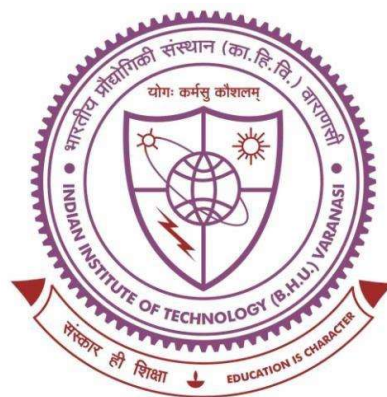


**Estimation of biophysical and biochemical parameters
using optical satellite images and sensor onboard UAV**



**A thesis submitted in fulfilment for the Award
of Degree of**

Doctor of Philosophy

By

Bhagyashree Verma

**DEPARTMENT OF PHYSICS
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI-221005**

Roll Number: 17171502

2023

*Dedicated with love to my parents, dadi,
friends, and critics*



भारतीय
प्रौद्योगिकी
संस्थान
काशी हिन्दू विश्वविद्यालय



INDIAN
INSTITUTE OF
TECHNOLOGY
BANARAS HINDU UNIVERSITY

CERTIFICATE

It is certified that the work contained in the thesis titled *“Estimation of biophysical and biochemical parameters using optical satellite images and sensor onboard UAV”* by *Bhagyashree Verma* has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of the comprehensive examination, candidacy, and SOTA for the award of Ph.D. Degree.

Signature:

Rajendra Prasad
08/06/2023

Supervisor

Rajendra Prasad
(Professor)
Department of Physics
Indian Institute of Technology
(Banaras Hindu University)
Varanasi-221005 (UP)

Professor
Department of Physics
Indian Institute of Technology
(Banaras Hindu University)
Varanasi-221005



INDIAN
INSTITUTE OF
TECHNOLOGY
BANARAS HINDU UNIVERSITY



भारतीय
प्रौद्योगिकी
संस्थान
काशी हिन्दू विश्वविद्यालय



INDIAN
INSTITUTE OF
TECHNOLOGY
BANARAS HINDU UNIVERSITY

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: Estimation of biophysical and biochemical parameters using optical satellite images and sensor onboard UAV

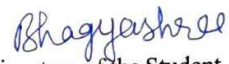
Name of the Student: Bhagyashree Verma

Copyright Transfer

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the “*DOCTOR OF PHILOSOPHY*”.

Date: 08/06/2023

Place: IIT (BHU), Varanasi


Signature of the Student

(Bhagyashree Verma)

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for the author's personal use provided that the source and the Institute's copyright notice are indicated.

ACKNOWLEDGMENT

*I will forever be grateful to my supervisor **Prof. Rajendra Prasad**, Department of Physics, Indian Institute of Technology (BHU), for providing the research guidance, improving my skills, and teaching me lessons about life and professional ethics. He supported me in all sorts of ways. I don't think that thank word is enough here for him, but yes, I would always owe him. I am also extremely thankful to **Dr. Prashant K. Srivastava** (Institute of Environment and Sustainable Development, BHU) for his support, resources and suggestions that helped me in my research work. I would also like to thank my RPEC members, **Dr. Sunil K. Singh** (Internal expert) Department of Physics, Indian Institute of Technology (BHU), **Dr. Shishir Gaur** (External expert), Department of Civil Engineering, the Indian Institute of Technology (BHU). I use this opportunity to express my gratefulness to the Head and all the faculty members of the Department of Physics, Indian Institute of Technology (BHU), Varanasi. I am also thankful to all the non-teaching and technical staff members of the Department of Physics for their kind support.*

*I would like to thank all my lab mates, seniors, and juniors **Dr. Ajeet K. Vishwakarma, Dr. Ruchi Bala, Dr. Vijay P. Yadav, Dr. Suraj A. Yadav, Shubham K. Singh, and Bharat Prajapati** for providing me a conducive environment for carrying out my research work. Although there are couple of lab mates who made their way in my life as my good friends and supporters, **Dr. Jyoti Sharma and Sumana Khamrai**, I wish them the best in all their future endeavour.*

*This place has also given me memories and friends to cherish for the longest time in my life, my roommate and my good friend, **Manisha Dixit**, who has always been stood up with me, in good times and in bad, her constant care and support kept me in line and sane during troublesome time of the research.*

