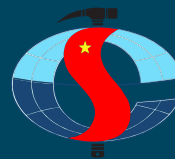




THE STATE COUNCIL FOR PROFESSORSHIP
INTERDISCIPLINARY PROFESSOR COUNCIL
OF THE EARTH AND MINING SCIENCES



IES - VAST

INSTITUTE OF EARTH SCIENCES
VIETNAM ACADEMY OF SCIENCE AND TECHNOLOGY

Advances in the Earth, Mining and Environmental Sciences for Safe and Sustainable Development

Volume 2

Earth, Mine, and Environmental Sciences for
Green, Sustainable, and Prosperous Development
in the Era of a Nation's Rise



PUBLISHING HOUSE FOR SCIENCE AND TECHNOLOGY

PUBLISHING HOUSE FOR SCIENCE AND TECHNOLOGY

A16, 18 Hoang Quoc Viet Road, Nghia Do, Ha Noi

Marketing & Distribution Department: **024.22149040**;

Editorial Department: **024.37917148**

Administration Support Department: **024.22149041**

Fax: **024.37910147**, Email: **nxb@vap.ac.vn**; Website: **www.vap.ac.vn**; **ebook.vap.ac.vn**

**ADVANCES IN THE EARTH, MINING
AND ENVIRONMENTAL SCIENCES FOR SAFE
AND SUSTAINABLE DEVELOPMENT**

Volume 2:

**Earth, Mine, and Environmental Sciences for Green, Sustainable,
and Prosperous Development in the Era of a Nation's Rise**

**Institute of Earth Sciences, Vietnam Academy of Science and Technology
The State Council for Professorship, Interdisciplinary Professor Council
of the Earth and Mining Sciences**

Responsible for Publishing

Director, Editor in Chief

PHAM THI HIEU

Editor:

Computing Technique:

Cover design:

Le Phi Loan, Nguyen Van Vinh

Nguyen Van Vinh

Nguyen Thanh Hung

Corporate publishing: Institute of Earth Sciences

Address: No. 68 Huynh Thuc Khang Street, Lang Ward, Hanoi

ISBN: 978-604-357-453-1

Registered number for Publication: 4637-2025/CXBIPH/01-64/KHTNVCN.

Decision number for Publication: 94/QĐ-KHTNCN was issued on December 02, 2025.

Copyright deposit were completed in 4th quarter, 2025.



THE STATE COUNCIL FOR PROFESSORSHIP
INTERDISCIPLINARY PROFESSOR COUNCIL
OF THE EARTH AND MINING SCIENCES



IES - VAST

INSTITUTE OF EARTH SCIENCES
VIETNAM ACADEMY OF SCIENCE AND TECHNOLOGY

ADVANCES IN THE EARTH, MINING AND ENVIRONMENTAL SCIENCES FOR SAFE AND SUSTAINABLE DEVELOPMENT

Volume 2:

**Earth, Mine, and Environmental Sciences for Green,
Sustainable, and Prosperous Development
in the Era of a Nation's Rise**



PUBLISHING HOUSE FOR SCIENCE AND TECHNOLOGY

SERIES EDITORS

Mai Trong Nhuan
VNU University of Science
Vietnam National University, Vietnam

Tran Thanh Hai
Hanoi University of Mining and Geology
Vietnam

ASSISTANT EDITORS-IN-CHIEF

Vu Thi Minh Nguyet
Institute of Earth Sciences, Vietnam
Academy of Science and Technology

Do Minh Duc
VNU University of Science
Vietnam National University, Vietnam

ADVISORY COMMITTEE

Tran Tuan Anh
Vietnam Academy of Science and
Technology, Vietnam

Tran Hong Thai
Vietnam Academy of Science and
Technology, Vietnam

Hoang Ngoc Ha
Hanoi University of Mining and Geology,
Vietnam

Nguyen Cao Huan
Association of Geography Vietnam

Nguyen Manh Khai
VNU University of Science
Vietnam National University, Vietnam

Nguyen Tai Tue
VNU University of Science
Vietnam National University, Vietnam

Nguyen Tien Giang
VNU University of Science
Vietnam National University, Vietnam

Pham Hoang Hai
Institute of Environment and Sustainable
Development, Vietnam

Phan Van Tan
VNU University of Science
Vietnam National University, Vietnam

Rajinder Bhasin
Norwegian Geotechnical Institute, Norway

Tran Duc Thanh
Institute of Science and Technology for
Energy and Environment, Vietnam Academy
of Science and Technology

Truong Quang Hai
Institute of Vietnamese Studies and
Development Science

Vo Trong Hung
Hanoi University of Mining and Geology
Hanoi, Vietnam

Nguyen Dang Hoi
Joint Vietnam-Russia Tropical Science and
Technology Research Center

EDITORS

Nguyen Xuan Anh
Institute of Earth Sciences, Vietnam
Academy of Science and Technology

Phan Thi Thanh Hang
Institute of Earth Sciences, Vietnam
Academy of Science and Technology

Lai Hop Phong
Institute of Earth Sciences, Vietnam
Academy of Science and Technology

Takeshi ITO
National Institute of Technology Akita & D-
Academy Tohoku, Japan

Pawel Kroh
University of the National Educational
Commission, Institute of Biology and Earth
Sciences, Poland

Łukasz Pawlik
University of Silesia, Institute of Earth
Sciences, Poland

Tran Anh Tuan
Institute of Earth Science, Vietnam
Academy of Science and Technology

Hendy Setiawan
Universitas Gadjah Mada
Indonesia

Nguyen Thanh Hoan
Institute of Earth Sciences, Vietnam
Academy of Science and Technology

SweePeng Koay
Universiti Sains Malaysia, Penang Malaysia

Dang Quang Khang
VNU University of Science Vietnam
National University, Vietnam

Wenbing Shi
Guizhou University
China

Foreword

The publication series “*Advances in the Earth, Mining and Environmental Sciences for Safe and Sustainable Development*” was conceived as a platform to promote scientific innovation, interdisciplinary collaboration, and knowledge exchange in support of safer, greener, and more sustainable development. *Volume 1: Advanced Technologies and Artificial Intelligence in the Earth and Environmental Sciences* established this foundation by highlighting the rapid emergence of digital technologies, artificial intelligence, and computational approaches that are reshaping the way we observe, analyze, and understand the Earth system.

Building upon this momentum, *Volume 2: Earth, Mine, and Environmental Sciences for Green, Sustainable, and Prosperous Development in the Era of a Nation’s Rise* extends the vision of the series into a broader scientific and societal context. While Volume 1 emphasized technological advancement, Volume 2 focuses on how these technologies - along with traditional and emerging scientific approaches - are being integrated to address real-world challenges related to environmental stewardship, sustainable resource management, climate resilience, and green growth.

This volume comprises 79 peer-reviewed articles contributed by authors from 10 countries and regions, reflecting an expanding network of international collaboration and the growing global commitment to advancing Earth, mining, and environmental sciences. The diversity of institutional backgrounds and research approaches represented here underscores the relevance of these topics to the shared pursuit of green, resilient, and inclusive development.

The volume is structured into three thematic parts, each representing a critical axis of sustainability-oriented research:

Part 1 – Earth, Mine and Environmental Sciences towards the Sustainability

This part brings together studies on geohazards, geotechnical engineering, mining science, hydrogeology, and environmental geology. The contributions highlight innovative approaches to landslide and geohazard assessment, advanced geotechnical modeling and underground construction behavior, sustainable mining practices, and environmental monitoring for land, water, and geological systems. These works reinforce the essential principles of ensuring safety, environmental protection, and sustainable resource utilization, forming the foundation for resilient national progress.

Part 2 – Digital Transformation for Prosperous Development

The second part illustrates how AI, machine learning, remote sensing, WebGIS, and geospatial intelligence are revolutionizing data acquisition, environmental monitoring, hazard prediction, and decision-making. The studies presented explore big data and deep learning techniques for landslide modeling, WebGIS-based early warning systems, UAV and hyperspectral imaging applications, groundwater forecasting, air quality assessment, and digital transformation-driven environmental governance. These contributions

demonstrate the transformative role of digital technologies in fostering prosperous, evidence-based, and future-ready development.

