George V Thomas
V. Krishnakumar *Editors*

Soil Health Management for Plantation Crops

Recent Advances and New Paradigms

Springer

Soil Health Management for Plantation Crops

George V Thomas • V. Krishnakumar
Editors

Soil Health Management for Plantation Crops

Recent Advances and New Paradigms

Springer

Editors
George V Thomas
Former Director
ICAR- Central Plantation Crops Research Institute
Kasaragod, Kerala, India

V. Krishnakumar
Former Principal Scientist and Head
ICAR- Central Plantation Crops Research Institute
Kayamkulam, Kerala, India

ISBN 978-981-97-0091-2 ISBN 978-981-97-0092-9 (eBook)
https://doi.org/10.1007/978-981-97-0092-9

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Paper in this product is recyclable.

Foreword

Plantation crops, being perennial tree crops with long life span, are important with respect to their capacity to deliver ecosystem services, including regulatory and supportive services, to build up healthy agro-ecosystems. Plantation crops sustain livelihood and socio-economic status of millions of people globally in tropical agro-ecosystem. The production systems of plantation crops are experiencing stress due to environmental factors concerning production base deterioration, dwindling biodiversity resources and decline in soil fertility. There is an urgent need to transform the plantation agriculture systems to make them more productive, environmentally sustainable and resilient while preserving and enhancing the ecological base of farming.

It is now recognized that anthropogenic interventions since the advent of organized agriculture, particularly intensive use of synthetic fertilizers alone as nutrient source and application of chemical pesticides with the objective of increasing production and the unscientific management practices followed, had adverse impact on soil resource base and fertility. In the prevailing agricultural scenario, degradation of soil characterized by decline in quality and decrease in goods and services of ecosystems is considered an important constraint in achieving sustainable agricultural production. The situation calls for new directions in soil health management based on integrated approaches with focus on ecological principles to attain sustainable intensification in plantations. Soil, a dynamic system in which close interplay among abiotic and biotic entities governs several chemical and biogeochemical processes and enzyme activities, needs to be managed intelligently to harness its potential to sustain biological productivity, maintain environmental quality and promote plant health and productivity. To mitigate the climate change, the great potential of plantation crops as carbon sinks needs to be harnessed as they are committed to the same piece of land for long number of years and capable of retaining more carbon per unit land area than other vegetation.

The book provides information on new paradigms of soil health-based pathways for sustaining plantation crops and diversified systems based on perennial crops. This compilation identifies technological interventions to translate science into action to mitigate environmental footprint and climate change. I congratulate the editors for taking the initiative in bringing out this compilation which will be of great value to researchers, students, extension personnel, developmental agencies and policy planners.

Government of India, Department of Agricultural Research and Education (DARE), Indian Council of Agricultural Research (ICAR), Ministry of Agriculture and Farmers Welfare

New Delhi, India
31 October 2023

Himanshu Pathak

Preface

Soil, the critical resource which forms the basis of all terrestrial life, is very vital in food systems in view of the fact that sustainable agricultural production depends on the health, quality and functionality of the soil. Enhancing and sustaining soil health are critical to the health of plants, animals, people, environment and the planet. In the past century, the intensification of agriculture using chemicals and fertilizers, though contributed to several fold increase in production and productivity of crops, had adverse impact on soil quality and environment. Unsustainable agricultural practices, soil erosion, pollution, climate change and dwindling biodiversity resources have led to deterioration of soil health. In the emerging scenario, as the world population grows and global demand for food is escalating, it has become crucial to enhance agricultural production ensuring soil quality and health as well as the ecosystem services of soil.

Plantation crops including palms—coconut, arecanut and oil palm; beverage crops—tea, coffee and cocoa; commercial crops—cashew and rubber and spices—black pepper and small cardamom, in general, are high-value crops with considerable significance in terms of livelihood security, commerce and trade, and they are grown in several countries in tropical humid regions in resource-limited soils with poor physical properties and low native fertility. Their cultivation in high rainfall regions in light-textured soils leads to leaching of nutrients, thereby depleting the soil of precious nutrients. Being perennial in nature, they mine nutrients from very limited volume of soil and hence, nutrients have to be replenished to maintain the fertility of the soil. Soil constraints with respect to very low organic carbon content, multi-nutrient deficiencies, low carbon sequestration, strong acidic or alkaline reactions, salinity and low cation exchange capacity have been reported to affect the plantation crops, necessitating technological interventions with appropriate soil health improvement strategies to achieve sustainability in production. Global climate change has become a reality and plantation crops, committed to the same land for decades, face bigger challenge from climate change effects. Therefore, it is felt necessary to prepare a book by compiling research results from around the world (where various plantation crops are being cultivated) to refocus attention on the dangers of continuing soil degradation as well as on the need to take up appropriate measures for ensuring a positive nutrient balance for various plantation crops.

At the time when soil deterioration has become a serious constraint affecting the agricultural productivity, it was felt necessary to gather the basic information as well as the latest findings on soil health available globally on each of the plantation crops to form the strong basis in our scientific pursuit to address the challenges faced by the crops. Soil health management strategies should aim at improvement in biological, chemical and physical features of soil that are essential to long-term, sustainable agricultural productivity with minimal environmental impact. Future strategies for sustainable agriculture through soil health management need to be based on biodiversity and conservation-based plantation agriculture to enhance sustainable system productivity and ecosystem services. Strategies to enhance carbon sequestration by terrestrial woody biomass and below ground systems assume great significance to mitigate the adverse effect of climate change on plantation production systems. Optimizing beneficial interactions with rhizosphere microorganisms has been proposed to reduce reliance on external inputs, increase pathogen resistance, and alleviate abiotic stresses. Also, further research is needed to elucidate the dynamic interaction between crop plants, the rhizosphere micro-biome and the environment to harness micro-biome to increase crop yield and quality.

This book containing various chapters contributed by experts in various plantation crops elucidates state-of-the-art information, providing new paradigms of soil health-based pathways for sustaining plantation crops and diversified systems. The book covers soil characteristics, soil fertility constraints, issues of soil contamination, indicators of soil health (physico, chemical and biological properties) and soil health assessment, use of soil amendments, impact of climate change on plantation soils, fertility management for healthy soils, soil biodiversity and biological functions and micro-biome and meta-genomic approach. The book also includes technological options to achieve sustainable production encompassing soil health improvement comprising multistrata multispecies cropping systems, integrated farming system, conservation agriculture practices, cover cropping and green manuring, crop residue recycling, bio-fertilizer and bio-stimulant technologies and organic farming systems. The book is also enriched with a special directional chapter focusing soil biological fertility as a new foundation for sustainability in plantation crops. We are sure that this book will be immensely useful to professionals, academicians and other stakeholders interested in sustainable production of plantation crops.

Konni, India George V. Thomas
Kayamkulam, India V. Krishnakumar

Acknowledgement

It is our proud privilege to place on record our respectful gratitude to Dr Himanshu Pathak, Secretary, Department of Agricultural Research and Education and Director General, Indian Council of Agricultural Research, Government of India, for his encouragement and guidance by contributing foreword for the book.

