

**COLLABORATIVE INNOVATION, LIFE CYCLE ANALYSIS
AND NETWORK OPTIMISATION – ESSAYS ON FOOD
SUPPLY CHAIN SUSTAINABILITY**

A THESIS

Submitted by

Ramesh K

for the award of the degree

of

**DOCTOR OF PHILOSOPHY
Under Joint Doctoral Degree Program**



**Department of Management Studies
Indian Institute of Technology Madras**



**Business School
University of Technology Sydney**

DECEMBER 2020

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, **Ramesh K**, declare that this thesis, is submitted in fulfilment of the requirements for the award of **Doctor of Philosophy**, in the Business School at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree except as fully acknowledged within the text.

This thesis is the result of a research candidature jointly delivered with **Indian Institute of Technology, Madras** as part of a Collaborative Doctoral Research Degree.

The research presented and reported in this thesis was conducted in accordance with the National Statement on Ethical Conduct in Human Research 2007. The proposed research study received human research ethics approval from the University of Technology Sydney Human Research Ethics Committee, Approval Number - ETH8-2983. This research is supported by the Australian Government Research Training Program.

Production Note:

Signature: Signature removed prior to publication.

Date: 14th Dec 2020

QUOTATIONS

*The deeper a well is dug, the more the water that springs;
the more one learns, the more the wisdom it brings (396).*

- THIRUVALLUVAR

DEDICATION

I wish to dedicate to

My Parents,

My Supervisors,

My Friends,

My Wife,

My Son,

Agaram Foundation,

&

My Well Wishers

All these people made me what I am today.

THESIS CERTIFICATE

This is to certify that the thesis titled **LIFE CYCLE ANALYSIS AND NETWORK OPTIMISATION –ESSAYS ON FOOD SUPPLY CHAIN SUSTAINABILITY**, submitted by **RAMESH K**, to the Indian Institute of Technology Madras, Chennai and University of Technology Sydney, Australia, for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work done by him (her) under my (our) supervision. The contents of this thesis (or project report), in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Place: Chennai

Date: 14th Dec 2020

Production Note:

Signature removed
prior to publication.

Dr Arshinder Kaur

Research Supervisor

Professor

Dept. of Mgmt. Studies, IIT Madras

Chennai 600036, India.

Production Note:

Signature removed
prior to publication.

Dr Renu Agarwal

Research Co-Supervisor

Associate Professor

UTS Business School

NSW 2007, Australia

Production Note:

Signature removed
prior to publication.

Dr Christopher Bajada

Research Co-Supervisor

Associate Professor

UTS Business School

NSW 2007, Australia

ACKNOWLEDGEMENTS

My PhD would not have been possible without the wishes, blessings and support of many people in my life.

First, I would like to thank my research supervisors, Dr Arshinder Kaur, Dr Renu Agarwal and Dr Christopher Bajada, for their continuous support and guidance throughout this journey. Dr Arshinder Kaur always encouraged me to go one step further and let me work individually without any pressure. She always had time for me whenever I had an idea and I wanted to discuss. She has encouraged me to go for the Joint Doctoral Program, which had a very big impact on my research as well as on my personal journey. That's when Dr Renu, the agile person, became my co-supervisor. Dr Renu has been very supportive throughout my research journey and especially during my stay in Australia. I used to knock her door, just like a friend, for every discussion, be it personal or academic. I learnt to spend time productively, manage multiple works and to be a responsible person. Dr Christopher (Chris), a very kind person, provided different perspectives in my research work and supported in my research journey. My heartfelt thanks to you all for believing in me and shaping me to this level in this long journey.

I would like to thank the members of my doctoral committee Dr C. Rajendran, Dr Satyanarayana K N, Dr RK Amit, and Dr Rahul Marathe at IIT Madras and Dr Sanjoy Paul at UTS Business School for their constant support and guidance throughout my research journey.