Part 3 – Green Development: Perspectives of the Earth, Mine and Environmental Sciences

The final part focuses on the scientific foundations and practical pathways toward green growth, environmental restoration, and sustainable livelihoods. The articles cover marine and coastal ecosystem management, microplastic pollution, wastewater treatment, green materials and circular economy solutions, biodiversity and climate-related studies, greenhouse gas monitoring, and sustainable tourism planning. Collectively, these contributions reflect a holistic, interdisciplinary approach to green development, integrating environmental science, socio-economic considerations, and policy-relevant insights.

As a whole, Volume 2 presents a comprehensive and timely collection of scientific advances that align with national and global priorities for sustainability. It showcases how Earth, mining, and environmental sciences are evolving to meet the challenges of a rapidly changing world, advancing the shared goal of a safer, greener, and more prosperous future.

We extend our sincere appreciation to all authors, reviewers, editors, and supporting institutions for their dedication and contributions. Their collective efforts have made this volume a meaningful addition to the scientific literature and a valuable reference for researchers, practitioners, policymakers, and students.

Editorial Board

TABLE OF CONTENT

Foreword

v

PART 1: EARTH, MINE AND ENVIRONMENTAL SCIENCES TOWARDS THE SUSTAINABILITY

1	GEOTECHNICAL APPROACHES FOR GEOHAZARDS DUE TO CLAY SWELLING BEHAVIOR	3
	Takeshil Ito and Saiichi Sakajo	
2	OPTIMIZING LANDSLIDE SUSCEPTIBILITY MAPPING: INVESTIGATING SAMPLE RATIOS AND VALIDATION METHODS USING RANDOM FOREST IN THE NAM MA WATERSHED, NORTHERN VIETNAM	13
	Van-Trung Chu, Shou-Hao Chiang, and Tang-Huang Lin	
3	PRELIMINARY ANALYSIS OF LANDSLIDE-GENERATED SEISMIC SIGNALS: POTENTIAL FOR REAL-TIME DETECTION AND EARLY WARNING IN VIETNAM	22
	Pham Van Tien, Ha Thi Giang, Nguyen Van Duong, Pham The Truyen, Vu Cao Minh, Dao Minh Duc, Lukasz Pawlik, Pawel Kroh, Bui Phuong Thao	
4	ASSESSING RAINFALL INDUCE LANDSLIDE THRESHOLD IN VAN CHAN – GIA HOI AREA, LAO CAI PROVINCE	30
	Duong Thi Toan	
5	EXPERIMENTAL STUDY ON PHYSICAL SIMULATION OF MINING SLOPE COLLAPSE UNDER THE EFFECT OF RAINFALL	39
	Wenbing Shi, Fengliang, Tongwei Tao, Xingyuan Jiang, Shaozheng Xiong	
6	LANDSLIDE SUSCEPTIBILITY MAPPING ALONG HIGHWAY 40B, VIETNAM, USING LOGISTIC REGRESSION	51
	Giang Nguyen Khac Hoang	
7	MORPHOLOGICAL FACTORS CONTROLLING LANDSLIDE FORMATION IN NORTHERN VIETNAM – REMARKS AFTER THREE YEARS OF OBSERVATIONS	59
	Pawel Kroh, Łukasz Pawlik, Pham Van Tien, Le Hong Luong	
8	STUDY OF REFORESTATION FOR REDUCING SLOPE FAILURE AND GLOBAL WARMING	66
	SweePeng Koay, Kazuho Ito, Satoshi Murakami, Zaharin Yusoff	
9	IMPROVING THE PROCESS OF MINING THE STEEP COAL SEAM. CASE STUDY OF THE SEAM 6(7) IN NAM KHE TAM MINE, QUANG NINH, VIETNAM	74
	Phi Hung Nguyen, Hoang Hiep Do, Manh Tung Bui	
10	INVESTIGATION OF THE INFLUENCE OF THE SOIL'S ELASTIC MODULUS SURROUNDING THE SQUARE TUNNEL ON THE INTERNAL FORCE VALUES IN THE TUNNEL LINING	89
	Manh Tung Bui, Anh Son Do, Chi Thanh Nguyen	

11	IMPROVING POWER QUALITY IN UNDERGROUND MINES' GRID BY UTILIZING SVC SYSTEM	95
	Ho Viet Bun, Le Xuan Thanh	
12	SIMULATION OF CONVEYOR'S MOTOR FOR ANALYZING POWER CONSUMPTION IN VIETNAMESE UNDERGROUND MINES' GRID	104
	Nguyen Dinh Tien, Le Xuan Thanh	
13	RESEARCH OF THE RELATIONSHIP BETWEEN ROCK MASS ELASTIC MODULUS AND THE MAXIMUM SURFACE SUBSIDENCE FOR DEVELOPING A GEOMECHANICAL MODEL OF THE KHE CHAM COAL MINE	113
	Chung Pham Van, Nghia Nguyen Viet, Long Nguyen Quoc, Canh Le Van, Dinh Thanh Tuan	
14	CONSTRUCTION OF A GRAVITY MODEL FOR THE EAST SEA FOR APPLICATION IN WAVE ENERGY POTENTIAL ASSESSMENT	119
	Nguyen Van Sang, Nguyen Thanh Thuy	
15	APPLICATION OF HIGH-FREQUENCY RADAR SYSTEM IN MONITORING THE POTENTIAL OF MARINE ENERGY IN VIETNAM	127
	Kim Cuong Nguyen, Xuan Loc Nguyen, Ngoc Anh Tran, Ba Thuy Nguyen	
16	CHARACTERISTICS OF GRAVITY ANOMALIES IN THE CUU LONG BASIN, VIETNAM	133
	Tran Tuan Duong, Tran Tuan Dung, Nguyen Quang Minh, Tran Trong Lap, Nguyen Thi Nhan	
17	GEOCHEMICAL CHARACTERIZATION OF LITHIUM MINERALIZATION IN THE LA VI AREA (CENTRAL VIETNAM): IMPLICATIONS FOR DEPOSIT-TYPE CLASSIFICATION AND RESOURCE – ENVIRONMENTAL GOVERNANCE	139
	Nguyen Van Niem, Do Duc Nguyen, Pham Nguyen Ha Vu, Nguyen Minh Trung, Bui Huu Viet	
18	GEOCHEMICAL CHARACTERISTICS AND ASSESSMENT OF HEAVY METAL CONTAMINATION IN GROUNDWATER: A CASE STUDY FROM THE MOUNTAINOUS REGION OF HA GIANG, NORTHERN VIETNAM	158
	Do Thi Thu, Pham Thi Dung, Tran Tuan Anh, Pham Thanh Dang, Nguyen Thi Lien, Nguyen Xuan Qua, Nguyen Thi Thu, Le Thi Phuong Dung, Doan Thi Thu Tra, Vu Dinh Hai, Bui Thi Sinh Vuong, Nguyen Trong Tai	
19	ENVIRONMENTAL PROTECTION AND LANDSCAPE RESTORATION SOLUTIONS IN MINERAL EXPLOITATION AT LOC AN MINE CLUSTER, PHUOC HAI COMMUNE, HO CHI MINH CITY	171
	Au Nguyen Hai, Thi Tuyet Nhi Pham, Hong Minh Vy Tat, Khanh Linh Luu	
20	URBAN EXPANSION MONITORING USING SENTINEL-1 AND SENTINEL-2 DATA FUSION ON GOOGLE EARTH ENGINE	180
	Hung Nguyen Manh, Tuan Vu Anh, Toan Dao Duy, Son Le Mai, Giang Nguyen Cong, Hang Le Thi Thu	