We are indeed grateful to the directors of plantation crops research institutes viz. Dr KB Hebbar, ICAR-Central Plantation Crops Research Institute, Kasaragod; Dr R Dinesh, ICAR-Indian Institute of Spices Research, Kozhikode; Dr K Suresh, ICAR-Indian Institute of Oil Palm Research; Dr Dinakara Adiga, ICAR-Directorate of Cashew Research, Puttur; Dr MD Jessy, Rubber Research Institute of India, Kottayam; Dr R Victor J Ilango, Tea Research Institute, Valparai and Dr M Senthil Kumar, Central Coffee Research Institute, Balehonnur, for their valuable support in permitting the scientists to contribute the chapters on the respective crops. Our sincere gratitude to Dr KUK Nampoothiri and Dr Anitha Karun, Former Directors of ICAR-Central Plantation Crops Research Institute, Kasaragod, for their encouragement and support to bring out this book. We thank Shri SR Prabhu, Chief Scientific Officer, TerraBioGen Technologies, Burnaby, British Columbia, Canada, for his sincere help in enriching this book. The editors wish to thank profusely the authors of individual chapters for their painstaking efforts in collecting voluminous information and compiling them within the timeframe.

It is with great pleasure that we thank the publisher, M/s Springer Nature, for the excellent printing and time bound publication of the book.

ICAR-Central Plantation Crops Research Institute
Kasaragod, Kerala, India
George V. Thomas

ICAR-Central Plantation Crops Research Institute
Regional Station, Kayamkulam, Kerala, India
V. Krishnakumar

About the Book

Plantation crops are perennials, cultivated in tropical and sub-tropical agro-ecosystems in a contiguous area and comprise estate crops which include tea, coffee and rubber and small holders' plantation crops such as coconut, arecanut, oil palm, cashew, cocoa and spices. They are high-value crops with considerable significance in livelihood security, commerce and trade and are grown in ecologically vulnerable regions such as coastal belts, hilly areas and regions with high rainfall and high humidity, which makes maintenance of soil health a major challenge.

Sustainable agricultural production depends on the health, quality and functionality of the soil, the critical resource which forms the basis of all terrestrial life. Enhancing and sustaining soil health are critical to the health of plants, animals, people, environment and the planet. In the emerging scenario, it has become very crucial to enhance agricultural production ensuring soil quality and health as well as the ecosystem services of soil.

This book contains chapters contributed by experts in various plantation crops and elucidates state-of-the-art information, provides new paradigms of soil health-based pathways for sustaining plantation crops and diversified systems. The book covers soil characteristics, soil fertility constraints, issues of soil contamination, indicators of soil health and soil health assessment, use of soil amendments, impact of climate change on plantation soils, fertility management for healthy soils, soil biodiversity and biological functions and micro-biome as well as meta-genomic approach.

The book also includes technological options to achieve sustainable production encompassing soil health improvement comprising multistrata multispecies cropping systems, integrated farming system, conservation agriculture practices, cover cropping and green manuring, crop residue recycling, bio-fertilizer and bio-stimulant technologies and organic farming systems. The book is also enriched with a special directional chapter focusing soil biological fertility as a new foundation for sustainability in plantation crops. The book intends to share the advances made in soil health management for the benefit of researchers, academicians and other stakeholders to address the complex problems.

Contents

Editors and Contributors

About the Editors

George V. Thomas is formerly Director of the Central Plantation Crops Research Institute (CPCRI), Kerala, India, one of the main Horticultural Institutes under the Indian Council of Agricultural Research (ICAR). After completing his Master's and Doctoral degrees in Microbiology from Punjab Agricultural University, Dr Thomas joined Agricultural Research Service of ICAR at CPCRI in 1978 and rose to the position of Director of the Institute. During his tenure as Director (2006–2014), he guided research programmes on plantation crops-coconut; arecanut and cocoa and plantation crop-based cropping systems. Dr Thomas, in his research career spanning 36 years on plantation crops, on basic and applied aspects of soil microbiology and on-farm residue biomass recycling, could highlight the potential of microorganisms and organic farming technologies for management of soil health and fertility leading to sustainable improvement in yields of these crops. His work towards creating wealth from waste biomass of coconut has fetched him the prestigious ICAR Outstanding Team Research Award for the biennium 2005–2006, as team leader, for the work 'Value addition to coconut waste biomass through biological approaches for enhancing soil health, crop productivity and income generation'. He contributed immensely with significant outcomes as Consortia Leader for a National Agricultural Innovation Project—NAIP of ICAR and Country Leader for a project from International Fund for Agricultural Development (IFAD-COGENT).

For his leadership role in crop improvement programme of coconut, Dr Thomas was selected as Chairman of the International Coconut Genetic Resources Network (COGENT) of Biodiversity International in July 2012. Dr Thomas visited China, Philippines, Thailand, Cote d' Ivoire and Sri Lanka, for scientific deliberations in connection with international collaborative projects on plantation crops. He is a Fellow of the Indian Society for Plantation Crops (ISPC), Confederation of Horticulture Associations of India (CHAI), Association of Microbiologists of India (AMI) and Honorary Fellow, Society for Applied Biotechnology (SAB). He was also President of the Indian Society for Plantation Crops (2008–2009) and served as Editor, Journal of Plantation Crops (2001–2006) and recipient of Dr CS Venkataram Memorial Award.

Dr Thomas has to his credit over 200 research publications including research papers in high impact factor international and national journals, reviews, technical bulletins, and book chapters and edited 10 books. As Emeritus Scientist (2016–2020) of Kerala State Council for Science, Technology and Environment, he contributed significantly to the research on 'Bioconversion of residues from major crops of Kerala to value-added organic resource for sustainable farming'. Dr Thomas also served as Director, Council for Food Research and Development of Government of Kerala.

Address for correspondence: Vettimoottil house, Peroorkulam, Vakayar PO, PIN 689698, Kerala, India

Contact No.: 91-9446051847; E mail: georgevthomas52@gmail.com

V. Krishnakumar Born on 6 September 1957, in Kayamkulam, Kerala, India, earned his graduation and post-graduation in Agriculture from the College of Agriculture, Vellayani, Thiruvananthapuram, under the Kerala Agricultural University and doctoral degree in Agronomy from the Tamil Nadu Agricultural University, Coimbatore, India. He started his career as Assistant Professor, KAU during 1982. He has worked both in the State and Central Government service as Assistant Agronomist in the Rubber Research Institute of India (Rubber Board), Kottayam (Ministry of Commerce, Govt. of India); Senior Scientist (Transfer of Technology and Agronomy and Soil Science) in the Indian Cardamom Research Institute (Spices Board), Myladumpara, Idukki, Kerala (Ministry of Commerce, Govt. of India). He joined the ICAR service as Senior Scientist (Agronomy) at ICAR-Central Plantation Crops Research Institute, Kasaragod, during December 2001 and later served as Principal Scientist (Agronomy) and Head, ICAR-CPCRI Regional Station, Kayamkulam (from April 2005 to September 2019).

