillage, organic manure additions, pesticide / herbicide / fertilizer additions and quantity and quality of different litter inputs in the systems had influenced the physical and chemical properties and organic matter quantity and quality of the systems.The rubber-pineapple system, which had undergone heavy tillage during the planting time had resulted in deterioration of physical properties of the system. In the rubber- *Pueraria* system, the heavy input of higher quality litter has contributed towards improvements in physical, chemical properties and soil organic matter quality. Similarly the higher crop residue turnover in banana system had improved the system compared to rubber-pineapple system especially in the soil physical properties of the system. Comparatively lesser OC in mature rubber system was observed. The higher OC status in *Pueraria* system could be due to the heavy input of quality litter. The OC status of rubber-pineapple system was lower than other systems and tillage could be major reason for that. The heavy mechanical tillage during the planting time might have resulted in faster decomposition and also could be due to the translocation of finer particles to the down layers through rain water. Also the negligible turnover of crop residues in the system affected the OC status adversely in pineapple system. Another important observation is on pH in banana system. The heavy input of organic manure might have contributed towards the higher buffering capacity and improvement in soil acidity. The C concentration was more in lower soil size fractions in all the systems studied. The C in the lowest fraction might get linked to mineral components and this may retard the C decomposition rates. Among the studied systems, *Pueraria* system had the highest C association in the macro sized fraction. The higher quality of *Pueraria* litter especially due to the higher cellulose content have contributed to the higher labile C pool in the system. The recalcitrant C species such as lignin and polyphenols were much higher in rubber system. The POSC was also more in *Pueraria* system. The data from the UV-Vis and IR spectra revealed that more weathering or condensation had taken place in soils under mature rubber system. More aromatic behavior is expressed by the SOM in mature rubber system. Also the SOM in rubber-pineapple and rubber-banana systems were more aromatic in nature than rubber-*Pueraria* system.

Based on the physical, chemical, organic matter quality parameters as well as UV-Vis and IR spectral evidences, it is rather clear that the SOM under mature rubber system had undergone more weathering and condensation and much of the total C in the system is associated with recalcitrant pool while the rubber-*Pueraria* system have relatively much higher content of labile C pool, which can contribute significantly towards nutrient release especially in the growing phase of rubber. Among the intercrops, banana system is definitely superior in terms of SOM quality. The physical and chemical properties of rubber-banana system were superior to rubber-pineapple system.

The four systems studied at Mundakayam were mature rubber, rubber-*Mucuna,* rubber- banana and rubber-pineapple. It was observed that the four systems differed markedly in their soil physical and chemical properties. As at Amayannoor, the management practices such as tillage, organic manure additions and pesticide/herbicide/fertilizer additions affected soil physical properties. Quantity and quality of litter inputs also had influenced the soil properties. The higher litter input in rubber-*Mucuna* system had positively influenced the physical propeties of the system. Similarly the crop residue additions in banana system also reflected positively in improving soil quality especially when compared to rubber-pineapple system. The heavy mechanical tillge and applicatioon of agro chemicals in the pineapple system might have adversely affected the rubber-pineapple system. As at Amayannoor, lower OC status was noted in the mature rubber system compared to *Mucuna* system. Pineapple system had lower OC as at Amayannoor. As observed at Amayannoor, banana system had higher pH since heavy input of organic manure might have contributed towards the higher buffering capacity. Carbon content was invariably higher in lower size fractions. Among the studied systems, *Mucuna* system had the highest C association in the macro sized fraction.

Based on spectral studies, it is clear that SOM under mature rubber system is expressing more aromatic behavior compared to other systems. Tillage operations in pineapple and banana systems had resulted in more aromaticity. Based on the physical, chemical, organic matter quality parameters as well as UV-Vis and IR spectral evidences, it is clear that SOM under mature rubber system had undergone more condensation hence expressing more aromaticity and much of the total C in the system was found to be associated with recalcitrant pool while the rubber-banana and rubber-*Mucuna* systems had relatively higher contents of labile C pool which can contribute significantly towards nutrient release especially in the growing phase of rubber. Banana is a better inter crop than pineapple in terms of improving soil quality.

The three systems studied at Erumely were mature rubber, immature rubber with *Mucuna,* immature rubber with *Pueraria.* Based on the physical, chemical, organic matter quality parameters as well as UV-Vis and IR spectral evidences, SOM under mature rubber system had undergone more weathering and condensation and much of the total C in the system was found to be associated with recalcitrant pool while the rubber-*Pueraria* system had relatively much higher contents of labile C pool which can contribute significantly towards nutrient release especially in the growing phase of rubber.