21	APPLICATION OF LSTM-ARIMA MODEL IN AIR QUALITY FORECASTING IN BARRIA – VUNG TAU PROVINCE	190
	Ho Minh Dung, Ton Minh Hien	
22	SPATIAL CONVERGENCE AND HOTSPOT CLUSTERING OF PROVINCIAL HUMAN DEVELOPMENT INDEX IN VIET NAM	201
	Truong Van Canh	
23	OPERATIONALIZING SF-MST AND GSTC INDICATORS FOR SUSTAINABLE TOURISM ASSESSMENT: THE CASE OF CON DAO, VIETNAM	210
	Tran Thi Tuyen	
24	METHODS FOR ASSESSING ENVIRONMENTAL CARRYING CAPACITY FOR SUSTAINABLE TOURISM DEVELOPMENT: A CASE STUDY OF SA PA NATIONAL TOURIST AREA	220
	Quyen Ngo Thi, Truc Nguyen Ngoc, Huong Nguyen Thi Quynh	
25	INTRODUCTION OF NOVEL TECHNOLOGIES AND MODELS FOR ON-SITE CONVERSION OF COAL BOTTOM ASH AND COAL FLY ASH INTO HIGH-VALUE MATERIALS	230
	Nguyen Ngoc Truc, Do Xuan Duc, Ngo Thi Quyen, Dinh The Hien	
26	INFLUENCE OF TWIN STACKED TUNNELS EXCAVATION ON PILE BEHAVIOR – A CASE STUDY IN HO CHI MINH CITY	240
	Tien Nguyen Tai, Vi Pham Van, Chuong Phan Hoang	
27	ACCELERATING VIETNAM'S TRANSITION FROM COAL-FIRED POWER TO RENEWABLE ENERGY: CHALLENGES AND STRATEGIC SOLUTIONS	251
	Vu Thi Phuong Thao, Bui Manh Tung, Nguyen Duc Toan	

PART 2: DIGITAL TRANSFORMATION FOR PROSPEROUS DEVELOPMENT

28	BIG DATA, MACHINE AND DEEP LEARNING TECHNIQUES FOR LANDSLIDE MODELING, PREDICTION, AND DETECTION	259
	Łukasz Pawlik, Hieu Trung Tran, Pham Van Tien, Paweł Kroh	
29	DEVELOPMENT AND APPLICATION OF A WEBGIS-BASED EARLY WARNING SYSTEM FOR LANDSLIDES	264
	Duong Thi Toan, Do Minh Duc	
30	INSTALLATION OF COST-EFFECTIVE LANDSLIDE EARLY WARNING SYSTEMS IN SOUTH AND SOUTH-EAST ASIAN COUNTRIES	279
	Rajinder Bhasin, Lloyd Tunbridge, Do Minh Duc, Khang Dang	
31	DEEP LEARNING-ASSISTED DETECTION OF COASTLINE SHIFTS AT CUA DAI, VIETNAM	285
	Kinh Bac Dang, Tuan Linh Giang	

32	WARNING SYSTEM FOR LAND SUBSIDENCE RISK DUE TO DROUGHT AND GROUNDWATER EXTRACTION: A STEP TOWARD SUSTAINABLE DEVELOPMENT	293
	Doan Quang Tri, Pham Tien Duc	
33	FROM PERCEPTION TO IDENTIFICATION AND ACTION: DESIGNING DIGITAL CO-CREATION PLATFORMS TO PROMOTE WILLINGNESS TO PAY FOR DROUGHT RISK MANAGEMENT - A REGIONAL CASE STUDY FROM EAST ASIA	302
	Wen Chin, Hsu, Chi-Wei, Peng	
34	SMART HEALTH MONITORING AND INFORMATION MANAGEMENT FRAMEWORK FOR DROUGHT-AFFECTED COMMUNITIES: A DIGITAL TRANSFORMATION APPROACH TO CLIMATE RESILIENCE	310
	Hsiao-Ting Tseng, Chien-wen Shen	
35	OPTIMIZING UAV-BASED HYPERSPECTRAL VEGETATION INDICES FOR ESTIMATING LEAF CHLOROPHYLL CONTENT IN RICE	321
	Lan Thi Pham, Phu Vinh Nguyen, Canh Van Le, Son Si Tong, Trang Thi Thu Nguyen	
36	FOREST CANOPY HEIGHT MAP IN CUC PHUONG NATIONAL PARK USING FIELD DATA AND AI-EXTRACTED FEATURES ALPHAEARTH FOUNDATIONS (AEF)	334
	Duc Anh Ngo, Anh Tuan Vu, Viet Luong Nguyen, Tien Cong Nguyen, Nhat Kieu Thi Truong, Thanh Binh Nguyen	
37	UAV HYPERSPECTRAL IMAGING AND MACHINE LEARNING FOR FRESH TEA YIELD ESTIMATION	345
	Duc-Duy Nguyen, Si-Son Tong, Hoang-Long Nguyen	
38	AI ₄ BIOCHAR: INTEGRATING AI-DRIVEN FIELD BOUNDARY RECOGNITION FOR SUSTAINABLE BIOCHAR DEVELOPMENT IN VIET NAM	358
	Alessandro Flammini, Mehmet Furkan Celik, Claudia Paris, Francesco Nicola Tubiello	
39	FORECASTING GROUNDWATER LEVEL DECLINE AND SALTWATER INTRUSION IN THE COASTAL AQUIFERS OF THE RED RIVER DELTA BY 2030 AND 2040	363
	Trung Dang Tran, Thu Trinh Hoai, Hung Nguyen Kim, Huong Tran Thi Thuy, Anh Bui Thi Bao, Hang Pham Thi Thu, Tung Nguyen Xuan, Hung Pham Duc, Ngan Phan Kieu	
40	GRAVITY ANOMALY MODELING OVER THE GULF OF THAILAND FROM AIRBORNE GRAVITY DATA	377
	Tham Bui Thi Hong, Thanh Le Duy, Hoai Do Thi, Thu Trinh Thi Hoai	
41	UTILIZING REMOTE SENSING AND STATISTICAL METHODS TO ASSESS THE IMPACT OF LAND USE ON SOIL ORGANIC CARBON	385
	Trong Dieu Hien Le, Pham Phuong Thanh Bui	

42	INTEGRATING GEOSPATIAL DATA FOR RUSLE SOIL EROSION MODELING IN GOOGLE EARTH ENGINE: A CASE STUDY OF THE DAK NONG PLATEAU, VIETNAM	394
	Ngoc Hoang Thi Huyen, Son Nguyen Thai, Ha Nguyen Manh, Dung Bui Quang, Linh Giang Tuan	
43	UNDERSTANDING VEGETATION RECOVERY AFTER DISTURBANCE BY NATURAL HAZARDS USING GEOSPATIAL TECHNOLOGIES	408
	Takashi Oguchi	
44	7-SEAS URBAN-AQ: A REGIONAL INITIATIVE FOR UNDERSTANDING URBAN AIR QUALITY IN SOUTHEAST ASIA	416
	Nguyen Xuan Anh, Pham Xuan Thanh, Nguyen Van Hiep, Nguyen Nhu Vinh, Bui Ngoc Minh, Pham Le Khuong, Do Ngoc Thuy, Markova I. S.	
45	RANDOM FOREST-BASED PM _{2.5} ESTIMATION USING MULTISOURCE REMOTE SENSING DATA: A CASE STUDY OF HO CHI MINH CITY	426
	Dai Long Nguyen, Thu Ha Hoang Thi, Kim Cuc Luong Thi, Van Manh Nguyen, Ngoc Bich Uyen Vo, Thi Hai Yen Ngo	
46	SEGMENTING TRAFFIC ACCIDENT RISK USING REMOTE SENSING AND GIS DATA: A COMPARATIVE ANALYSIS OF RANDOM FOREST AND WEIGHTED OVERLAY METHODS	438
	Ha Le Thi, Thao Vu Thi Phuong, Thao Do Thi Phuong	
47	APPLICATION OF MACHINE LEARNING AND WEBGIS FOR LAND-USE PLANNING INFORMATION UTILIZATION TO SUPPORT DIGITAL TRANSFORMATION OF LAND ADMINISTRATION	447
	Nguyen Xuan Linh, Tran Quoc Binh, Pham Le Tuan, Bui Ngoc Tu	
48	THE NORMAL GEOMAGNETIC FIELD MODEL OVER VIETNAM AND ADJACENT AREAS FROM SWARMSATELLITE	456
	Thanh Le Truong, Mai Nguyen Thi, Minh Le Huy, Dung Nguyen Thanh, Thanh Nguyen Ha, Vinh Nguyen Ba, Nam Vu Dao, Hien Phi Thi Thu, Hai Phan Thanh	
49	ANALYSIS OF DEFORMATION DISPLACEMENT USING GNSS TECHNOLOGY IN THE LOCAL TOPOCENTRIC COORDINATE SYSTEM	467
	Hoang Ngoc Ha, Luu Anh Tuan, Le Ngoc Giang, Ngo Thi Men Thuong	
50	DATA QUALITY ASSESSMENT AND STATION CLASSIFICATION OF THE CORS STATIONS – CASE STUDY OF CORS STATION IN NGHE AN PROVINCE, VIETNAM	473
	Trong Tran Dinh, Huy Nguyen Dinh, Hue Tran Thi	
51	DESIGNING FOR VALUE: LINKING TRANSPARENCY AND INCENTIVES TO ECONOMIC, SOCIAL, AND ENVIRONMENTAL CO-CREATION	483
	Wen Chin Hsu, Chi-Wei Peng	