The main areas of functioning include Undertaking Field Research Programmes on cropping system for resource use efficiency, organic farming in plantation and spice crops; Farmer Community-Oriented Technology Dissemination Programmes; and Administration and Manpower Management Programmes. As a member of the team, he has bagged the prestigious 'Outstanding Interdisciplinary Team Research in Agriculture and Allied Sciences for the Biennium 2005–2006' instituted by the Indian Council of Agricultural Research. He is a recipient of the RL Narasimha Swamy Award and Fellow of the Indian Society for Plantation Crops. He has functioned as the Principal Investigator/Co-Investigator for various externally funded projects of the Dept. of Biotechnology, Dept. of Science and Technology, GOI; Coconut Development Board, GOI; Kerala State Planning Board, National Agricultural Technology Project-NATP and National Agricultural Innovation Project-NAIP, Government of India; and International Fund for Agriculture Development-IFAD/COGENT.

He was Assistant Editor, Journal of Natural Rubber Research of RRII (1987–1989) and Editor, Journal of Plantation Crops

(ISPC) during 2006–2011 and served as a member of the Editorial Board of the Annual Reports of ICAR-CPCRI and AICRP on Plantation Crops for several years. He has edited 14 books and published more than 100 research and technical articles apart from contributing chapters in various books, technical bulletins, popular articles, etc. He currently functions as a member of the Editorial Board of Current Science, a Fortnightly Research Journal, being published by the Current Science Association, Bengaluru, India, in collaboration with the Indian Academy of Sciences.

Address for correspondence: Kaleeckal Madhom, Palace Ward, Krishnapuram (P.O)-690533, Alappuzha Dist., Kerala, India.

Contact No.: 91-9447364877; E mail: dr.krishnavkumar@gmail.com

Contributors

J. D. Adiga ICAR-DCR, Puttur, Karnataka, India

K. S. Anil Kumar ICAR-NBSS & LUP, Regional Centre, Bangalore, Karnataka, India

C. Babou CCRI, Coffee Board of India, Chikkamagaluru, Karnataka, India

S. K. Behera ICAR-IISS, Bhopal, Madhya Pradesh, India

Ravi Bhat ICAR-CPCRI, Kasaragod, Kerala, India

Bhavishya ICAR-CPCRI, Regional Station, Vittal, Karnataka, India

N. K. Binitha College of Agriculture, KAU, Padannakkad, Kerala, India

K. Chandrappa CCRI, Coffee Board of India, Chikkamagaluru, Karnataka, India

N. Chandrashekar CCRI, Coffee Board of India, Chikkamagaluru, Karnataka, India

R. Dinesh ICAR-IISR, Kozhikode, Kerala, India

Murali Gopal ICAR-CPCRI, Kasaragod, Kerala, India

Alka Gupta ICAR-CPCRI, Kasaragod, Kerala, India

S. B. Hareesh CCRI, Coffee Board of India, Chikkamagaluru, Karnataka, India

N. Hariyappa CCRI, Coffee Board of India, Chikkamagaluru, Karnataka, India

S. Induja ICAR-CPCRI, Regional Station, Kayamkulam, Kerala, India

Mercykutty Joseph RRII, Rubber Board, Kottayam, Kerala, India

V. Krishnakumar ICAR-CPCRI, Regional Station, Kayamkulam, Kerala, India

Prafulla Kumari CCRI, Coffee Board of India, Chikkamagaluru, Karnataka, India

T. Raj Kumar UPASI TRF, Regional Centre, Coonoor, Tamil Nadu, India

S. Mangalassery ICAR-DCR, Puttur, Karnataka, India

K. Manorama ICAR-IIOPR, Pedavegi, Andhra Pradesh, India

Jeena Mathew ICAR-CPCRI, Regional Station, Kayamkulam, Kerala, India

M. Murugan CRS, KAU, Pampadumpara, Kerala, India

P. Murugesan UPASI TRF, Regional Centre, Coonoor, Tamil Nadu, India

A. Nadaf CCRI, Coffee Board of India, Chikkamagaluru, Karnataka, India

J. S. Nagaraja CCRI, Coffee Board of India, Chikkamagaluru, Karnataka, India

S. R. Prabhu TerraBioGen Technologies, Burnaby, Canada

U. K. Priya ICAR-CPCRI, Regional Station, Vittal, Karnataka, India

N. Rajib Pati CCRI, Coffee Board of India, Chikkamagaluru, Karnataka, India

V. Selvamani ICAR-CPCRI, Kasaragod, Kerala, India

M. Senthil Kumar CCRI, Coffee Board of India, Chikkamagaluru, Karnataka, India

P. Shivaprasad CCRI, Coffee Board of India, Chikkamagaluru, Karnataka, India

P. R. Sowmya CCRI, Coffee Board of India, Chikkamagaluru, Karnataka, India

V. Srinivasan ICAR-IISR, Kozhikode, Kerala, India

P. Subramanian ICAR-CPCRI, Kasaragod, Kerala, India

S. Sujatha ICAR-IIHR, Bengaluru, Karnataka, India

Surekha ICAR-CPCRI, Kasaragod, Kerala, India

K. Suresh ICAR-IIOPR, Pedavegi, Andhra Pradesh, India

George V. Thomas ICAR-CPCRI, Kasaragod, Kerala, India

Amok Uchoi ICAR-CPCRI, Research Center, Kahikuchi, Assam, India

G. L. Veena ICAR-DCR, Puttur, Karnataka, India

Plantation Crops and Soil Health Management: An Overview

George V. Thomas and V. Krishnakumar

Abstract

Plantation crops are perennials, cultivated in a contiguous area in agroecosystems mostly confined to tropical belt, and comprise estate crops which include tea, coffee, and rubber and small holders' plantation crops, viz., coconut, oil palm, arecanut, cashew, cocoa, and spices. The cultivation of these crops in ecologically vulnerable regions including coastal belts and hilly areas and in locations endowed with high rainfall and high humidity makes the maintenance of soil health a serious challenge. The agroecosystems of plantation crops are confronted with several constraints including multi-nutrient deficiencies, nutrient imbalances, decline in SOM and biological attributes affecting the soil health, and climatic aberrations, which influence the sustainability of production systems. Research programs undertaken in different countries resulted in the development of technologies to improve soil health and to achieve sustainability in production systems of plantation crops. This chapter covers a brief introduction to plantation crops, their production systems, and the strategies for soil health management such as diversification of nutrient sources including inorganic, organic, and bio-fertilizers; conservation agriculture practices; efficient biomass resource recycling practices; agroforestry/cropping/integrated farming systems; and microbiome approaches to achieve sustainable production. Efforts to augment agroecosystem properties through various nature-based technologies would enhance carbon sequestration and soil health in general, finally contributing to sustainability and resilience of this group of crops under adverse weather and edaphic conditions.