*In the Institute, so many friends, we cherished and spent healthy time together, so thanks to my friends, **Harshita Trivedi, Swati Suman, Manisha Chauhan, and Harsh Shukla**. My coursework era would not have been fun without my batchmates **Prem Chandra Bharti, Lavanya Ghosh, and Sambhab Dan**, working with them during project assignment was wonderful time.*

*I would also like to thank my dearest friends from school, Bachelor's, and Master's college times, **Harshit, Ranjana, Rimpay, Prity, Sneha, Shweta, Richa, Shalini, Vipul, Ritika, Akhilesh, Kavita, Pankaj, and Neha** for their continued support in my tough times since childhood. I am also grateful to **Prachi Singh** (Institute of Environment and Sustainable Development, BHU) for her continuous help in my research work, and emotional support throughout my time here. A very special mention to **Anushree Badola**, (University of Alaska, Fairbanks, USA), for her help in my project work and her very kind words and motivation throughout, without which it would not have been possible to bring forth my ideas to actuality.*

I would also like to thank the National Aeronautics and Space Administration (NASA), European Space Agency (ESA) for providing free access to the satellite data used in my research work. I also want to acknowledge Space Application Centre, Indian Space Research Organization (ISRO) for their support in data collection and providing AVIRIS-NG datasets. I wish to gratefully acknowledge the Ministry of Human Resource Development (MHRD) for providing me the financial support in the form of a fellowship.

*Last but not the least, I express my sincere gratitude and love to my beloved, caring and supporting parents and family members who always stood by me rendering me motivation, moral support, encouragement, love, and care. I am very much grateful to my papa, **Dr Bhagwat Prasad**, mummy, **Mrs. Meera Devi**, my dadi, elder brothers **Kapil K. Kushwaha** and **Vivek K. Kushwaha**, my sisters-in-law **Archana Verma** and **Divyashree H. K.** for sustaining and helping me throughout. I am also grateful to my extended family members especially my friendly and zealous cousins to keep me motivated, entertained and happy. During the last semester, me and my family was blessed with a newly born nephew, and in many ways, he encouraged me to be a better person. His sweet smile would take away all my sorrows and worries, kept me stress free during the stressed time of pre-submission seminar. I wish to be one of the sources of inspiration for the little guy.*

Department of Physics, IIT (BHU), Varanasi

Bhagyashree Verma

ABSTRACT

Hyperspectral (HS) sensors are essential for measuring minute changes in vegetation spectra, making it a useful tool to study vegetation parameters, for monitoring crop. Leaf Chlorophyll Content (LCC) indicate plant growth, stress, and nutrient availability, its detailed information is required in precision agriculture. Leaf Area Index (LAI), a biophysical vegetation parameter which indicates shadow imprint and density of vegetation. Hence, scientists must determine its precise quantity for monitoring of vegetation healthy growth.

Every object emits light in range of electromagnetic spectrum, in order to study such emissions and absorption HS sensors are required. These sensors acquire images in hundreds of bands with very high spectral resolution (as high as 5nm) making it a very useful tool to study any subjects that require information of very low spectral width. The parameters of interest in the present study are LCC and LAI.

HS images are not freely available, but multispectral images with low spectral resolution are widely available. The part of work in the thesis attempts to create AVIRIS-NG, a hyperspectral image, using Sentinel-2 image and a linear unmixing method called Universal Pattern Decomposition Method (UPDM), it decomposes each image pixel as a linear combination of many classes. Since, the image is reconstructed with three major classes present in the study site, so there is some information loss while simulation because there could be more than three classes present in the area. Ground-based LCC observations from a chlorophyll meter (Soil Plant Analysis Development (SPAD)) confirmed that the simulated AVIRIS-NG could calculate LCC efficiently. Further, generated image's wavelength range depends on the number of

multispectral bands, but its spatial resolution is the same as the base image (multispectral image). Thus, an image from RedEdge MX installed on an Unmanned Aerial Vehicle (UAV), was used to simulate a half-range AVIRIS- NG image. The generated image was utilised to create a LAI and LCC map, which compared well to in-situ LAI and LCC.