**PART 3: GREEN DEVELOPMENT: PERSPECTIVES OF
THE EARTH, MINE AND ENVIRONMENTAL SCIENCES**

52	ASSESSMENT OF CUMULATIVE IMPACTS ON COASTAL MARINE ECOSYSTEMS IN HA TINH PROVINCE Nguyen Tai Tue, Luu Viet Dung, Pham Lan Anh, Nguyen Doanh Khoa, Tran Dang Quy, Mai Trong Nhuan	493
53	AN INTEGRATED MULTI-SCALE FRAMEWORK FOR URBAN HEAT RISK MONITORING AND ADAPTATION: EVIDENCE FROM TAIWAN Hsiao-Ting Tseng, Meng-Hua Hsu, Yue-Lin CHEN	502
54	ADJUSTING OF THE BUFFER ZONE BOUNDARIES IN HA LONG BAY WORLD NATURAL HERITAGE: SCIENTIFIC AND PRACTICAL FOUNDATIONS FOR SUSTAINABLE MANAGEMENT ORIENTATION Luu The Anh, Bui Manh Tung, Ngo Thi Hai Yen, Duong Anh Quan, Bui Ngoc Quy	509
55	PRELIMINARY SURVEY OF MICROCLIMATE AND ENVIRONMENTAL CONDITIONS IN SHOW CAVES IN HOA BINH AND PHONG NHA – KE BANG AREAS Vu Thi Minh Nguyet, Nguyen Thuy Duong, Czuppon György, Stieber József , Van Phu Hung, Ha Tung Lam, Bui Van Quynh	522
56	ASSESSING AND MITIGATING URBAN HEAT RISK IN A RAPIDLY URBANIZING SUBTROPICAL CITY: A REVIEW AND APPLICATION FOR CASE STUDY OF TAOYUAN, TAIWAN Cheng-Ling Kuo, Wenqian Chang, Yuei-An Liou	535
57	SHRIMP FARMING WASTEWATER TREATMENT BY AQUATIC PLANTS Nguyen Minh Phuong, Nguyen Huu Hung	546
58	SUSTAINABLE RECOVERY OF STRUVITE FERTILIZER FROM SWINE WASTEWATER BY FLUIDIZED BED HOMOGENEOUS CRYSTALLIZATION Nguyen Gia Cuong, Le Van Giang, Nguyen Thi Thuy, Bui Ngoc Quy, Luu The Anh	554
59	RECOVERY OF ALUMINUM FROM WASTEWATER VIA FLUIDIZED BED HOMOGENEOUS CRYSTALLIZATION Le Van Giang, Nguyen Thi Thuy, Nguyen Thi Thu, Bui Ngoc Quy	562
60	UPCYCLING ELECTRONIC WASTE INTO CATALYTIC MATERIALS FOR SUSTAINABLE WATER TREATMENT VIA CATALYTIC WET PEROXIDE OXIDATION OF METHYLENE BLUE DYE Hai Nguyen Tran and Dong Thanh Nguyen	569
61	DISTRIBUTION CHARACTERISTICS OF TRACE ELEMENTS IN SOIL, BAT XAT AREA, LAO CAI PROVINCE Nguyen Thi Lien, Pham Thi Dung, Tran Tuan Anh, Pham Thanh Dang, Nguyen Xuan Qua, Doan Thi Thu Tra, Do Thi Thu, Cu Sy Thang, Nguyen Thi Thu, Le Thi Phuong Dung	582

62	SOIL GEOMOGRAPHIC CHARACTERISTICS IN THE MOUNTAINOUS REGION OF SA THAY	591
	Nguyen Van Dung	
63	EFFECT OF THE INITIAL CLAY-WATER CONTENT ON THE COMPRESSIVE STRENGTH OF SOIL-CEMENT-RICE STRAW ASH ADMIXTURE	597
	Nguyen Thanh Duong	
64	ASSESSMENT OF MARINE DEBRIS POLLUTION INDEX AT SOME BEACHES IN NGHE AN PROVINCE	604
	Dang Tran Quan, Duong Thi Lim, Nguyen Tran Dinh, Nguyen Thi Hue	
65	ASSESSMENT OF MICROPLASTIC POLLUTION IN COASTAL WATERS OF THE CAI LON – CAI BE ESTUARY, VIETNAM	616
	Nguyen Thi Thu Uyen, Pham Lan Anh, Tran Dang Quy, Nguyen Dinh Thai, Dang Bao Duong, Nguyen Hai Nam, Nguyen Doanh Khoa, Nguyen Thi Huyen Trang, Ha Ngoc Anh, Luu Viet Dung	
66	STATUS OF PLASTIC WASTE GENERATION IN THE CAI LON – CAI BE ESTUARY, AN GIANG PROVINCE, VIETNAM	624
	Pham Lan Anh, Nguyen Tai Tue, Luu Viet Dung, Tran Dang Quy, Mai Trong Nhuan	
67	EVALUATION OF CAFFEINE CONTENT IN OYSTER MUSHROOMS CULTIVATED ON SPENT COFFEE GROUNDS UNDER URBAN AGRICULTURE CONDITIONS	633
	Nguyen Thi Thanh Thao, Tran Thi An	
68	SELECTION OF PHOSPHATE-SOLUBILIZING BACTERIA AND EVALUATION OF THEIR ABILITY TO RESIST PLANT PATHOGENIC FUNGI	642
	Mai Van Dinh, Manh Ha Nguyen	
69	ASSESSING THE INFLUENCE OF GEOGRAPHICAL FACTORS ON THE DISTRIBUTION OF THE GENUS PHALLUS IN THE SREPOK RIVER BASIN, VIETNAM: IMPLICATIONS FOR CONSERVATION AND SUSTAINABLE DEVELOPMENT OF VALUABLE FUNGAL RESOURCES	650
	Nguyen Thi Bich, Nguyen Thanh Long, Phan Thi Thanh Hang, Nguyen Vu Viet, Nguyen Thi Thuy, Nguyen Ngoc Thang, Ngo Thanh Nga	
70	ASSESSMENT OF RAIN CHANGES IN NINH BINH PROVINCE IN THE PERIOD 2000 – 2024	663
	Trinh Nguyen Dieu, Lan Vu Thi Thu, Son Hoang Thanh, Tuan Bui Anh	
71	ASSESSMENT OF PRECIPITATION VARIATION TRENDS IN NGHE AN PROVINCE UNDER THE CONTEXT OF CLIMATE CHANGE	671
	Le Thi Nguyet	
72	MONITORING THE GREEN HOUSE GASES CONCENTRATION IN BINH DUONG PROVINCE USING SENTINEL-5P REMOTE SENSED DATA AND GIS TECHNOLOGY	678
	Le Thanh Khong, Tran Thi An	