G. V. Thomas (✉)
ICAR-Central Plantation Crops Research Institute, Kasaragod, Kerala, India

V. Krishnakumar
ICAR-Central Plantation Crops Research Institute, Regional Station, Kayamkulam, Kerala, India

G. V. Thomas, V. Krishnakumar (eds.), *Soil Health Management for Plantation Crops*, https://doi.org/10.1007/978-981-97-0092-9_1

Keywords

Plantation crops · Cropping systems · Soil health management · Biomass recycling · Carbon sequestration · Soil microbiome · Soil biodiversity · Integrated nutrient management · Agroforestry systems

Abbreviations

AMF	Arbuscular mycorrhizal fungi
CEC	Cation exchange capacity
CSA	Climate-smart agriculture
DRIS	Diagnosis and recommendation integrated system
FYM	Farm yard manure
GHG	Greenhouse gases
GIS	Geographical information system
HDMSCS	High-density multispecies cropping system
INM	Integrated nutrient management
MBC	Microbial biomass carbon
MRT	Mean residence time
PGPR	Plant growth promoting rhizobacteria
PSB	Phosphorus solubilizing bacteria
RS	Remote sensing
SOC	Soil organic carbon
SOM	Soil organic matter

1 Introduction

Plantation crops are perennials, cultivated on an extensive scale in a contiguous area mainly in the tropics, and also in certain areas in subtropics, owned and agricultural operations carried out by individual farmers or companies at the estate level. They are important for livelihood and economy as they meet a wide range of human requirements including food, edible oil, beverages, and other confectionary items, fuel, fiber, and industrial raw materials (Rethinam 2000). A range of plantation crops including coconut, arecanut, oil palm, cashew, cocoa, coffee, tea, rubber, and spices are cultivated in humid tropics and subtropical belts in different parts of the world (Table 1).

Plantation crops are broadly classified as estate crops which include tea, coffee, and rubber and small holder's plantation crops such as coconut, arecanut, oil palm, cashew, cocoa, and spices. They are high-value crops with significant commercial importance and play a vital role in improving economy of many countries through export earnings and employment generation and by reducing poverty of millions of people, more so in the rural sector (Anandaraj 2015). The major socioeconomic features of small holder plantation crop sector include predominance of fragmented,

Table 1 Plantation crops of economic importance and their geographic distribution and economic produce

Common name	Scientific name	Botanical family	Geographic distribution	Economic produce
Coconut	*Cocos nucifera* L.	Arecaceae	Tropical	All parts of the tree including nut for edible oil, natural drink, fiber, food, and other products
Arecanut	*Areca catechu* L.	Arecaceae	Tropical	Nut for chewing
Oil palm	*Elaeis guineensis* Jacq.	Arecaceae	Tropical	Fruit bunches for oil
Cashew	*Anacardium occidentale* L.	Anacardiaceae	Tropical	Culinary nut
Cocoa	*Theobroma cacao* L.	Sterculiaceae	Tropical	Beans for production of chocolate
Tea	*Camellia sinensis* (L.) O Kuntze	Theaceae	Tropical/ subtropical	Processed leaves for beverage preparation
Coffee	*Coffea arabica* L. *C. canephora* Pierre	Rubiaceae	Tropical/ subtropical	Processed beans for beverage preparation
Rubber tree	*Hevea brasiliensis* Muell. Arg	Euphorbiaceae	Tropical	Latex as natural rubber
Spices				
Black pepper	*Piper nigrum* L.	Piperaceae	Tropical	Black pepper berries used as spice
Small cardamom	*Elettaria cardamomum* Maton	Zingiberaceae	Tropical	Dried capsules used as spice

small, and marginal holdings and resource-poor farm environment, often with less marketable and marketed surplus.

Most of the commercial plantations are established after clearing natural forests. Given this fact, maintaining soil fertility throughout the lifespan of these perennial crops is a critical issue to be addressed in the plantation sector. Despite these facts, being perennial crops with long a lifespan, plantation crops are also important in view of their role in ecosystem services through carbon sequestration resulting from the generation of massive belowground and aboveground biomass, continuous lignocellulosic biomass addition through litter fall, and protection of soil from heavy rainfall through massive canopies and their overall impact on the protection of the environment. Sustainable and mature vegetation is the key to a balanced ecosystem, which provides a permanent solution to accelerated erosion problems (Santha 2006). Well-established and sustainably managed plantations help to protect soil health. To be sustainable, a managed land use system should imitate the structure and functioning of natural ecosystems, which are the results of natural selection over long periods (Ewel 1999). Even in agroforestry, loss of nutrients during the harvest, especially when rotations are short, may exceed the rate of replenishment by weathering of minerals and by atmospheric inputs. Furthermore, global warming accelerates soil organic matter (SOM) oxidation, making degradation of nutrient-poor soils faster in the tropics. Consequently, there is a major uncertainty, that is, whether the tropical tree plantations or agroforests could be grown perpetually on the same site without serious risk to their vitality and productivity (Kumar 2008). The only viable option available is to manage these plantation crops more sustainably by following principles of agroecology. In various chapters included in this book, a great deal of information has been provided on sustainable intensification of plantation crop sector.

2 Global Status of Plantation Crops

The global scenario of plantation crops with respect to area and major producing countries is presented in Table 2. Coconut, arecanut, and oil palm are the tropical palms grown as plantation crops at global level.

Coconut (*Cocos nucifera* L.), the environmentally friendly multipurpose palm mostly grown in small holdings in the tropics, is an agriculturally and economically important crop, interwoven with lives and cultures of people in Southeast Asia, the Pacific region, Africa, and some countries in Latin America. Asia and Pacific region accounts for a major share of area occupying 10.67 million ha (87%) and

Table 2 Global status of area and major producing countries of plantation crops

Crop	Area (m ha)	Major producing countries	Reference
Coconut	12.26	Indonesia, Philippines, India, Sri Lanka, Malaysia, Oceania	ICC (2020)
Arecanut	1.57	India, Bangladesh, Myanmar, Indonesia	FAOSTAT (2021)
Oil palm	24.13	Indonesia, Malaysia, Thailand, Colombia, Nigeria, Guatemala, Papua New Guinea, Cote d'Ivoire	USDA (2022)
Cashew	7.10	Cote d'Ivoire, India, Vietnam, Burundi, Philippines, Tanzania	https://numerical.co.in/numerons/collection/
Cocoa	14–15	Cote d'Ivoire, Ghana, Nigeria, Cameroon, Indonesia	Amponsah-Doku et al. (2021)
Coffee	10.0	Brazil, Indonesia, Ethiopia, Cote d'Ivoire, Colombia, Vietnam, Mexico, Uganda, India, and Peru	Jha et al. (2014)
Tea	5.0	China, India, Sri Lanka, Kenya, Malawi, Rwanda, Tanzania, Uganda	Wang et al. (2020)
Rubber	11.0	Thailand, Indonesia, Malaysia, India, Vietnam, Côte d'Ivoire, China	Singh et al. (2021)
Black pepper	1.5	Vietnam, Brazil, Indonesia, India	https://www.ipcnet.org/history-of-pepper/
Small cardamom	70,410 ha for India	Guatemala, India, Indonesia	Spices Board (2021)

production of 10.11 million metric tons of copra equivalent (86%) (ICC 2020). The coconut palm, revered as *Kalpavriksha* or *tree of life*, is important as a source of large number of products meeting daily requirements of people and traded internationally including coconut oil as vegetable oil, coconut water as a natural health drink, virgin coconut oil, desiccated coconut, coconut milk, milk powder, coconut shell powder, activated carbon, coir as the best natural fiber, coir products, and many others.