Furthermore, denoising the vegetation spectra of diverse agricultural species using AVIRIS-NG imagery using different types of wavelets was used to improve LCC estimation accuracy. After noise removal, several Feature Selection Methods (FSMs) were employed to choose absorption bands relevant to chlorophyll content such as Recursive Feature Elimination (RFE), Regularised Random Forest (RRF), Least Absolute Shrinkage and Selection Operator (LASSO), and Partial Least Square (PLS). These FSMs selected the top three absorption bands to create new LCC retrieval Vegetation Indices (VIs). These VI indicators are used to form linear regression models for LCC mapping. PLS-based LCC retrieval model performed the best, whereas LASSO-generated chlorophyll model performed the least.

Another study used PLS's (Variable Importance in Projection) VIP score to select important VIs for LCC and LAI retrieval of various agricultural crops under different treatments such as fertilizers and irrigation. Twenty-Five hyperspectral VIs for LCC and seven canopy VIs for LAI assessment were tested using Support Vector Regression (SVR with linear, radial, and polynomial kernels), Partial Least Square Regression (PLSR), Hybrid neural fuzzy inference system (HyFIS), and Random Forest Regression (RFR). VIP from PLS and R^2 were determined for each VI to find the most sensitive information for vegetation parameters.

LAI was found to be most sensitive in red-edge reflectance region. The green, red, and red-edge VIs indices were responsive to lentil and maize crop bed temporal LCC values. However, for Mustard the temporal LCC values were sensitive to VIs generated from green, red, and NIR bands. Top three indices with the highest VIP and R^2 values were used as ideal inputs to create different machine learning models. SVR-Rad generated model gave the best estimation among others.

Conclusively, the work shows a successful attempt in generating models for LAI and LCC estimation, using different remote sensing technique such as from a simulated hyperspectral image, denoised hyperspectral image, and from a spectroradiometer data.

TABLE OF CONTENTS

CERTIFICATE	i
DECLARATION BY THE CANDIDATE	ii
COPYRIGHT TRANSFER CERTIFICATE	iii
ACKNOWLEDGEMENT	v
ABSTRACT	vii
TABLE OF CONTENTS	xi
LIST OF FIGURES	xvii
LIST OF TABLES	xxi
LIST OF ABBREVIATIONS	xxiii
LIST OF SYMBOLS	xxvii
CHAPTER 1: INTRODUCTION	1-25
1.1 REMOTE SENSING: FUNDAMENTALS	1
1.2 TYPES OF REMOTE SENSING	2
1.2.1 Active Remote sensing	2
1.2.2 Passive Remote sensing	3
1.3 ELECTROMAGNETIC RADIATION (EMR) IN REMOTE SENSING	3
1.4 DIFFERENT INTERACTION BETWEEN THE ATMOSPHERE AND EMR	4
1.4.1 Scattering	5
1.4.1.1 Rayleigh scattering	5
1.4.1.2 Mie scattering	5
1.4.1.3 Non-selective scattering	5
1.4.2 Absorption	6
1.5 INTERACTION BETWEEN THE EARTH SURFACE AND THE EMR	7
1.6 SPECTRAL RESPONSE/SIGNATURE CURVE	7
1.7 DIFFERENT TYPES OF RESOLUTION IN REMOTE SENSING	9

1.7.1 Spatial resolution	10
1.7.2 Temporal resolution	10
1.7.3 Spectral resolution	11
1.7.4 Radiometric resolution	11
1.8 HYPERSPECTRAL REMOTE SENSING	12
1.8.1 Applications of hyperspectral remote sensing	14
1.9 UNMANNED AERIAL VEHICLE (UAV)	16
1.10 REVIEW OF LITERATURE	16
1.10.1 Importance of LAI and LCC	18
1.11 RESEARCH OBJECTIVES	20
1.12 CONTENT OF THE THESIS	23
CHAPTER 2: SATELLITE IMAGES, INSTRUMENTS, AND STUDY AREA	27-39
2.1 REMOTELY SENSED IMAGES	27
2.1.1 Airborne Visible InfraRed Imaging Spectrometer-Next Generation (AVIRIS-NG)	27
2.1.2 Sentinel-2	29
2.1.3 MICASENSE RedEdge MX	31
2.2 HAND HELD INSTRUMENTS	32
2.2.1 FieldSpec 4	32
2.2.2 Soil Plant Analysis Development (SPAD)	34
2.2.3 LAI-2200C PLANT CANOPY ANALYZER	34
2.2.3.1 Measurement of LAI	35
2.3 STUDY AREA	36
2.3.1 ANAND DISTRICT, GUJARAT (Study area 1)	37
2.3.2 VARANASI DISTRICT, UTTAR PRADESH (Study area 2)	38