73	UNDERSTANDING GEN Z'S ATTITUDES AND BEHAVIORAL INTENTIONS TOWARDS GREEN DESTINATIONS: IMPLICATIONS FOR SUSTAINABLE TOURISM DEVELOPMENT IN VIETNAM	688
	Phan Trinh Thi, Nga Nguyen Thi Phuong	
74	ASSESSING FISH FARMERS' PERCEPTIONS OF ENVIRONMENTAL DRIVERS SHAPING CULTURED FISH COMMUNITIES IN CHAU DOC, VIETNAM	700
	Noor Syafiq Bin Abdul Rashid, Dung Duc Tran, Thien Duc Nguyen, Edward Park	
75	EVALUATION OF THE INFLUENCE OF CRACK GEOMETRY IN HIGH-PERFORMANCE CONCRETE MEMBERS USING NON-DESTRUCTIVE TESTING FOR STRUCTURAL SAFETY MANAGEMENT	709
	Nhan Pham Thi, Phi Dang Van	
76	ASSESSMENT OF INTERFACIAL BONDING OF RECYCLED POLYMER FIBERS FROM WASTE FISHING NETS IN CONCRETE	718
	Dang Van Phi	
77	PROPOSING A SOLUTION TO BUILD PEDESTRIAN TUNNELS COMBINED WITH COMMERCIAL SPACES IN BIG CITIES IN VIET NAM	724
	Dang Van Kien, Trivié Jeremy, Daniel Dias, Do Ngoc Anh, Vo Trong Hung, Tran Tuan Diep, Nguyen Khoa Linh	
78	RESEARCH ON THE EFFECT OF THE THERMODYNAMICS IN THE LPG STORAGE CAVERN OF CAI MEP	734
	Vu Tien Dung, Dang Van Kien, Nicolas Gitzinger, Ngo Minh Hoang, Le Sy Ha	
79	ANTI-SALINITY SOLUTIONS FOR CIVIL STRUCTURES: A BRIEF REVIEW	743
	Trong Van Nguyen, Ngoc Truc Nguyen, Thao Ly Nguyen	

Optimizing UAV-based hyperspectral vegetation indices for estimating leaf chlorophyll content in rice

Lan Thi Pham^{1,*}, Phu Vinh Nguyen², Canh Van Le¹, Son Si Tong³,
Trang Thi Thu Nguyen⁴

¹Hanoi University of Mining and Geology, Hanoi, Vietnam

²Lam Dong Forest Protection and Development Fund (Lam Dong FPDF), Vietnam

³University of Science and Technology of Hanoi, Hanoi, Vietnam

⁴Public administrative service center of Tan Dong Hiep ward, Ho Chi Minh, Vietnam

*Email: vinhphuqbrv@gmail.com

Abstract: Accurately determining chlorophyll content in plants is crucial for assessing their health and overall vitality, as chlorophyll plays a key role in photosynthesis and growth. In recent years, remote sensing techniques have emerged as a valuable tool for non-destructive monitoring of chlorophyll levels, enabling large scale assessment of crop health. This study investigates the most effective hyperspectral indices for monitoring leaf chlorophyll status in rice, with the goal of improving the accuracy of chlorophyll content estimation through remote sensing techniques. The research evaluates several vegetation indices, with a particular focus on the Normalized Difference Vegetation Index (NDVI) derived from selected spectral bands. Using field data and high-resolution hyperspectral imagery, the study identifies optimal spectral bands for estimating chlorophyll content, highlighting significant correlation between reflectance in the red (R) and near-infrared (NIR) bands. The optimized NDVI indices (NDVI₁, NDVI₂, and NDVI₃) were compared, revealing that NDVI₃ demonstrates the strongest positive relationship with chlorophyll content. These findings emphasize the importance of selecting appropriate spectral bands for chlorophyll estimation, offering insights for precision agriculture practices aimed at improving rice crop management. A multiple linear regression was employed to estimate the LCC in rice leaves, with the model showing an accuracy of R^2 of 0.55 and RMSE of 1.55. By

advancing the application of hyperspectral imaging in agriculture, this study demonstrates its potential to improve crop health monitoring and optimize rice cultivation practices. Ultimately, the research underscores the role of remote sensing in promoting sustainable agricultural practices and enhancing yield management.

Keywords: Chlorophyll, rice, hyperspectral.

INTRODUCTION

Leaf chlorophyll content is a critical physiological trait in rice with broad implications for photosynthetic efficiency, stress responses, and yield potential. Chlorophyll is essential for light harvesting, and its higher concentration typically indicates enhanced photosynthetic efficiency and improved leaf nitrogen status (Jang et al., 2022; Jia et al., 2022). Under partial submergence, the decline in chlorophyll content indicates stress response and serves as an indicator of submergence tolerance in vegetative-stage rice (Nio et al., 2022). Therefore, the accurate, non-destructive estimation of chlorophyll content in rice leaves is essential for large-scale phenotyping and precision agriculture. Traditional chlorophyll measurement methods, which rely on manual sampling and laboratory analysis, which are time-consuming and inefficient. Most studies also use optical sensors restricted to the visible spectrum (Cao et al., 2020). Recent advancements have

demonstrated the use of SPAD values, alongside multispectral, and hyperspectral imaging combined with machine learning techniques for chlorophyll estimation at both leaf and canopy levels in rice (Cao et al., 2020; Thi & Van, 2025; Y. Wang et al., 2023).

Spectral reflectance in green, red, red-edge, and near-infrared bands, along with vegetation indices such as the Normalized Difference Vegetation Index (NDVI), Difference Vegetation Index (DVI), Ratio Vegetation Index (RVI), Green Normalized Difference Vegetation Index (GNDVI), MERIS Terrestrial Chlorophyll Index (MTCI), and Excess Green Index (ExG), have been used to develop leaf chlorophyll content (LCC) estimation models for wheat, maize, and barley. These models were constructed using regression methods, including Multiple Linear Regression (MLR), Partial Least Squares Regression (PLSR), Support Vector Regression (SVR), Random Forest Regression (RFR), and Backpropagation Neural Network (BP-NN) (Ban et al., 2022). However, to the best of our knowledge, there is a lack of studies addressing the estimation of leaf chlorophyll content (LCC) in rice (*Oryza sativa* L.) using hyperspectral UAV-based remote sensing in the Red River Delta region.

Hyperspectral data have been widely used to estimate chlorophyll content across various crops (Du & Luo, 2024; H. Liu et al., 2023). Hyperspectral data provide narrow-band information that targets chlorophyll absorption and red-edge dynamics, enabling VIs that correlate with foliar chlorophyll content and SPAD-equivalent measures in rice leaf. This spectral-biochemical linkage underpins reliable chlorophyll assessment in UAV campaigns, with demonstrated utility across growth stages (H. Liu et al., 2023; Pengphorm et al., 2024). In practice, VIs that emphasize chlorophyll-absorbing bands (around 670 nm) and red-edge/NIR bands are particularly effective for assessing rice chlorophyll content when collected from UAV platforms (Pengphorm et al., 2024). Indices like NDVI, DVI, RVI, and GNDVI have also been

modeled for leaf chlorophyll content in wheat, maize, and barley (Deng et al., 2018; J. Wang et al., 2021; Zhang et al., 2019). GNDVI-like approaches that emphasize the green channel can provide sensitivity to chlorophyll content across developmental stages and stress conditions in rice leaves (Pengphorm et al., 2024). Additionally, NDRE-based indices may offer higher sensitivity to chlorophyll variation under certain canopy conditions, sometimes outperforming NDVI in detecting vigor differences and chlorophyll content in rice fields, particularly when red-edge information is well captured by the UAV sensor (de Lima et al., 2021). While these studies demonstrated the effectiveness of VIs in estimating leaf chlorophyll content, the specific spectral bands of hyperspectral imagery used to derive these indices have not been thoroughly investigated.