I also would like to thank the former and present Head of the Department - Dr L. Prakash Sai and Dr G. Arunkumar at DoMS, IIT Madras and Dr Bronwen Dalton at Management Discipline Group of UTS Business School, for their timely support in all the academic related activities.

I thank Mr Venkatraman Sir, Ms. Sivagami mam, Mr Bala Sir and Mani Anna from IIT Madras and Ms Ashleigh Hall, Ms Stella, Ms Caroline and Ms Nancy from UTS

Business School for their administrative support at all times.

Special thanks to my friends Kumar Srinivasan, Rajan Ranjith Kumar, Subburaj Rajagopal, Ramakrishnan Murugesan, Hariharan T S, Sri Vidhya Bhavani, Preethi Raja, Vandhana, Aswathy, Balaji Sir, Surya, Nibu John Thomas, Aravind, Sivamani Karthikeyan, Nilanjan, Swaminathan, Richard, Sivarama Anandha Krishnan, Vasanthraj, Dhandabani, Karthicanand, Anukesh and Anik Mukjherjee who have been supportive in all the ups and downs of this journey.

I wish to express my heartfelt thanks to my roommates in Australia - Eniyan, Santhosh Ganesan, Nikhil, Richard, Saravanan, Saba, Vignesh, Sathish, Sreejith and Santhosh Loganathan for making my stay a joyful and memorable one. Without their support and care, my stay wouldn't have been so peaceful.

I also wish to thank Dr Moira Scerri, Dr Sanjoy Paul, Dr Hussian Rammal, Dr Deborah Edwards and Ms Phi Yen Phan for being so friendly and supportive during my stay at UTS Business School. Moira is someone who always had time for me every morning to greet and talk a few words. I have learnt a lot from these people in terms of dedication, timeliness, commitment, professionalism and professional and personal life balancing.

I thank all my mentors of Agaram foundation for shaping me to this level with continuous motivation and support.

Finally, I thank my family, friends and all my well-wishers for their love, support and faith.

Thank You.

ABSTRACT

KEYWORDS: Food Supply Chain; Operations Research; Sustainability; Network Design; Food Waste Valorisation; Life Cycle Assessment; Farmer Producer Organisation; Multi-objective Optimisation; India.

The food supply chain is characterised by long lead times for the production of agricultural products, seasonality in production and consumption of food products, variation in quality and yield of products, special requirements for handling food products such as cold storage and perishable nature of food products – all of which make the management of the food supply chains complex and difficult. The presence of isolated and independent operations across the food supply chain also hampers collaborative efforts and leads to economic inefficiencies and environmental degradation. This is further compounded by food waste across the stages of the food supply chain – from the early stages of harvesting to processing, packaging, handling, storage, distribution and consumption. According to the Food and Agriculture Organisation, approximately one third of the global food production is wasted or lost annually. Collectively these issues necessitate research on this area as a means for developing effective solutions that ensure the effective management of food supply chain operations to meet the growing demand for food.

Further, in this contemporary business world, competition from globalisation, increased food mile due to globalisation and trade, a heightened awareness by the consumer for high quality products and transparency in operations, rising population and their food demand and strict government regulations places greater pressures on the limited resources needed to make goods and services. A culmination of such factors now mean that sustainable practices are becoming a necessity rather than a preference. Further, the increasing demand for food products to meet the growing population puts

pressure on natural resources and necessitates the sustainable way of producing and consumption of natural resources as well as reducing the food wastages at all stages of the food supply chain. Accordingly, there is a need for research that identifies opportunities for improving the sustainability of the food supply chain.