The C mineralization or soil respiration study clearly indicated that SOM decomposition is influenced by organic matter quality. The C mineralization experiment of the four systems *viz.,* mature rubber, rubber-*Pueraria,* rubber-banana and rubber- pineapple at location, Amayannoor revealed that CO_2 evolution was highest in rubber-*Pueraria* system followed by rubber-banana, rubber-pineapple and mature rubber systems. The C mineralization rate was significantly and positively correlated to WSC, HWEC, POSC, OC and C in macro sized fraction indicating that the labile carbon pools such as WSC, HWEC, POSC and C in macro sized fraction can be used as good soil quality indicators in rubber growing soils. As C mineralization was highly correlated with WSC and HWEC, estimation of any of these C fractions will serve as a tool to study the dynamics of labile C in rubber growing soils.

It could be observed that the different land use patterns in rubber had influenced soil properties and SOM quality. The banana is better and more beneficial in improving soil quality compared to pineapple as an intercrop in rubber. The heavy mechanical tillage operations as well as less crop residue turn over in pineapple system need to be viewed seriously as the study indicated deterioration of soil quality. Alternate or additional SOM management options need to be developed for the restoration of soil quality in heavy tilled pineapple soils. Similarly, *Pueraria* was found to be more beneficial in improving soil quality compared to *Mucuna* in rubber system. The *Pueraria* litter due to its higher quality generates more labile SOM pool and C mineralisation was faster in the system. During the growing phase of rubber, *Pueraria* cover crop would be a better option for faster and higher nutrient turn over and improving soil quality when compared to *Mucuna* as a cover crop in rubber system. The SOM under mature rubber system had undergone more condensation or humification and may remain in the system for longer periods. Though the nutrient turnover will be slower in the mature system, it would be environmentally beneficial as greenhouse gas emission would be at a lower rate. Certain indices such as WSC, HWEC, POSC and C in macro sized fraction are influencing C mineralization or soil microbial activity and can be used as good soil quality indicators in rubber soils.

Highlights

- The three major litter species in rubber plantation *viz.*, *Hevea*, *Pueraria* and *Mucuna* vary in quality, decomposition rate and nutrient release. Rubber litter had significantly higher content of lignin and polyphenols and lower contents of nitrogen and phosphorus than *Pueraria* and *Mucuna. Pueraria* litter had significantly higher cellulose, phosphorus and lower lignin and polyphenols than the other two litter species. Higher nitrogen and calcium and lower cellulose contents were present in *Mucuna* litter. The rate of decomposition of the three litter species decreased in the order *Pueraria* >*Mucuna* > *Hevea.*
- Carbon content in the soil particle size fractions increases with decrease in size.
- Major portion of carbon in soil is associated with silt- clay sized fraction.
- Among the different systems at Amayannoor, the labile pool of SOM was more in immature rubber with *Pueraria* and immature rubber with banana.
- Among the different systems at Mundakayam, labile pool of SOM was more in immature rubber with banana system.
- Among the three systems at Erumely, the labile pool of SOM was more in immature rubber with *Pueraria.*

- UV-Vis and FTIR spectroscopic characterizations indicated more condensation in mature rubber system than the immature systems at all locations.

- Carbon mineralization rate was more in immature rubber systems than in mature rubber systems. At Amayannoor the rate of carbon mineralization was in the order, rubber-*Pueraria* > rubber-banana = rubber-pineapple > mature rubber.

- The carbon mineralization was positively influenced by the labile C pool *viz.,* water soluble carbon and hot water extractable carbon.

- The WSC, HWEC, POSC and C in macro sized fraction are good indicators C mineralization and can be used as soil quality indices in rubber soils.

- The cover crop *Pueraria* generated more labile C pool and improves soil quality than the cover crop *Mucuna.*

- The intercrop, banana is better than pineapple in improving soil quality in rubber systems.

- SOM is more condensed and aromatic in mature rubber systems.

- Labile C pool comprising cellulose and carbohydrates are more in immature rubber systems with cover crop, *Pueraria* and inter crop, banana.

- Heavy mechanical tillage in pineapple system adversely affected the soil quality. Subsequent management may be required for restoration of soil quality.

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