Therefore, this study employs UAV-based hyperspectral data to identify the most effective vegetation indices (VIs) for estimating leaf chlorophyll content (LCC) in rice. The main objectives are as follows: (1) to determine the optimal hyperspectral bands for calculating VIs; (2) to select the most suitable VIs for LCC estimation in rice; and (3) to estimate LCC using multiple linear regression (MLR).

STUDY AREA AND DATA

Study area

The experimental area covers a total of 6500m², located in Ban Nguyen commune, Phu Tho province. This region is designated specifically for rice cultivation, characterized by flat terrain, which is ideal for applying systematic agricultural practices. Additionally, the area is conveniently positioned near irrigation canals, which ensures efficient water distribution for the crops. The experimental plots are structured in a square configuration, each measuring 10m x 10m, and are separated by embankments with a width of 1 meter, providing clear boundaries between the plots. TBR225 (T) and Japonica 02 (J) are popular rice varieties in this locality, are shown in Fig. 1. Within the total area, 27 plots are dedicated to the cultivation of the local rice variety TBR225

(T), a commonly grown variety in the region. These plots are sequentially labeled from T1 to T27, ensuring consistency in both the size and layout of the plots. Furthermore, the Japonica 02 rice variety (J), imported from Japan, is cultivated in 28 separate plots, labeled from J1 to J28. This setup allows for comparative analysis between the TBR225 and Japonica 02 varieties, focusing on their growth patterns and yield performance. Overall, the experimental area consists of 55 plots, providing a comprehensive framework for evaluating the growth dynamics and productivity of different rice cultivars under the local agricultural conditions

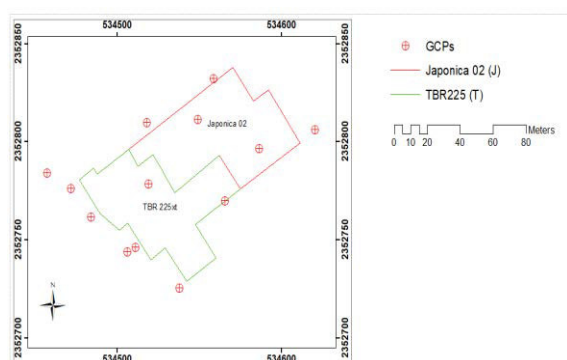


Figure 1. Study area

Hyperspectral UAV system

Hyperspectral UAV images were captured between 10:00 AM and 11:45 AM on May 6, 2022, under favorable weather conditions characterized by clear skies and bright sunlight. The UAV-based hyperspectral remote sensing system consists of three primary components: a UAV platform for payload transportation, a gimbal for camera stabilization, and a hyperspectral imaging subsystem. All components are carefully integrated and synchronized before image acquisition to ensure stable operation and data accuracy. The UAV used in this study is a DJI Matrice 600 Pro hexacopter with a takeoff weight of 15.5 kg, providing adequate lift capacity and flight stability for hyperspectral data collection. The gimbal system, DJI Ronin-MX, employs three-axis brushless motors and multiple sensors to maintain the planned

orientation of the camera, allowing both automatic and manual control during flight.

At the core of the system is the OCI-F hyperspectral camera. Operating in push-broom mode, the camera utilizes a CCD sensor with 800 linear detectors to capture 122 spectral bands covering the 400–960 nm range. It records data at 60 frames per second, enabling high-precision detection of spectral variations across surface features. The camera is connected to a Next Unit of Computing (NUC) that runs *SpecGrabber* software for calibration, parameter configuration, and real-time monitoring. A GNSS receiver linked to the NUC ensures accurate geolocation for each data frame, while a dedicated rechargeable battery ensures stable power supply during flight operations. This integration allows the hyperspectral camera to acquire high-quality, spatially and spectrally accurate imagery suitable for advanced remote sensing analysis.

During hyperspectral data preprocessing, several issues were encountered that affected image quality and accuracy, including geometric distortion, spectral noise, light bias, data corruption, and misregistration (Minh Khanh Luong et al., 2024). Geometric distortion primarily resulted from UAV motion and wind effects, which could not be fully compensated by the gimbal, leading to misaligned image frames and corrupted hyperspectral cubes. Image stitching between overlapping flight lines (50% sidelap) often produced visible seams and illumination inconsistencies, referred to as light bias, which required correction prior to analysis. Geometric correction was performed first using ground control markers and reference coordinates extracted from RGB orthoimages, with at least ten reference points applied to each hyperspectral cube. Spectral correction was subsequently conducted based on field spectrometer measurements to eliminate source bias. The correction followed a radiometric calibration approach where UAV hyperspectral signals were adjusted using the ratio of reference spectra from field spectrometer data to UAV-measured values at

corresponding field points. This process ensured that all hyperspectral cubes were geometrically aligned and spectrally balanced, providing accurate reflectance data for subsequent analysis.

METHODOLOGY

The workflow of this study is illustrated in Fig. 2. The overall procedure integrates hyperspectral data acquired from an unmanned aerial vehicle (UAV) with field measurements to estimate leaf chlorophyll content (LCC). Initially, hyperspectral images were collected using a UAV over the experimental area. The raw data were subjected to geometric and radiometric correction to minimize the effects of illumination variability and viewing geometry. Subsequently, several vegetation indices (VIs) sensitive to chlorophyll absorption features were calculated from the

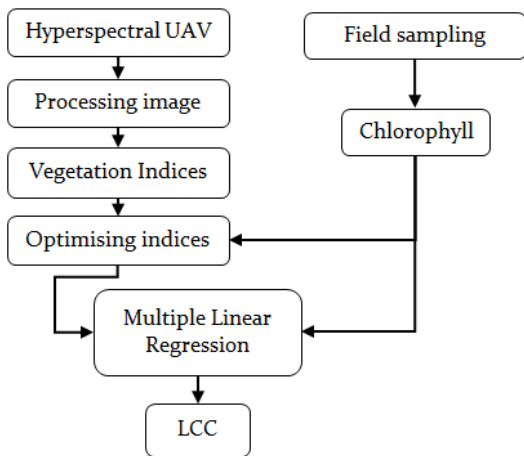


Figure 2. Overall methodological workflow

Vegetation Indices

The NDVI serves as an indirect indicator of vegetative greenness and, by extension, photosynthetic capacity and chlorophyll-related characteristics at both leaf and canopy levels (L. Wang et al., 2020). In this study, NDVI₁, NDVI₂, and NDVI₃ were used to analyze the relationship between LCC and these indices. NDVI₁ responds to the original NDVI developed by Rouse, et al (1974) (J.W. Rouse & R.H.Hass, 1974). NDVI₂ was calculated using the R band, which has the lowest spectral reflectance

corrected hyperspectral imagery. Second, field sampling was conducted concurrently with UAV data acquisition. Leaf samples were collected from representative plots, leaf chlorophyll content was determined in situ using a SPAD meter (Chlorophyll Meter LCPM-A1), and the chlorophyll values recorded were expressed as SPAD units. Third, an optimization process was applied to identify vegetation indices showing the strongest correlation with the SPAD-derived chlorophyll values. These optimal indices were then used as predictors in a multiple linear regression (MLR) model to estimate LCC from the hyperspectral data. Finally, the integration of UAV-based hyperspectral data and SPAD-derived chlorophyll measurements offers a robust framework for assessing plant physiological status and nutrient characteristics.

within the red region, and the NIR band, which has the highest reflectance within the near-infrared region. Finally, NDVI₃ was determined using the R and NIR bands that showed the highest correlation with SPAD values.