Based on the review of existing literature, this study has identified and addressed several research gaps. First, firms today are striving to adopt innovations to ensure their survival, value creation and success. Innovation is increasingly seen as an outcome of a collaborative process, involving various stakeholders both within and outside the firms, in supply chain relationships. This leads to the notion of supply chain innovation, which has been widely accepted as an important ingredient for improving the organisational and supply chain performance of firms. Inefficient practices such as improper crop selection, the involvement of too many intermediaries, flood irrigation, over-fertilization and food waste necessitate innovative practices that will improve the sustainability of the food supply chain. In this regard, there is a lack of studies that investigate how collaboration among food supply chain entities leads to innovative practices and how these innovative practices, in turn, improve the sustainability of the food supply chain. Based on the case study approach, using the case of the Indian farmer producer organisations, this study has identified several innovative practices and the sustainable outcomes.

Second, whilst India is the major producer and exporter of many crops, there is a lack of research that evaluates the environmental impact of the Indian FSCs. The environmental impact of the same product varies according to the resources consumed and so it is important that the environmental impact of individual supply chains be considered. There is a lack of studies that use the result of the environmental impact assessment to identify the operational and resource inefficiencies in FSC and address it. In this study, based on the life cycle assessment approach as per the guidelines provided by ISO 14040 and 14044, the environmental impact of resources consumed for producing 215kg of mango pulp across the various stages food supply chain is calculated. The operational and resource inefficiencies causing these inefficiencies are identified from the result of life cycle assessment and a framework is proposed considering resource recovery and operational efficiency improvement practices for redesigning of mango

food supply chain that improves environmental sustainability.

Third, food supply chain network design – a strategic decision has a significant impact on sustainability due to the involvement of a large amount of resources. Despite the significance of implementing sustainability practices, existing studies have majorly considered economic dimension alone or economic and environmental dimensions alone, leaving the impact of food supply chain operations on society. Food waste across the stages of the food supply chain has a significant negative impact on sustainability. There is a lack of studies considering food waste recovery plant as one of the entities of the food supply chain and model it despite the opportunity available for food waste valorisation. Accordingly, this study has proposed a multi objective mixed integer linear programming model for designing a sustainable food supply chain network considering the three dimensions of sustainability, shelf life and food waste recovery plant. The proposed model is applied to a real case of processed mango fruit supply chain in India. The case study elucidates trade-offs and the impact of focusing only on a particular dimension of sustainability. The impact of considering shelf life on all three dimensions of sustainability, inventory and waste generated are analysed and presented.

This study advances the existing literature on the sustainable food supply chain, provides several managerial implications to the practitioners and policy recommendations to the government and policymakers. The limitations of this present study and possible future research directions are provided.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	i
ABSTRACT	iii
LIST OF TABLES	xii
LIST OF FIGURES	xiv
GLOSSARY	xvi
ABBREVIATIONS	xviii
NOTATION	xix
CHAPTER 1: INTRODUCTION	1
1.1 Supply Chain Management	2
1.2 Food Supply Chain Management	3
1.3 Sustainable Food Supply Chain Management	5
1.4 Sustainable Food Supply Chain Network Design	7
1.5 Food Waste and Food Waste Valorisation	8
1.6 Circular Economy	8
1.7 Supply Chain Innovation	9
1.8 Supply Chain Collaboration	10
1.9 Agriculture and Food Supply Chain in India	11
1.9.1 Challenges to Agri-food Supply Chain in India	13
1.9.2 Horticulture in India	17
1.10 Motivation for this Research and Research Gaps	20
1.11 Research Questions	22
1.12 Research Aim and Objectives	22
1.13 Thesis Outline	23