CHAPTER – 3: EVALUATION OF SIMULATED AVIRIS-NG IMAGERY USING A SPECTRAL RECONSTRUCTION METHOD FOR THE RETRIEVAL OF LEAF CHLOROPHYLL CONTENT	41-65
3.1 INTRODUCTION	41
3.2 MATERIALS AND METHODOLOGY	44
3.2.1 Study area and data acquisition	44
3.2.2 Remotely sensed and ground data	45
3.2.2.1 Hyperspectral data	45
3.2.2.2 Multispectral data	45
3.2.2.3 Ground data	46
3.2.3 Simulating AVIRIS-NG from Sentinel-2 using UPDM	46
3.2.3.1 Computing standard spectra	46
3.2.3.2 Spectral unmixing	50
3.2.4 Classification using Spectral Angle Mapper (SAM)	53
3.2.5 Calculation of vegetation index for the retrieval of LCC	55
3.4 RESULTS AND DISCUSSION	55
3.4.1 Simulation of AVIRIS-NG imagery	55
3.4.2 Classification over simulated image	56
3.4.3 Class separability analysis	59
3.4.4 LCC Retrieval	60
3.5 CONCLUSION	63
CHAPTER – 4: ESTIMATING BIOPHYSICAL AND BIOCHEMICAL PARAMETERS FROM A HALF RANGE PSEUDO HYPERSPECTRAL IMAGE GENERATED FROM UAV	67-80
4.1 INTRODUCTION	67
4.2 METHODOLOGY	69
4.2.1 Study area and data acquisition	69

4.2.2 Aerial image acquisition	70
4.2.3 Simulating a pseudo hyperspectral imagery using SRF of AVIRIS-NG and RedEdge MX	72
4.2.3.1 Computing standard spectra	72
4.2.3.2 Spectral unmixing	72
4.3 RESULTS AND DISCUSSION	74
4.3.1 Simulation of half range AVIRIS-NG	74
4.3.2 LAI/LCC retrieval mapping	76
4.3.3 Performance indices	76
4.4 CONCLUSIONS	79
CHAPTER – 5: LEAF CHLOROPHYLL CONTENT RETRIEVAL FOR AVIRIS-NG IMAGERY USING DIFFERENT FEATURE SELECTION AND WAVELET ANALYSIS	81-102
5.1 INTRODUCTION	81
5.2 METHODOLOGY	84
5.2.1 Study site	84
5.2.2 Datasets	85
5.2.3 Wavelet Analysis (WA)	86
5.2.4 Feature Selection Methods (FSM)	87
5.2.4.1 Recursive Feature Elimination (RFE)	87
5.2.4.2 Regularised Random Forest (RRF)	88
5.2.4.3 Least Absolute Shrinkage and Selection Operator (LASSO)	89
5.2.4.4 Partial Least Square (PLS)	89
5.3 LCC RETRIEVAL	90
5.4 RESULTS AND DISCUSSION	91
5.4.1 Wavelet analysis	91
5.4.2 Selection of Optimum Bands	93
5.4.3 LCC mapping	95

5.5 CONCLUSIONS	102
CHAPTER – 6: INVESTIGATION OF OPTIMAL VEGETATION INDICES FOR RETRIEVAL OF LEAF CHLOROPHYLL CONTENT AND LEAF AREA INDEX USING ENHANCED LEARNING ALGORITHMS	103-139
6.1 INTRODUCTION	103
6.2 METHODOLOGY	106
6.2.1 Study area and in-situ data collection	106
6.2.2 Leaf spectral data	109
6.2.3 Selection of vegetation indices	109
6.3 STATISTICAL ANALYSIS	113
6.3.1 Support Vector Regression (SVR)	113
6.3.2 Random Forest Regression (RFR)	114
6.3.3 Partial Least Regression (PLS)	115
6.3.4 Hybrid neural Fuzzy Inference System (HyFIS)	115
6.3.5 Performance indices	116
6.4 RESULTS AND DISCUSSION	116
6.4.1 PLS and R2 analysis-based selection of optimal VIs	118
6.4.2 Predictors, response variable, and calibration\validation datasets for model development	124
6.4.3 Enhanced learning algorithms inversion for LAI and LC retrieval	125
6.4.3.1 LAI retrieval of Lentils, Maize, Mustard crop using SVR, RFR, PLSR, and HyFIS models	125
6.4.3.2 LCC retrieval of Lentils, Maize, Mustard crop using SVR, RFR, PLSR, and HyFIS models	126
6.5 CONCLUSION	138