Arecanut (*Areca catechu* L.), a monocot palm, is an important cash crop, and the economic produce is the fruit known as *betel nut* or *supari* used for masticatory purposes. The arecanut forms the economic backbone to the extent of 10 million people in India and a few other countries. The arecanut products are consumed globally by about 700 million people, particularly among the South, East, and Southeast Asian communities. India is a major producer of arecanut contributing to 57% of the global production, and the remaining 43% is contributed by China, Bangladesh, Myanmar, and other countries (Bedi and Scully 2014; Patil et al. 2022).

Oil palm (*Elaeis guineensis* Jacq.), popularly known as "African oil palm" or "red oil palm," is the world's highest oil yielding crop, with a capacity of 5–10 times higher oil yield ha^{-1} than any other vegetable oil crops. Palm oil produced from the mesocarp of the fruit of oil palms has gained importance not only as an important edible oil traded internationally but also for its commercial applications including biofuel production.

Cashew (*Anacardium occidentale* L.), also referred to as "wonder nut," one of the leading edible nuts traded internationally, was primarily introduced as soil binding crop by Portuguese in India. Grown primarily in less fertile soils under rainfed conditions in terrains including slopes of hills, this perennial horticultural crop has become an important plantation crop due to its potential to provide livelihood security to the growers, empower rural women in the processing sector, create employment opportunities, and generate foreign exchange through exports (Rejani and Yadukumar 2010).

Cocoa, coffee, and tea are the commercial beverage crops grown in plantation scale in several countries. The cocoa tree (*Theobroma cacao* L.), though a native to the lowland rainforests of the Amazon basin, is now grown in 58 countries mostly around the equator. Africa is the world's largest producer, and about 70% of the production comes from four West African countries: Côte d'Ivoire, Ghana, Nigeria, and Cameroon (www.worldcocoafoundation.org/in-the-news/world-cocoa-production/). Cocoa known as the "food of God's" is the backbone of chocolate industry and the second most important organic crop, known for its capabilities to safeguard ecosystems. Considering the insufficient supply of cocoa beans, ten of the largest chocolate multinationals launched a cocoa sustainability scheme named "cocoa action," with an investment of 500 million USD to enhance sustainable cocoa production in West Africa to support cocoa planters and the chocolate industry (van Vliet et al. 2021).

Coffee (*Coffea* spp.), one of the most widely consumed beverages, is grown in more than 80 countries in tropical and subtropical regions of the world. The three primary coffee growing regions of the world, viz., Central and South America, Africa, and the Middle East and Southeast Asia, are located along the equatorial zone between the Tropic of Cancer and the Tropic of Capricorn, widely known as the "bean belt." Even though coffee crop is cultivated within the "bean belt," the products from different regions have unique regional flavors, making the popular phrase "geography is a flavor" very meaningful. Different factors contribute to the flavors in a particular region, and the distinctiveness of the flavors is attributed to differences in soil chemical properties, weather parameters, sunshine, altitude, and processing method adopted.

Tea (*Camellia sinensis* (L.) O. Kuntze) crop, an evergreen perennial shrub or small tree, is the source of the world's most consumed drink after water. Though native to East Asia, tea crop is cultivated in 52 countries in the world mostly in tropics and subtropics. As an important cash crop, tea contributes to significant export earnings in several developing countries apart from its socioeconomic importance, employment generation, and poverty alleviation.

Rubber tree (*Hevea brasiliensis* Muell. Arg), the perennial tree crop, contributes over 90% of natural rubber in the world. A native of Amazonian river basin, rubber crop is an economically important industrial crop that produces latex, which is converted to various rubber products, used in aviation, automobile, medical, industrial, and consumer sectors. Over 85% of global production is from small holdings in Asia. Growing demand for rubber latex has been the driving force for rapid expansion of area in rubber cultivation. Thailand, Indonesia, Vietnam, and India are the major rubber producers in the world. Rubber tree is grown mostly in monoculture as well as in various diversified systems.

Spices have been used in Indian cooking since at least 2000 BC. Black pepper (*Piper nigrum* L.), known as "the king of spices," is a flowering vine, and its fruit is dried and used as spice in food and also used in medicines. A native of Malabar Coast of India, black pepper spread from India through trade to the rest of the world.

Small cardamom (*Elettaria cardamomum* Maton), known as "the Queen of Spices," is a herbaceous perennial rhizomatous plant native to Western Ghats of South India. Its dried ripe fruit having strong and punchy aroma and taste is used as a spice and is traded as an important spice commodity in international markets.

Clove (*Syzygium aromaticum* (L.) Merr. and Perry), nutmeg (*Myristica fragrans* Houtt.), cinnamon (*Cinnamomum verum* Brecht. & Presl.), allspice (*Pimenta dioica* (L.) Merr., and vanilla (*Vanilla planifolia* Andr.) are the tropical spices grown mainly as mixed crops in coconut and arecanut plantations.

3 Soil and Climatic Requirements of Plantation Crops

Plantation crops are cultivated under humid tropical conditions, and the cultivation of certain plantation crops are also extended to subtropical conditions. This group of crops is grown essentially in a wide range of soils between 28°N and 28°S latitudes of the equator. As these crops and their cropping systems are in ecologically vulnerable regions including coastal belts, hilly areas, and undulating terrains, experiencing high rainfall, soil health management is vital due to poor nutrient status of soil caused by soil erosion, fast oxidation of SOM, and nutrient loss. In view of the very narrow range of climatic requirements for the optimal growth and productivity of plantation crops, the information on ideal climatic and soil conditions is of vital importance due to current scenario of climatic aberrations and deterioration of the production environment. The suitable soil and climatic requirement of different plantation crops are presented in Table 3. Among the plantation crops, the coconut palm grows up to 1000 m above MSL, but most of the cultivation is confined to an altitude of 600 m (Ohler 1999). The highly adaptable nature of coconut palm is evident from the establishment and productivity of the crop under diverse soil

Table 3 Soil and climatic requirements of plantation crops

Crop	Altitude (m)	Temperature (°C)	Rainfall (cm year^{-1})	Soil requirement	Soil pH
Arecanut	Up to 1000[a]	14–36; growth adversely affected <10 and >40	150–500	Laterite, red and sandy loam, alluvial and deltaic	Acidic to neutral
Cashew	Up to 1000	15–35	100–200	Hard degraded laterites, red sandy loam, and coastal sands	5.5–7.5
Cocoa	Up to 900	Maximum annual average of 30–32 and minimum average of 18–21	150–200	Deep soil with sufficient organic matter, nutrients, and a depth of at least 1.5 m	Acidic to neutral
Coconut	Up to 1000	27 ± 5 to 7	100–300	Coarse sand is its natural habitat; deep soils with good physical structure and chemical properties are most ideal. Laterite, coastal sandy, alluvial, red sandy loam suitable	5.5–7.0
Coffee	1000–1500	*C. arabica*: 15–24 *C. canephora:* 24–30	100–250	Light, deep friable, well-drained, loamy, rich in humus and exchangeable bases, especially K	4.5–6.5
Oil palm	Up to 200	22–32	200–300	Loamy or alluvial, well-drained soils, at least 1 m deep; rich in organic matter	4.0–6.0
Rubber	Up to 450	21–35	200–300	A variety of soils, mostly acidic, of the humid tropics. Deep soils from underlying sheet rocks	3.2–6.2