CHAPTER 2: LITERATURE REVIEW	25
2.1 Sustainable Food Supply Chain	26
2.1.1 Need for Sustainability	26
2.1.2 Economic Dimension of Sustainability	27
2.1.3 Environmental Dimension of Sustainability	29
2.1.4 Social Dimension of Sustainability	32
2.2 Sustainable Food Supply Chain Network Design	34
2.2.1 Supply Chain Decision Levels	34
2.2.2 Sustainable Food Supply Chain Network Design	36
2.3 Food Waste	45
2.3.1 Status of Food Waste	45
2.3.2 Impact of Food Waste on Sustainability	46
2.3.3 Food Waste Reduction Measures	47
2.4 Circular Economy	48
2.5 Collaboration and Innovation for Sustainability	50
2.5.1 Supply Chain Innovation	50
2.5.2 Supply Chain Collaboration Leads to Supply Chain Innovation	51
2.5.3 Supply Chain Innovation Contributes to Supply Chain Sustain-	
ability	52
2.6 Summary and Research Gaps	53
CHAPTER 3: RESEARCH METHODOLOGY	56
3.1 Introduction	56
3.2 Case Study for Analysing the relationship between SCC, SCI and SCS	59
3.3 Life Cycle Analysis for Environmental Impact Assessment	60
3.4 Analytical Modelling for Supply Chain Design	63
3.5 Conclusion	65
CHAPTER 4: COLLABORATIVE INNOVATION AND SUSTAINABIL-	
ITY IN THE FOOD SUPPLY CHAIN- EVIDENCE FROM FARMER PRO-	
DUCER ORGANISATIONS	66
4.1 Introduction	66

4.2	Framework and Economic Model Development	68
4.2.1	Conceptual Framework	68
4.2.2	Economic Model for the Collaborative Business Model of FPO	70
4.3	Methodology	74
4.3.1	Sample Selection	74
4.3.2	Data Collection and Analysis	75
4.4	Research Findings and Discussions	78
4.4.1	Innovative Practices Emanating from Collaboration and Leading to Sustainable Outcomes	78
4.4.2	Integrated Framework on Collaboration and Innovation in Sustainable Food Supply Chain	88
4.5	Discussion	89
4.6	Conclusion	90
CHAPTER 5: REDESIGNING A FOOD SUPPLY CHAIN FOR ENVIRONMENTAL SUSTAINABILITY – AN ANALYSIS OF RESOURCE USE AND RECOVERY		91
5.1	Introduction	91
5.2	Conceptual Framework	93
5.3	Methodology	99
5.3.1	LCA for Mango FSC	99
5.4	Development of Framework for Sustainable Mango FSC by Analysing Resources	112
5.4.1	Operational Efficiency Improvement and Resource Recovery Practices for Mango Cultivation Stage	113
5.4.2	Operational Efficiency Improvement and Resource Recovery Practices for Mango Pulp Production Stage	114
5.4.3	Operational Efficiency Improvement and Resource Recovery Practices for Mango Pulp Packaging Stage	115
5.4.4	Operational Efficiency Improvement and Resource Recovery Practices for Mango Transportation Stage	115
5.4.5	Sensitivity Analysis of Resource Usage and Environmental Impact	117
5.5	Discussion	118

5.6	Conclusion	119
CHAPTER 6: A MULTI-OBJECTIVE OPTIMIZATION OF FOOD SUPPLY CHAIN NETWORK FOR SUSTAINABILITY CONSIDERING PERISHABILITY AND FOOD WASTE VALORIZATION		120
6.1	Introduction	120
6.2	Problem Description and Model Formulation	122
6.2.1	Problem Description	122
6.2.2	Model Formulation	126
6.2.3	Objective Functions	133
6.3	Solution Approach	145
6.3.1	Multi-objective Optimization	145
6.3.2	Augmented Epsilon Constraint Method	146
6.4	Results and Discussions	147
6.4.1	Details of Case Study Considered and Data Collected	147
6.4.2	Estimation of Price Function for Mango	151
6.4.3	Results and Discussion	152
6.5	Discussion	160
6.6	Conclusion	161
CHAPTER 7: DISCUSSION AND CONCLUSION		163
7.1	Introduction	163
7.2	Key Research Findings	164
7.2.1	Collaboration for Sustainability	165
7.2.2	Redesigning for Environmental Sustainability	167
7.2.3	FSC Network Design for Sustainability	168
7.2.4	Interplay between Essays - Collaboration, LCA and Network Design	170
7.3	Contributions and Implications	172
7.3.1	Theoretical Contributions	172
7.3.2	Managerial Implications	172
7.3.3	Policy Recommendations	173
7.4	Limitations and Directions for Future Research	174