CHAPTER – 7: CONCLUSIONS, FUTURE PLANS AND SCOPE	141-143
7.1 CONCLUSIONS	141
7.2 FUTURE PLANS AND SCOPE	142
LIST OF PUBLICATIONS	145
REFERENCES	149

LIST OF FIGURES

Figure 1.1 Remote sensing process.....	1
Figure 1.2 (a)Active Remote Sensing; (b) Passive Remote Sensing.....	2
Figure 1.3 Electromagnetic radiation.....	3
Figure 1.4 Atmospheric window in Remote sensing.....	6
Figure 1.5 Typical vegetation spectra.....	8
Figure 1.6 Different types of resolutions: (a) Spatial resolution; (b) Temporal resolution; (c) Spectral resolution; (d) Radiometric resolution	10
Figure 1.7 Multispectral imaging (MSI) vs Hyperspectral imaging (HSI).....	13
Figure 2.1 The AVIRIS-NG instrument accomodation in the DHC-6 aircraft.	28
Figure 2.2 Components of the AVIRIS-NG sensor.	28
Figure 2.3 Sensor of Sentinel-2	30
Figure 2.4 (a) RedEdge MX camera; (b) VTOL-Lite TALV-2400.....	32
Figure 2.5 (a) FieldSpec 4; (b) SPAD-502Plus; (c) LI-COR.	33
Figure 2.6 Absorbance of visible light by chlorophyll.	34
Figure 2.7 Light interception by LAI-2200C at five different angles.	35
Figure 2.8 Study area 1 in Anand, Gujarat.	37
Figure 2.9 Study area 2 in Varanasi district, Agrcultural farm,(BHU).	38
Figure 3.1 Workflow of the study.....	45
Figure 3.2 (a) Simulated AVIRIS-NG (bands 97, 56, and 36); (b) Sentinel-2 imagery (bands 8, 4, and 3); (c) clipped area for Sentinel-2 imagery; (d) AVIRIS-NG imagery (bands 97, 56, and 36); (e) clipped area for simulated AVIRIS-NG imagery.....	48
Figure 3.3 (a) Spectral response function for the sensors of AVIRIS-NG (for the first 90 bands); (b) spectral response function for the sensors of Sentinel-2.....	49-50

Figure 3.4 Comparison of vegetation spectra for AVIRIS-NG and simulated AVIRIS-NG.	53
Figure 3.5 Comparison of soil spectra for AVIRIS-NG and simulated AVIRIS-NG.	53
Figure 3.6 Classification on the simulated image.....	54
Figure 3.7 ROC curve for the classification with AUC values.	59
Figure 3.8 Class seperability chart.....	60
Figure 3.9 Chlorophyll map for the simulated AVIRIS-NG.	61
Figure 3.10 Comparison of LCC estimated with in-situ data.	62
Figure 4.1 RGB image of study site taken from RedEdge MX.....	70
Figure 4.2 (a & b) SRF of AVIRIS NG sensors and RedEdge MX.	74
Figure 4.3 Simulated half range hyperspectral image (3800-1000nm)	75
Figure 4.4 (a & b) LAI and LCC maps for the study site (left and right, respectively) ..	77
Figure 4.5 Comparison of estimated LAI and LCC w.r.t. observed values.....	78
Figure 5.1 AVIRIS-NG coverage with a zoomed image of the campaign site.	85
Figure 5.2 Flowchart of the methodology for LCC retrieval.....	86
Figure 5.3 WA of a vegetation spectra using bior3.7 at level 3.	92
Figure 5.4 WA of a vegetation spectra using rbio3.7 at level 3.....	92
Figure 5.5 WA of a vegetation spectra using db7 at level 3.....	93
Figure 5.6 (a-d). Variable importance from different FS algorithms.	94
Figure 5.7 Comparison between raw spectra and denoised spectra using bior3.7.	95
Figure 5.8 Taylor plot comparing models.	99
Figure 5.9 Chlorophyll map for the entire AVIRIS-NG imagery.....	100
Figure 5.10 Comparison of estimated and measured LCC.....	101
Figure 6.1 (a) Maize, (b) Mustard, and (c) Lentils crops.....	106
Figure 6.2 Flowchart of the methodology.	106