Additionally, other vegetation indices were calculated using the formulas presented in Table 1. The R_{NIR}, R_{RE}, R_R, R_B, and R_G bands were identified as those showing the highest correlation with SPAD values.

Table 1. Vegetation indices (Where R_{NIR}, R_{RE}, R_R, R_B, and R_G correspond to spectral reflectance values in the NIR, red-edge, red, blue, and green bands, respectively)

No.	Vegetation indices	Formulas	Reference
1	Difference Vegetation Index	$DVI = R_{NIR} - R_R$	(Jordan, 1969)
2	Enhanced Vegetation Index	$EVI = 2.5(R_{NIR} - R_R) / (\rho_{NIR} + 6R_R - 7.5R_B + 1)$	(Huete et al., 2002)
3	False Color Vegetation Index	$FCVI = 1.5(2R_{NIR} + R_B - 2R_G) / (2R_G + 2R_B - 2R_{NIR} + 127.5)$	(Jiang et al., 2019)

No.	Vegetation indices	Formulas	Reference
4	Green Normalized Difference Vegetation Index	$GNDVI = (R_{NIR} - R_G)/(R_{NIR} + R_G)$	(Buschman & Nagel, 1993)
5	Leaf Chlorophyll Index	$LCI = (R_{NIR}/R_{RE}) - 1$	(A. A. Gitelson et al., 2003)
6	Modified Chlorophyll Absorption in Reflectance Index	$MCARI = R_{RE} - R_R - 0.2(R_{RE} - \rho_G)R_{RE}/R_R$	(Daughtry et al., 2000)
7	Modified Adjusted Vegetation Index	$MSAVI = 0.5(2R_{NIR} + 1 - \sqrt{(2R_{NIR} + 1)^3 - 8(R_{NIR} - R_R)})$	(Qi et al., 1994)
8	Modified Simple Ratio	$MSR = ((R_{NIR}/R_R) - 1)/((R_{NIR}/R_R) + 1)$	(Chen, 1996)
9	Normalized Difference Red Edge Index	$NDRE = (R_{NIR} - R_{RE})/(R_{NIR} + R_{RE})$	(Gamon & Surfus, 1999)
10	NIR Shoulder Region Index	$NSRI = R_{NIR}/R_{RE}$	(L.-y. Liu et al., 2014)
11	Optimized Adjusted Vegetation Index	$OSAVI = (R_{NIR} - R_R)/(R_{NIR} + R_R + 0.16)$	(Rondeau x et al., 1996)
12	Photochemical Reflectance Index	$PRI = (R_G - R_B)/(R_G + R_B)$	(Gamon et al., 1997)
13	Red Edge Chlorophyll Index	$RECI = (R_{NIR} - R_{RE})/R_{RE}$	(A. Gitelson & Merzlyak, 1994)
14	Ratio Vegetation Index	$RVI = R_{NIR}/R_R$	(Jordan, 1969)
15	Transformed Vegetation Index	$TVI = (R_G - R_R)/(R_G + R_R)$	(Broge & Leblanc, 2001)
16	Structure-Intensive Pigment Index	$SIPi = (R_{NIR} - R_B)/(R_{NIR} + R_B)$	(Peñuelas et al., 1994)

Select optimising indices

Section 3.1 indicates that a total of 19 vegetation indices were considered for use in LCC estimation. The Pearson correlation coefficient was used to assess the relationship between 16 leaf chlorophyll content (LCC) samples and the corresponding values of each VI. VIs with a correlation coefficient (r) below 0.5 were excluded from the LCC estimation model.

In addition, Variance Inflation Factor (VIF) was used to eliminate variables and prevent overfitting in the LCC estimation model. The multicollinearity index was calculated using the following formula 1:

$$VIF = \frac{1}{1-R^2} \quad (1)$$

where R^2 represents the coefficient of determination obtained from a separate regression analysis of each index against all other indices. Some studies indicate that VIF values above 10 often denote multicollinearity concerns that warrant attention (Agustín Estrada-Peña & Fuente, 2014; Salmerón Gómez et al., 2020), suggesting that such variables should be excluded from model development (Agustín Estrada-Peña & Fuente, 2014).

Chlorophyll Estimation model

Multiple Linear Regression (MLR) is a statistical technique used to model the relationship between one dependent variable and multiple independent variables. In this study, MLR was employed to estimate leaf chlorophyll content (LCC) based on selected vegetation indices (VIs).

The Multiple Linear Regression is a statistical technique used to model the relationship between one dependent variable and multiple independent variables. In this study, MLR was employed to estimate leaf chlorophyll content (LCC) based on selected vegetation indices (VIs).

$$Y = \sum_{i=1}^n W_i X_i \quad (2)$$

where: Y - Leaf chlorophyll concentration;

W_i - Weight of vegetation index i;

X_i - Value of vegetation index i;

n – Number of criteria (VIs).

The accuracy of the MLR model was assessed by comparing the estimated LCC values with the measured ones using a SPAD meter and used as ground truth for model validation, including the coefficient of determination (R^2), and the root mean square error (RMSE). These metrics are calculated as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (3)$$

$$RMSE = \frac{1}{n} \sum_{i=1}^n [y_i - \hat{y}_i] \quad (4)$$

where: y_i = measured LCC, using a SPAD meter;

$\hat{y}_i$ = estimated LCC;

$\bar{y}$ = mean of measured LCC;

n = number of samples.

A higher R^2 and lower RMSE values indicate better model performance and stronger predictive accuracy.

RESULTS

Indices selection

Optimized NDVI

NDVI is calculated by the difference between the reflectance in the near-infrared (NIR) and red (R) bands. Based on the analysis of the provided graph in Fig. 3, the selection of appropriate spectral bands for calculating the NDVI (Normalized Difference Vegetation Index) is crucial. NDVI was measured in R800 and R640, divided by their sum (J.W. Rouse & R.H.Hass, 1974). In this study, NDVI₁ was calculated using B87 (R800 = 801.868nm) and B51 (R640 = 639.115nm)

In Fig. 3, B59 exhibits the lowest DN value of 4.31, which corresponds to the central wavelength of 675.435nm, a region where vegetation strongly absorbs light for photosynthesis. Thus, B59 is selected as the representative R (Red) band. On the other hand, B117 shows the highest DN value of 138.48, which corresponds to the near-infrared (NIR) band (central wavelength of 936.148nm), a region where vegetation strongly reflects light, particularly from the leaves.

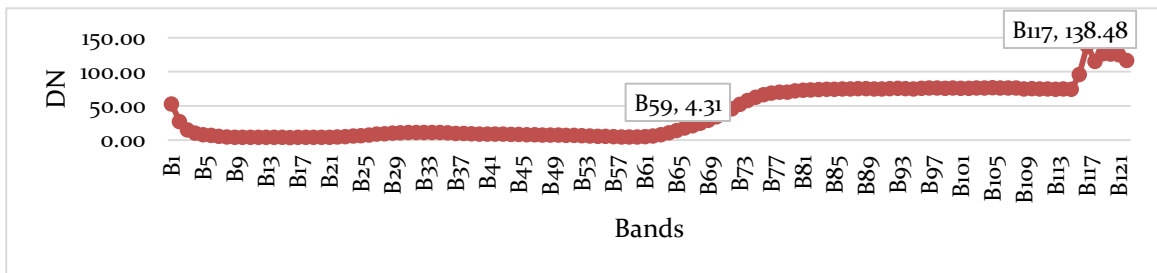


Figure 3. The average spectra of rice plant

As a result, NDVI₂ was calculated using the following equation 5:

$$NDVI_2 = \frac{B_{117} - B_{59}}{B_{117} + B_{59}} \quad (5)$$

Fig. 4 shows the correlation between different spectral bands and chlorophyll content. The red bands exhibit a negative correlation, with the band showing the highest correlation being B66 (707.143 nm), which has an r value of -0.47. In contrast, the near-infrared bands display a positive correlation,

with the strongest correlation observed for band B114 (922.775 nm), which has an r value of 0.39. Thus, by utilizing B114 (near-infrared) and B66 (red) bands, the NDVI can be computed to estimate chlorophyll content. The negative correlation observed in the red band (B66) suggests that chlorophyll content decreases as reflectance in this band increases, while the positive correlation in the near-infrared band (B114) indicates that chlorophyll content

increases with higher reflectance in this spectral region.