7.5 Conclusion	175
APPENDIX A: QUESTIONNAIRE - CHAPTER 4	177
REFERENCES	203
LIST OF PUBLICATIONS.	204

LIST OF TABLES

Table	Title	Page
1.1	Area, Production and Yield of Major Crops ((DAC&FW, 2020, p.6)) .	12
1.2	Area, Production, and Productivity of Horticulture Crops during the past 10 Years (DAC&FW, 2019, p.75)	18
1.3	Season and Characteristics of Most Commonly Grown Mango Variety in India	19
2.1	Economic Benefit of Sustainable Practices	28
2.2	Existing Literature on Sustainable Food Supply Chain Network Design - Contributions to Research	37
2.3	Existing Literature on Sustainable Food Supply Chain Network Design - Key Considerations	40
3.1	Gaps and Objectives Addressed in each Chapters, and Research Methodology Followed	58
4.1	Summary of the four FPO Case Organisations	75
4.2	Questionnaire used in the Interview Process	77
4.3	Innovative Practices emanated from Collaboration at each level of the SCOR model	79
4.4	Innovative Practices, Innovation Type and Sustainability Dimension - Plan Level	80
4.5	Innovative Practices, Innovation Type and Sustainability Dimension - Source Level	84
4.6	Innovative Practices, Innovation Type and Sustainability Dimension - Make Level	85
4.7	Innovative Practices, Innovation Type and Sustainability Dimension - Deliver Level	86
4.8	Innovative Practices, Innovation Type and Sustainability Dimension - Return Level	87

5.1	Inventory data for Cultivation, Pulp Production and Packaging Stage .	104
5.2	Environmental Impacts Corresponding to Different Stages of Mango FSC	107
5.3	Environmental Impacts Corresponding to the Cultivation Stage of Mango FSC	108
5.4	Environmental Impacts Corresponding to the Processing Stage of Mango FSC	109
5.5	Environmental Impacts Corresponding to the Packaging Stage of Mango FSC	110
5.6	Environmental Impacts Corresponding to the Transportation Stage of Mango FSC	111
6.1	Parameter Values from Case Study	148
6.2	Payoff Table - Objective Function Values based on Priority	152
6.3	Non-Dominated Solutions (Cost Measured in terms of Thousand Million INR)	157
6.4	Price Function vs Cost	160
A.1	Questionnaire used in the Interview Process	178

LIST OF FIGURES

Figure	Title	Page
1.1	Introduction Chapter Structure	1
1.2	Structure of the Food Supply Chain	4
1.3	Agri-Food Supply Chain in India	12
1.4	Overall Structure of the Thesis	24
2.1	Literature Review Chapter Structure	25
2.2	Impact of Food Waste on Food Supply Chain’s Sustainability (adopted from Gokarn and Kuthambalayan (2017)	46
3.1	Research Process Flowchart	57
3.2	Methodology Chapter Structure	59
3.3	Steps Involved in Life Cycle Assessment	62
3.4	Steps Involved in Analytical Modelling	64
4.1	Chapter Structure	68
4.2	Conceptual Framework	69
4.3	Effects of Innovation and Scale Efficiency of FPOs	71
4.4	Trade-off Between Environment Outcomes and Profitability	73
4.5	Technological Interventions Supporting FSC Operations (Icons used in the Figure are Downloaded from www.flaticon.com)	82
4.6	Framework of Classification of Innovative Practices at each Level of SCOR model	88
5.1	A Theoretical Sustainable Food Supply Chain Framework	93
5.2	Chapter Structure	94
5.3	SFSC Conceptual Framework for Improving Operational Efficiency and Resource Recovery	95