Figure 6.3 Schematic of the crop beds, Maize (MZ), Lentils (LT), and Mustard (MST) under different treatments.....	107
Figure 6.4 Temporal variation of in-situ LCC for various crop beds.	117
Figure 6.5 Temporal variation of in-situ LAI for various crop beds.	118
Figure 6.6 VIP of canopy scale hyperspectral VIs related to LAI and their R^2 variation utilizing PLSR for Lentils, Maize, and Mustard crop.	120
Figure 6.7 VIP of canopy/leaf scale hyperspectral VIs related to LCC and their R^2 variation utilizing PLSR for Lentils CB-1, CB-2, CB-3, and CB-4.....	121
Figure 6.8 VIP of canopy/leaf scale hyperspectral VIs related to LCC and their R^2 variation utilizing PLSR for Maize CB-1, CB-2, CB-3, and CB-4.....	122
Figure 6.9 VIP of canopy/leaf scale hyperspectral VIs related to LCC and their R^2 variation utilizing PLSR for Mustard CB-1, CB-2, CB-3, and CB-4.....	123
Figure 6.10 RFR optimization by minimizing average squared error using forward tree selection technique for Lentil, Maize, and Mustards LAI retrieval.....	128
Figure 6.11 Performance of all enhanced learning algorithms for LAI retrieval using three optimum Vis for (a) Lentils, (b) Maize, and (c) Mustard crop.....	129
Figure 6.12 RFR optimization by minimizing average squared error using forward tree selection technique for Lentils CBs LCC retrieval.....	130
Figure 6.13 RFR optimization by minimizing average squared error using forward tree selection technique for Lentil, Maize, and Mustards LAI retrieval.....	131
Figure 6.14 RFR optimization by minimizing average squared error using forward tree selection technique for Mustard CBs LCC retrieval.	132
Figure 6.15 Performance of all enhanced learning algorithms for LCC retrieval using three optimum VIs for Lentils (a) CB-1; (b) CB-2; (c) CB-3; and (d) CB-4.	133

Figure 6.16 Performance of all enhanced learning algorithms for LCC retrieval using three optimum VIs for Maizes (a) CB-1; (b) CB-2; (c) CB-3; and (d) CB-4..... 134

Figure 6.17 Performance of all enhanced learning algorithms for LCC retrieval using three optimum Vis for Mustards (a) CB-1; (b) CB-2; (c) CB-3; and (d) CB-4..... 135

LIST OF TABLES

Table 1.1 Various known hyperspectral sensors along with their resolution details	13
Table 2.1 Bands specification of Sentinel-2.	30
Table 2.2 Bands specification of RedEdge MX.....	31
Table 3.1 Performance assessment of the classifier.....	57
Table 3.2 Producer and user accuracy of each class for the classified image.....	58
Table 4.1 Specifications of UAV and RedEdge MX.....	71
Table 5.1 RMSE values of each wavelet type for level 3.	91
Table 5.2 Correlation between each calculated VIs from all the methods w.r.t LCC values.	96
Table 5.3 LCC retrieval models.....	99
Table 6.1 Sowing dates and stages of crops.	107
Table 6.2 VIs at canopy related to LAI.....	110
Table 6.3 VIs at canopy /leaf scale related to chlorophyll content.	111
Table 6.4 Optimized SVR model parameters for Mustard's LCC estimation.....	136
Table 6.5 Optimized SVR model parameters for Maize's LCC estimation.	136
Table 6.6 Optimized SVR model parameters for Lentils's LCC estimation.	137
Table 6.7 Optimized SVR model parameters for Maize, Mustard and lentils LAI estimation.	137

LIST OF ABBREVIATIONS

A	Absorption
AGL	Above Ground Level
ALI	Advance Land Imager
AVIRIS	Airborne Visible InfraRed Imaging Spectrometer
AVIRIS-NG	Airborne Visible InfraRed Imaging Spectrometer - Next Generation
AUC	Area Under Curve
BHU	Banaras Hindu University
CARI	Chlorophyll Absorption Ratio Index
CASI	Compact Airborne Spectrographic Imager
CB	Crop Bed
CCI10	Chlorophyll Content Index 10
CS	Class Separability
CWC	Canopy Water Content
DN	Digital Number
DoY	Day of Years
DWT	Discrete Wavelet Transform
EMR	Electromagnetic Radiation
EnMAP	Environmental Mapping and Analysis Program
ESA	European Space Agency
EO-1	Earth Observation-1
ETM+	Enhanced Thematic Mapper Plus
FA	Fourier Analysis
FS	Feature Selection