(continued)

Table 3 (continued)

Crop	Altitude (m)	Temperature (°C)	Rainfall (cm $year^{-1}$)	Soil requirement	Soil pH
Tea	700–2500	23–30	250–300	High land well-drained and deep sandy loam to silty loam soils and >2% organic matter	4.0–6.5 (4.5–5.5 optimal)
Spices—black pepper	Up to 1500	Favorable range: 23–32 Ideal: around 28	125–200	Heavy clay to light sandy clays rich in humus with a porous friable nature, high organic matter, and high base saturation with Ca and Mg	Near neutral pH
Small cardamom	600–1200	10–35	150–400	Grows well in forest loamy soils	Acidic, 4.2–6.8

[a] Nuts from higher altitudes are of inferior quality than nuts from lower altitudes

conditions varying in texture, chemical composition, drainage, acidity, and alkaline calcareous nature (Khan et al. 1978).

Cashew crop is flexible in its soil requirement and is cultivated in high and low rainfall regions. The crop shows best growth in deep and well-drained red sandy loam, lateritic, and coastal sands which are slightly acidic pH. For ideal growth, oil palm requires well-drained, deep, loamy alluvial soils rich in organic matter with good water permeability. Rubber plants require highly deep, well-drained porous soils which are moderately acidic. Coffee and tea crops require cooler temperature for ideal growth. The optimum temperature for coffee is around 18 °C, but can withstand temperatures up to 30 °C. Altitude variation also makes a difference in the performance of crops. According to Khan et al. (2002), tea crops prefer high altitude and are followed by coffee. Hill slopes are ideal for black pepper. The general soil characteristics and the range of available nutrients in plantation crop soils are summarized by Tandon and Ranganathan (1988).

4 Soil Degradation as a Major Constraint Affecting Sustainability

In the present crop production scenario, the health of agroecosystems is under severe stress causing a decline in ecosystem services due to sub-optimal management practices followed, use of agrochemicals, and excessive soil disturbance, adversely affecting the productivity and sustainability of crops. At a global level, the land area prone to soil degradation is about 2 billion ha, of which 29.7% (596 million ha) is agricultural land (Lal 2001). The agroecosystems of plantation crops, predominantly occupied by small and marginal holdings and characterized by acidic soils with poor physical characteristics and low native fertility, are confronted with multiple soil health problems. Malhotra et al. (2017) in a review on soil fertility constraints in coconut stated that the production base had multiple soil health problems related to soil acidity, low cation exchange capacity (CEC), and poor nutrient reserve. Soil health in littoral sandy soils was affected by the physicochemical characteristics including high bulk density, poor aggregate stability, poor water holding capacity, high soil temperature, and poor soil fertility status, impeding the productivity of the palm (Reddy and Upadhyay 2002). The symbiotic association of arbuscular mycorrhizal fungi (AMF) with coconut roots was reported to be significantly affected as evidenced by the degree of colonization and intensity of infection in coconut roots in plots which received the recommended doses of fertilizers (Harikumar and Thomas 1991), indicating that chemical fertilization in coconut plantations adversely affect soil properties and soil biology. A study on mapping of soil constraints in Tamil Nadu using remote sensing (RS) and geographical information system (GIS) indicated that 31.5% of total coconut area had soil constraints, particularly related to soil reaction, texture, drainage, and soil depth (Selvamani and Duraisami 2018). Another study on coconut plantations under different management treatments indicated that earthworm community was completely absent in monocropped coconut gardens maintained with tillage and recommended dose of chemical fertilizer inputs, while the density and biomass of earthworms were significantly high in cropping systems with profuse aboveground diversity and maintained with integrated nutrient management (Thomas et al. 2022).

Evidence shows that high rainfall in oil palm plantations leads to soil erosion which subsequently leads to leaching of soil nutrients, decline in organic matter and soil biota, loss of soil structure, and changes in infiltration rates (Lord and Clay 1999). Soil constraints have also been reported in several locations in coffee-growing areas of Wayanad district of Kerala, India (Shivaprasad et al. 2018). Deterioration of soil condition with respect to very low organic carbon content, multi-nutrient deficiencies, and low carbon sequestration have been reported in intensively cultivated cashew plots when compared to that in forest and scrub lands (Srinivasan et al. 2019). Nutrient constraints affecting cashew production in India have been delineated by Mangalassery et al. (2021). Arecanut-growing soils of Karnataka had strong acidic or alkaline reactions and low CEC in many locations as per the recently conducted state-wide survey (Vasundara et al. 2020). Most of the cashew growing soils had soil health constraints including deficiency of nitrogen (N) and micronutrients such as zinc (Zn) and boron (B) and low base status and CEC (Rejani et al. 2013). A study on spices growing soils revealed that soil acidification was alarming and 90% of the soils were found to be slightly to highly acidic warranting immediate intervention through amendments to restore the productivity. Indiscriminate use of phosphorus fertilizers has resulted in increased P concentration in soil, and it interfered with the uptake of other essential nutrients (Dinesh et al. 2014). These reports indicated that soil degradation is a major constraint influencing the sustainable productivity of plantation crops and it necessitates technological interventions to mitigate such problems with appropriate soil health improvement strategies to achieve sustainability in production. A well-managed plantation can also help to reduce soil degradation due to continuous organic matter addition and long-term soil cover, as proved in the case of date palm plantation's influence on controlling and mitigating desertification (Mihi et al. 2019).

5 Soil Health: The Most Important Foundation for Plantation Sustainability

The intensive agricultural practices including the application of chemical fertilizers and pesticides though enabled to enhance agricultural production several fold, but has led to degradation of soil and pollution of environment, thereby adversely impacted sustainability of agricultural production. Now, there is a greater realization that soil health is the most important foundation necessary to achieve sustainability in agriculture. Jarecki and Lal (2003) reported that strategies are to be formulated to manage the crop production systems as agroecosystems based on ecological principles with the objective of enhancing soil organic carbon (SOC) pool, soil life, and soil quality to achieve sustainability in agricultural production and food security.