5.4	Resource Substitution Effect from CE Practices (RM - Recycled Material, VM - Virgin Material)	96
5.5	Reduction in Resource use from Improving Operational Efficiency	98
5.6	Productivity Improvement from the Combined Effect of Improving Operational Efficiency and Resource Recovery	98
5.7	Existing Mango FSC	100
5.8	System Boundary and Process Flow (The Dotted Line Represents the Four Stages 1-4 within System Boundary)	102
5.9	Potential Causes of Environmental Impact at Each Stage of Mango FSC	112
5.10	Redesigned Environmentally Sustainable Mango FSC Framework	116
5.11	Sensitivity Analysis	118
6.1	Chapter Structure	122
6.2	Process Flow of Redesigned Mango Supply Chain	124
6.3	Price of Mango Over the Period	152
6.4	Quantity of Mango Procured (A) and Inventory of Mangoes (B) over the Period under Economic Objective Functions	153
6.5	Quantity of Mango Pulp (A) and Recycled Product Produced (B) across the Plants	154
6.6	Quantity of Mangoes Procured under Environmental Objective to meet the Demand for Pulp	155
6.7	Quantity of Mangoes Procured (A), Pulp (B) and Recycled Product (C) Produced, and Inventory Maintained (D) under Social Objective	156
6.8	Shelf Life vs Cost (A), Emission (B) and Jobs (C)	158
7.1	Chapter Structure	164

GLOSSARY

Food Supply Chain Management Sustainability	Management of series of activities from receiving farm inputs from suppliers, cultivation, processing, packaging and distribution of food products to the customers in fresh quality.
Life Cycle Assessment	The design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions and the environment.
FPO	Aims to calculate the environmental impacts of resources consumed and waste generated across the stages of the food supply chain.
Food Waste	Farmer Producer Organisations (FPO) are formed by the group of small farm landholders with the initial capital generated from the members of the FPO.
Food Supply Chain Network Design	Wholesome edible material intended for human consumption, arising at any point in the FSC that is instead discarded, lost or degraded.
Supply Chain Innovation	Aims to find the best configuration of supply chain operational elements by determining sourcing strategies such as supplier selection, selection of location, capacity and number of facilities to open and operate and distribution strategies to meet the demand.
Supply Chain Collaboration	An integrated change from incremental to radical changes in product, process, marketing, technology, resource and/or organisation, which are associated with all related parties, covering all related functions in supply chain and creating value for all its stakeholders.
Food Waste Valorisation	A close and long-term relationship in which supply chain partners work together to share resources, information, and risk using different coordination mechanisms as well as solve problems and make decisions jointly to achieve mutual objectives.
	Conversion of food waste into higher value product which can be used back in the same or different supply chain as an input/ingredient for producing a new product.

ABBREVIATIONS

AC	Acidification
CE	Circular Economy
DCT	Dynamic Capability Theory
EU	Eutrophication
FAO	Food and Agriculture Organisation
FSC	Food Supply Chain
FPO	Farmer Producer Organisation
FWAE	Fresh Water Aquatic Ecotoxicity
GHG	Green House Gas
GWP	Global Warming Potential
HT	Human Toxicity
IPP(S,M,D & R)	Innovative Practices at Plan (Source, Make, Deliver & Return) level
LCA	Life Cycle Assessment / Analysis
LRAC	Long-run Average Cost
MAE	Marine Aquatic Ecotoxicity
MOMILP	Multi-Objective Mixed-Integer Linear Programming
NGO	Non-governmental Organisation
OM	Operations Management
PO	Photochemical Oxidation
SCC	Supply Chain Collaboration
SCI	Supply Chain Innovation
SCM	Supply Chain Management
SCOR	Supply Chain Operations Reference
SCND	Supply Chain Network Design
SCS	Supply Chain Sustainability
SFO	Self Funded Organisation
SFSC	Sustainable Food Supply Chain
TE	Terrestrial Ecotoxicity