FSM	Feature Selection Method
FOV	Field of View
FWHM	Full Width at Half Maximum
GI	Greenness Index
GLM	Generalized Linear Model
GPS	Global Positioning System
GSD	Ground Sampling Distance
HS	Hyperspectral
HSI	Hyperspectral Imaging
HSS	Hyperspectral sensor
HyFIS	Hybrid Neural Fuzzy Inference System
HySIS	Hyperspectral Imaging Satellite
ISRO	Indian Space Research Organisation
IFOV	Instantaneous Field of View
IR	Infrared
LAI	Leaf Area Index
LCC	Leaf Chlorophyll Content
LiDAR	Light Detection and Ranging
MAE	Mean Absolute Error
MCARI	Modified Chlorophyll Absorption Ratio Index
MODIS	Moderate Resolution Imaging Spectroradiometer
MS	Multispectral
MSI	Multispectral Imaging
MSR2	Modified Simple Ratio 2
MSS	Multispectral Sensor

NASA	National Aeronautics and Space Administration
NIR	Near Infrared
NDR	Normalized Difference Ratio
NDVI	Normalized Difference Vegetation Index
OA	Overall Accuracy
OSAVI	Optimised Soil Adjusted Vegetation Index
OOB	Out of Bag
PLS	Partial Least Square
PLSR	Partial Least Square Regression
Rf	Reflection
RADAR	Radio Detection and Ranging
RDVI	Renormalized Difference Vegetation Index
RFE	Recursive Feature Elimination
RFR	Random Forest Regression
RGB	Red Green Blue
RMSE	Root Mean Square Error
ROC	Receiver Operating Characteristic
RRF	Regularised Random Forest
RTM	Radiative Transfer Model
SAM	Spectral Angle Mapper
SFM	Structure From Motion
SIPI	Structure Insensitive Pigment Index
SNAP	Sentinel Application Platform
SNR	Signal-to-noise Ratio
SONAR	Sound Navigation and Ranging

SPAD	Soil Plant Analysis Development
SR	Simple Ratio
SRF	Spectral Response Function
SVM	Support Vector Machine
SVR	Support Vector Regression
SWIR	Short Wavelength Infrared
T	Transmission
TAS	Throttle Aerospace Systems
TCARI	Transformed Chlorophyll Absorption Reflectance Index
TVI	Transformed Vegetation Index
UAV	Unmanned Aerial Vehicle
UPDM	Universal Pattern Decomposition Method
UV	Ultraviolet
VNIR	Very Near Infrared
VI	Vegetation Index
VIP	Variable Importance in Projection
VIS	Variable Importance Score
VS	Vegetation-Soil
VSA	Vegetation-Soil-Asphalt
VSC	Vegetation-Soil-Concrete
VSCA	Vegetation-Soil-Concrete-Asphalt
WA	Wavelet Analysis

LIST OF SYMBOLS

A	Angle between vectors (reference and original spectra)
E	Insensitive loss
B	Bias
α_i	Lagrange multiplier
$\varphi(s_i)$	Different kernel function (linear, polynomial, radial)
C	Regularisation constant
σ	Bandwidth
λ	Wavelength
$\bar{\lambda}$	Centre wavelength
R_i	Reflectance in i^{th} band
C_{mx}	Decomposition Matrix for multispectral image for class x
C_h	Decomposition Matrix for hyperspectral image
P_{mx}	Standard Matrix for multispectral image for class x
P_h	Standard Matrix for hyperspectral image
P_m^T	Transposed Standard Matrix for multispectral image
$f_{obs} \ f_{est}$	Standard deviation of observed and estimated data
m	Meter
cm	Centimetre
mm	Millimetre
μm	Micrometre
nm	Nanometre
$^\circ$	Degree

'	Minute
"	Second
<i>km</i>	Kilometre
<i>ft</i>	Feet
<i>Kts</i>	Knots
<i>sq</i>	Square
<i>R</i>	Correlation coefficient
<i>R</i> ²	Coefficient of Determination