Soil is now considered as a dynamic living entity and has the most important role in the functioning of terrestrial ecosystems. Lehman et al. (2015b) reported that soil degradation can be addressed only by augmenting soil health through adoption of appropriate agronomic management strategies. Accordingly, Tiedje et al. (2001) opined that soil biology can become at least one, if not the major driver, for soil functions to support crop production. According to Doran et al. (1996), soil health is "the continued capacity of soil to function as a living system, within the ecosystem and land use boundaries, to sustain biological productivity, quality of air and water environment, promote plant, animal and human health." Soil biota are the drivers of biological functions in soil to deliver ecosystem services. The delivery of ecosystem services is made possible by soil biota through the regulation of biogeochemical cycles, making available nutrients to primary producers, enhancing soil structure and fertility, microbial breakdown of pollutants, supply of clean drinking water, reducing the impact of floods and droughts, control of soil erosion, reduction of atmospheric greenhouse gases (GHG), bio-control of pests and pathogens, and supporting agricultural production through biological pathway.

The management strategies suggested by Lal (2015) for mitigation of soil degradation include steps for minimization of soil erosion, creating positive SOC and N budgets, enhancing the activity and species diversity of soil biota and improvement in structural stability and pore geometry. In order to reach the goal of sustainable production, there needs to be fresh thinking on the crop production strategies, with a distinct difference from the approach being followed now and caused the deterioration of the production environment. The new approach should focus on soil health as the central point and the management strategies designed in such a way to realize the potential of soil life and biological processes to build the soil biological fertility with less dependence on external chemical inputs.

Important biological indicators as far as soil quality is concerned are organic matter content, the biological functioning as evidenced by respiration, microbial biomass content, and mineralizable N levels. Activities of soil enzymes indicate the extent of biological functioning of soil as well as the transformation of nutrients and are considered as integrative indicators of soil health. These indicators will be helpful in comparing the soil health under different systems. Organic matter content is an important component of soil which determines not only its quality but also its water holding capacity and susceptibility to degradation (Feller et al. 2001). In addition, SOM performs an important function of carbon sequestration by serving as a source or sink to atmospheric CO_2 (Lal 2009). Soil quality and functionality depend on physical, chemical, biological, and ecological attributes which individually and through interaction develop conducive soil health conditions for growth and nutrition of crops (Lal 2016).

6 Organic Farming in Plantation Crops as a Soil Life-Centered Approach

The ever-increasing demand for safe and healthy food, free from pesticides and other residues, and concerns on environmental pollution due to indiscriminate use of agro-chemicals,are the major driving forces responsible for the interest in alternate systems of farming in modern agriculture. Since many of the plantation crops are consumed either directly (e.g., coconut, cocoa, coffee, tea, spices, cashew, oil palm) or used for industrial purposes (e.g., coconut oil, palm oil, and arecanut), organic production to meet consumer's needs is very much essential. In order to adopt organic farming, it is necessary that such technologies without the use of any inorganic fertilizers and plant protection chemicals are made available to the farmers for adoption in their farmlands.

Varied crop farming practices such as cultural, mechanical, and biological methods can be adopted to achieve sustainable agricultural production by encouraging and enhancing biological cycles within farming system by giving due credit to the soil flora and fauna, plants, and animals. Organic farming has been reported to be a viable strategy for sustainable production of certain horticultural crops and plantation crops (Singh and Thomas 2010). The holistic approach of crop production also provides social and ecological advantages and ensures long-term fertility of soil. In organic agriculture, nutrients are supplied through organic sources which become available through the activity of soil biota, are considered as "biologically derived nutrients," and work on the principle of "feeding the soil to make it living" rather than "feeding the plants."

Organic farming is practiced in 191 countries at the international level, covering an area of almost 76 million ha of land, which represents 1.6% of agricultural land worldwide, with the involvement of 3.4 million farmers. The international trade of organic food products is valued at 125 billion euros during 2021 (Willer et al. 2023). The region-wise land area under organic management in the world during 2021 for some of the perennial plantation crops is presented in Table 4. The crops considered are cocoa, coffee, coconut, and tea. The amenability of coconut palm for organic farming has been reported by Nampoothiri (2001). The prospects of organic cashew production in India have been reported by Chattopadhyay et al. (2015).

Table 4 Region-wise land area (ha) under organic management in the world (2021) (permanent crops)[a]

Region	Cocoa	Coffee	Coconut	Tea/mate, etc.
Africa	287,665	313,325	4069	24,280
Asia	380	73,799	250,263	178,160
Latin America	179,689	466,922	7061	3324
North America	–	115	–	–
Oceania	1935	68,238	48,226	–
Total	469,669	922,399	309,619	205,764

[a] Data tabulated only for a few plantation crops (Source: Willer et al. 2023; FiBL survey 2023)

7 Soil Fertility Management in Plantation Crops

7.1 Nutrient Management

Plantation crops, being perennial in nature, require continuous supply of nutrients, which are mined from limited volume of soil in the root zone of crops, necessitating nutrient additions to maintain fertility level of soils and plant productivity. The annual nutrient removal by different plantation crops has been worked out for a particular yield situation, and it varied from 19.1 to 93.5 kg N ha^{-1}, 8.7 to 25.2 kg P_2O_5 ha^{-1}, and 1.6 to 111.2 kg K_2O ha^{-1} (Khan et al. 2002). Plant productivity is determined by soil fertility and nutrient availability. In plantation ecosystems, due to continuous removal of nutrients from soil through harvesting, fertilizer application is necessary for maintenance of sustained growth and yield of perennial plantation crops. Nutrient management strategies are to be planned considering the native soil fertility, leaf nutrient status, nutrient uptake pattern, and yield level. A comparative assessment of nutrient partitioning in adult coconut palms revealed the uptake pattern of various nutrients to be in the order of K > N > Ca > S > P > Mg (Mathew et al. 2021). It is important to replenish the soil nutrients removed during crop production process and the nutrients lost by leaching and various environmental processes. Based on field experimentation, fertilizer dose for various plantation crops has been recommended (Table 5) to obtain optimum growth and productivity (Rethinam and Venugopal 1994). Most of the plantation crops require higher quantities of K for growth and fruiting.

Application of fertilizers in split doses has been recommended according to the stages of plant growth and nutrient demand. Soil test-based fertilizer application is proved to be an effective strategy to achieve higher productivity and nutrient use efficiency. Sadanandan et al. (2000) worked out diagnosis and recommendation integrated system (DRIS) norms for optimum yield in black pepper.

Fertigation systems, in which the fertilizers in soluble form are applied through the drip irrigation system in different splits, have been standardized for different plantation crops with considerable savings in the quantity of fertilizers as well as higher nutrient use efficiency (Dhanapal et al. 2005). Lignin, lignin sulfonate, and lignin acetate extracted from empty fruit bunches from oil palm served as additive

Table 5 Nutrient recommendation for various plantation crops in India

Sl. no.	Plantation crop	Recommended N, P_2O_5, K_2O
1	Coconut	500:320:1200
2	Arecanut, cocoa, and black pepper	100:40:140
3	Cashew	500:125:125
4	Oil palm	1200:600:1200
5	Coffee	140:90:450
6	Tea	450:90:450
7	Rubber	30:30:30
8	Cardamom	75:75:150

Sl. no. 1–4, the recommended dose is in g palm^{-1} or plant^{-1} year^{-1}, and for 5–8, the values are in kg ha^{-1} year^{-1}

substance for urea fertilizer, and the urea lignin formation showed slow-release properties (Arianie 2010).