NOTATION

Indices

i	Index for farmers location, $i = 1, 2, \dots, I$
j	Index for processing plant location, $j = 1, 2, \dots, J$
k	Index for distributor/retailer location, $k = 1, 2, \dots, K$
l	Index for waste recovery plant location, $l = 1, 2, \dots, L$
m	Index for market location for recycled products, $m = 1, 2, \dots, M$
t_1	Index for transportation mode (Mango), $t_1 = 1, 2, \dots, T$
t_2	Index for transportation mode (Pulp), $t_2 = 1, 2, \dots, T$
t_3	Index for transportation mode (Waste and Pectin), $t_3 = 1, 2, \dots, T$
p	Index for time period (days), $p = 1, 2, \dots, P$
a	Age of the mangoes procured in days, $a = 1, 2, \dots, SL_M$
b	Age of the mango waste generated in days, $b = 1, 2, \dots, SL_{MW}$

Economic-related parameters

Overall Transportation

TCM_{t_1ij}	Transportation cost per kg of mango from farmer i to processing plant j through transportation mode t_1
TCP_{t_1jk}	Transportation cost per kg of mango pulp from plant j to distributor k through transportation mode t_2
TCW_{t_1jl}	Transportation cost per kg of waste from plant j to waste recovery plant l through transportation mode t_3
TCR_{t_1lm}	Transportation cost per kg of recycled product from waste recovery plant l to market m through transportation mode t_3

Mango processing plant

FCP_j	Annual fixed cost for building and equipping processing plant j
VCP_j	Variable cost per kg for processing of mango at the processing plant j
PV_j	Maximum production volume (kg/day) of processing plant j
MQ	Quantity (kg) of mango required to produce one unit of mango pulp
CM_{pi}	Purchasing cost per kg of mango procured from farmer i in period p
HCW_j	Handling cost per kg of waste (peels, seeds) at the plant j
ICM_j	Inventory holding cost per kg of mango in processing plant j
ICP_j	Inventory holding cost per kg of mango pulp in processing plant j
QoP	Quantity (kg) of peels present per kg of mango waste

Waste recovery plant

- FCR_l Annual fixed cost for building and equipping waste recovery plant l
 VCR_l Variable cost per kg of recovery at the waste recovery plant l
 PV_l Maximum production volume (kg/day) of waste recovery plant l
 WQ Quantity of mango waste (kg) required to produce one unit of recycled product
 $ICMW_l$ Inventory holding cost per kg of mango waste in recovery plant l
 $ICRP_l$ Inventory holding cost per kg of recycled product in recovery plant l
 HCW_l Handling cost per kg of mango waste at the plant l

Environmental-related parameters

Overall transportation

- $EITM_{t_1ij}$ GHG emission associated with transportation of one kg of mango from farmer i to processing plant j through transportation mode t_1
 $EITP_{t_2jk}$ GHG emission associated with transportation of one kg of mango pulp from plant j to distributor k through transportation mode t_2
 $EITW_{t_3jl}$ GHG emission associated with transportation of one kg of waste from plant k to recovery plant l through transportation mode t_3
 $EITR_{t_3lm}$ GHG emission associated with transportation of one kg of recycled products from recovery plant l to market m through transportation mode t_3

Mango processing plant

- EIP_j GHG emission associated with the processing of one kg of mango at the plant j
 EIM_i GHG emission associated with the cultivation of one kg of mango at the farm i
 $EIIM_j$ GHG emission associated with holding inventory of mango (kg) in processing plant j
 $EIIP_j$ GHG emission associated with holding inventory of mango pulp (kg) in processing plant j
 $EIMW_j$ GHG emission associated with mango waste (kg) in processing plant j

Waste recovery plant

- EIR_l GHG emission of recovery one kg of mango waste at the waste recovery plant l
 $EIIMW_l$ GHG emission associated with holding inventory of mango waste (kg) in recovery plant l
 $EIIRP_l$ GHG emission associated with holding inventory of recycled product (kg) in recovery plant l
 $EIMW_l$ GHG emission associated with mango waste (kg) in waste recovery plant l