Integrated nutrient management (INM) involving the combined application of inorganic, organic, and bio-sources of nutrients enables to achieve the high productivity in plantation crops in a sustainable manner (Khan et al. 2002). Organic manures are important sources of nutrients for plantation crops but are required in higher quantities. Generation of green manures by growing of cover crops can be sustainable to generate biomass right in the gardens. Foliar application of nutrients, especially micronutrients, wherever needed are being adopted to overcome their deficiency.

7.2 Availability of Crop Residue Biomass in Plantations and Plantation-Based Cropping Systems

Crop residues form the largest harvest in the crop production process and a vital resource that can be recycled and utilized for a number of useful purposes. On the global scale, the availability of crop residue biomass is estimated to be 3.8 billion Mg (Lal 2005). One of the most important applications of crop residues is in the crop production process itself to enhance, maintain, and sustain the soil quality, to derive the essential environmental services, and to develop sustainable agroecosystems (Smil 1999). The multiple beneficial attributes derived from the application/incorporation of crop residues in soil include the reduction of soil erosion, enhancement of nutrient availability, stabilization of soil structure, reduction of bulk density, improvement in water retention, the use as energy source for microbial processes, increase of CEC, and finally enhancement of crop productivity (Lal 2005). The utilization of residue biomass in the crop production process is also important in the agroecosystem functioning as they promote biological functions by supplementation of SOC pool, enhanced proliferation, species diversity and activity of soil fauna, and mitigation of climate change by augmenting C sequestration and above all contributing significantly to global food security through enhancement of soil quality (Lal 2005).

Plantation crops produce large quantities of recyclable biomass which are valuable resources containing plant nutrients. Recycling of these residue biomass using biological agents or by amendments results in the production of value-added organic resource, which has application in crop production as a nutrient source as well as for soil health enhancement. The residues from certain plantation crops (e.g., coconut waste biomass) are lignocellulosic complexes with high lignin content. The natural decomposition of these wastes and the nutrient release are very slow processes due to chemical composition. The organic wastes have applications in crop production directly as mulch or after conversion to composts with the help of earthworms or microbial cultures. The recycled biomass can meet the major portion of nitrogen and a part of other nutrients required by the palms.

The quantity of recyclable biomass available from plantation crops and plantation-based cropping systems are presented in Table 6. The recyclable biomass available from coconut plantations includes mainly the fronds and husk, while bunch waste is available in very less quantities. The total availability of waste biomass from 1.93 million ha of coconut plantation in India has been estimated as 14.36 million tons annually (Biddappa et al. 1996). Waste biomass availability is higher in cropping systems when compared to that in monocrop cultivation. The coconut-based high-density multispecies cropping system (HDMSCS) at ICAR-CPCRI, Kasaragod, which has black pepper, clove, banana, and pineapple as component crops yielded 23.51 t ha^{-1} $year^{-1}$ of recyclable biomass. When the biomass from the HDMSCS is recycled, it contributed as much as 130 kg N ha^{-1}, 8.5 kg P ha^{-1}, and 121 kg K ha^{-1} (Palaniswami et al. 2007).

The extraction of coir fiber from coconut husk results in the generation of coir dust or coir pith, which constitutes 50–70% of the husk, and it accumulates near coir processing factories (Coir Board 2016). The global coconut production annually is 68 billion nuts from an area of 12 million ha (ICC 2020). Based on the report that processing of 10,000 coconut husks results in the production of one ton of coir pith as a by-product (Prabhu and Thomas 2002), it is possible to generate 6.8 million tons of coir pith annually, if all husks obtained from coconut cultivation are used for coir extraction (Jayasekhar and Chandran 2021). In practice, all husks produced are not used for coir extraction, and there is also lack of accurate data on coir pith production as all coir extraction units are not in organized sector. It is now estimated that the global production of coir pith is around 0.7 million tons annually by India and Sri Lanka together constituting 90% of the global production, of this Indian share is 0.5 million tons of coir pith annually (van Doren et al. 2017).

There is increasing interest in utilization of coir pith in a more productive way as a value-added organic resource in agrihorticulture as a suitable medium for growth of plants, organic manure after composting, soil amendment, carrier for biofertilizers, and substitute for peat moss (Prabhu and Thomas 2002). Coir fiber-based products are of value in environmental protection through soil bioengineering measures, to protect the banks of water resources by combining biological systems with engineering principles to restore deteriorated soil masses (Santha 2006). Coconut husk burial technology can help to conserve soil and water in all plantation crops. This technology was effective in reducing the runoff from 37% in control to 22% and soil

Table 6 Recyclable biomass generated in different plantation crops and plantation-based cropping systems

Plantation crop/cropping system	Type of recyclable biomass	Quantity of recyclable biomass (t ha^{-1} $year^{-1}$)	Reference
Coconut	Fronds, bunch waste, husk	14–16	Biddappa et al. (1996)
	Coir pith	0.7 million tons in India and Sri Lanka	van Doren et al. (2017)
Coconut-based HDMSCS[a] (coconut-black pepper-banana-clove-pineapple)	Coconut fronds, bunch waste, husk, leaves, pineapple stover, banana pseudo-stem, leaves	19.1–27.55	Thomas and Palaniswami (2005)
Arecanut	Leaves with leaf sheath, bunch waste, husk	8.7	Bavappa et al. (1986)
Arecanut-based HDMSCS[a] (arecanut-black pepper-cacao-banana-pineapple-clove-coffee)	Leaves with leaf sheath, bunch waste, husk, banana pseudo-stem, leaves, pineapple stover	14.3	Bavappa et al. (1986)
Cocoa	Leaf litter	8.5	Santana et al. (1988)
Oil palm	Fronds, male inflorescences, bunches that fail to develop	15–17	Sunitha and Krishnakumar (2006)
Rubber	Leaf litter	10–13	Onyibe and Gill (1992)
Cashew	Leaf litter	5.0	Usha and Vikraman Nair (2002)
Tea	Pruning	7.5–8.3	Zaman et al. (2011)
Coffee[b]	Solid and liquid from the cherries and shrubs	6.0–6.5	Glover and Beer (1986)

[a] *HDMSCS* high-density multispecies cropping system
[b] Includes the biomass addition from shade trees

loss by 49% compared to that in control in a cashew plantation and resulted in 30% increase in cashew yield (Rejani and Yadukumar 2010).

The arecanut palm yields significant quantities of recyclable biomass in the form of leaves with sheath, husk, and bunch waste. As the arecanut husk constitutes approximately 60–80% of the total weight of the nut, the quantity of husk produced is to the extent 5.5–6 metric t ha^{-1} $year^{-1}$, posing a significant disposal challenge (Vannarath and Thalla 2022). Arecanut husk fibers have high lignin and low ash content (Yuan et al. 2023) and might be of value in producing products useful in soil bioengineering similar to coconut fiber-based products. The high-density