Social-related parameters

JO_{PP_j}	Number of fixed job opportunities created from opening mango processing plant j
JO_{pj}	Number of job opportunities created from processing of one kg of mango in processing plant j
JOW_j	Number of job opportunities created from handling one kg of wastes at mango processing plant j
JOW_l	Number of job opportunities created from handling one kg of wastes at waste recovery plant l
JO_{WP_l}	Number of fixed job opportunities created from opening a new facility for mango waste recovery l
JO_l	Number of variable job opportunities created per kg of mango waste recovery l
JO_{t_1ij}	Number of job opportunities created from the transportation of one kg of mango from farmers i to processing plant j
JO_{t_2jk}	Number of job opportunities created from the transportation of one kg of waste from processing plant j to distribution centre k
JO_{t_3jl}	Number of job opportunities created from the transportation of one kg of waste from processing plant j to recovery plant l (n per unit quantity)
JO_{t_3lm}	Number of job opportunities created from the transportation of one kg of waste from recovery plant l to market m (n per unit quantity)
JO_{Inv_j}	Number of job opportunities created from handling one kg of waste in processing plant j
JO_{Inv_l}	Number of job opportunities created from handling one kg of waste in waste recovery plant l

Other parameters

D_{pk}	Demand for mango pulp (kg) from the distributor k in period p
D_{pm}	Demand for the recycled product (kg) from the market m in period p
M	Maximum number of mango processing plant to open
N	Maximum number of waste recovery plant to open
CF_{pi}	Capacity of the farmer (kg) i to supply mango in period p
SL_M	Shelf life (days) of mango
SL_{MW}	Shelf life (days) of mango waste
$MaxIM_j$	Inventory storage capacity (kg) for mango in processing plant j
$MaxIM_j$	Inventory storage capacity (kg) for mango pulp in processing plant j
$MaxIW_l$	Inventory storage capacity (kg) for mango waste recovery plant l
$MaxIRP_l$	Inventory storage capacity (kg) for the recycled product in waste recovery plant l

Decision variables

y_j	Binary variable takes the value of 1 if processing plant j is selected; 0 otherwise
z_l	Binary variable takes the value of 1 if waste recovery plant l selected; 0 otherwise
m_{pt_1ij}	Quantity (kg) of mangoes transported with t_1 from farmers i to processing plant j in period p
p_{pja}	Quantity (kg) of mango pulp produced at processing plant j using mango of age a in period p
tp_{pt_2jk}	Quantity (kg) of mango pulp transported with t_2 from processing plant j to distributor location k in period p
w_{pj}	Quantity (kg) of waste (peels and seeds) generated from the processing of mango at processing plant j in period p
tw_{pt_3jl}	Quantity (kg) of waste transported with t_3 from processing plant j to waste recovery plant l in period p
r_{plb}	Quantity (kg) of recycled product produced at waste recovery plant l using mango waste of age b in period p
tr_{pt_3lm}	Quantity (kg) of recycled product transported with t_3 from recovery plant l to market m in period p
$invm_{pja}$	Quantity (kg) of inventory of mango of age a in processing plant j in period p
$invp_{pj}$	Quantity (kg) of inventory of pulp in processing plant j in period p
$wastem_{pja}$	Quantity (kg) of mango goes waste after reaching its shelf life $a = SL_M$ in processing plant j at the end of period p
$inmw_{plb}$	Quantity (kg) of inventory of mango waste in recovery plant l with age b in period p
$invr_{pl}$	Quantity (kg) of inventory of recycled product in recovery plant l in period p
$wastmw_{plb}$	Quantity (kg) of mango waste goes as unusable for recovery after reaching its shelf life $b = SL_{MW}$ in waste recovery plant l at the end of period p
m_{pja}	Quantity (kg) of mango of age a available at the beginning of period p in processing plant j
mw_{plb}	Quantity (kg) of mango waste of age b available at the beginning of period p in waste recovery plant l