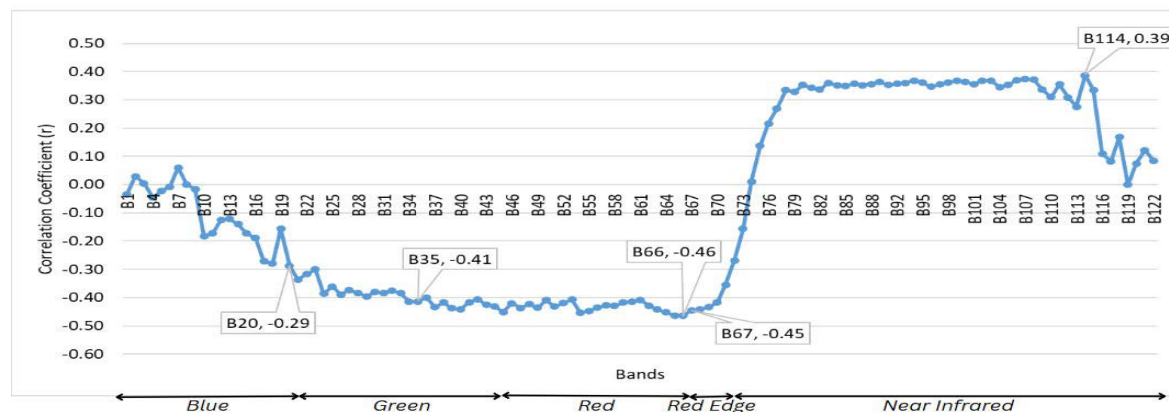


Figure 4. Correlation between SPAD value and R (a) and NIR (b)

As a result, NDVI₃ was calculated using the following equation 6.

$$NDVI_3 = \frac{B114 - B66}{B114 + B66} \quad (6)$$

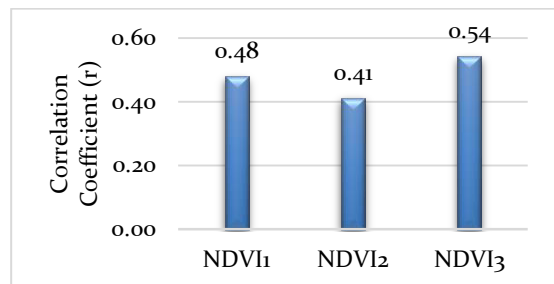


Figure 5. Correlation Coefficient between NDVIs and LCC

Fig. 5 shows the correlation coefficients (r) between three NDVI indices (NDVI₁, NDVI₂, and NDVI₃) and leaf chlorophyll content. NDVI₁ shows a moderate positive correlation with a coefficient of 0.48, suggesting a reasonably strong relationship between this index and chlorophyll content. NDVI₂ exhibits a slightly weaker correlation, with a coefficient of 0.41, indicating a less pronounced but still positive relationship. In contrast, NDVI₃ shows the highest correlation at 0.54, suggesting that this index has the strongest positive relationship with leaf chlorophyll content among the three. These findings highlight that while all three NDVI indices demonstrate a positive association with chlorophyll content, NDVI₃ is the most

effective at predicting or reflecting changes in chlorophyll levels.

Other Vegetation Indices

The absolute correlation coefficients, which show the closest relationship between LCC and bands of Blue, Green, Red, Red-edge and NIR are 0.29 (B20 - wavelength of 497.55 nm), 0.41 (B35 - wavelength of 566.21 nm), 0.46 (B66 - wavelength of 707.14 nm), 0.45 (B67 - wavelength of 711.67 nm), and 0.39 (B114 - wavelength of 922.78 nm) (Fig. 6). Therefore, B20, B35, B66, B67, and B114 were used to calculate other VIs in Table 1.

The correlation coefficients (R values) reveal both positive and negative relationships between the indices and LCC (Fig.6). It was found that several indices exhibit a moderate to strong positive correlation with LCC, with R values greater than 0.5. These indices include RVI (R = 0.56), RECI (R = 0.57), OSAVI (R = 0.54), NDRE (R = 0.55), MSR (R = 0.54), LCI (R = 0.57), GNDVI (R = 0.50), EVI (R = 0.56), DVI (R = 0.50), and NSRI (R = 0.57). These indices are considered to exhibit a significant positive relationship with LCC and can therefore be regarded as reliable tools for chlorophyll concentration assessment. On the other hand, certain indices display weaker or negative correlations with LCC. SIPI (R = 0.39) is associated with a moderate positive correlation, while TVI (R = 0.22) shows a relatively weak positive relationship.

Furthermore, PRI ($R = -0.23$), MSAVI ($R = -0.30$), and MCARI ($R = -0.29$) are found to have negative correlations with LCC, indicating an inverse relationship with chlorophyll concentration.

In conclusion, indices with correlation coefficients greater than 0.5, such as RECI, RVI, LCI, OSAVI, NDRE, MSR, DVI, NSRI, and EVI, are considered to be particularly effective in assessing LCC.

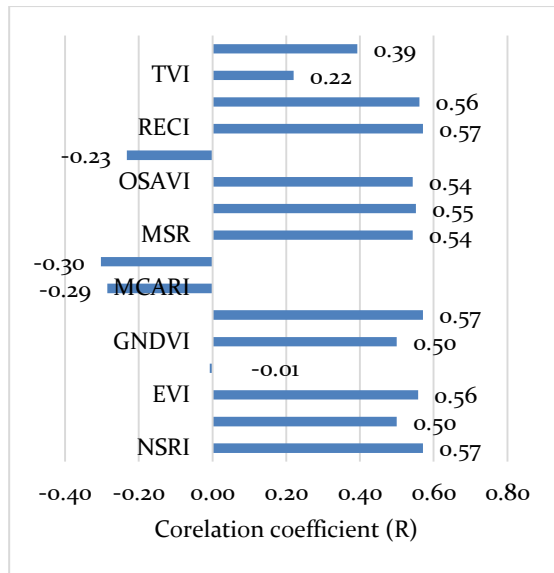


Figure 6. Correlation coefficient between other VIs and LCC

Leaf Chlorophyll Content Detection

The selected indices in Section 3.1 were applied to estimate LCC in rice. VIF was calculated to address the issue of multicollinearity. The Table 2 presents the VIFs of the indices.

Table 2. The Variance Inflation Factor (VIF) of VIs

Number	Indices	R ²	VIF
1	NDVI3	0.73	3.7037
2	NSRI	0.99	100
3	DVI	0.99	100
4	EVI	0.981	52.6316
5	GNDVI	0.84	6.25
6	LCI	0.99	100
7	MSR	0.99	100
8	NDRE	0.98	50

9	OSAVI	0.99	100
10	RECI	0.99	100
11	RVI	0.99	100

Among the indices assessed, NSRI, DVI, LCI, MSR, OSAVI, RECI, and RVI all displayed VIF values of 100, indicating significant multicollinearity and suggesting that their inclusion would likely lead to overfitting and instability in the model. Therefore, these indices were excluded from the final model to ensure robustness and accuracy in estimating LCC.

In contrast, indices with VIF values below 10, such as NDVI3 (VIF = 3.7037), and GNDVI (VIF = 6.25), exhibited lower levels of multicollinearity, making them more suitable for use in the model. Although NDRE had a VIF greater than 10, its specific sensitivity to chlorophyll content in rice justifies its potential inclusion. Despite its multicollinearity, NDRE was retained due to its significant contribution to LCC estimation, particularly when its unique features are deemed essential for the model's performance.

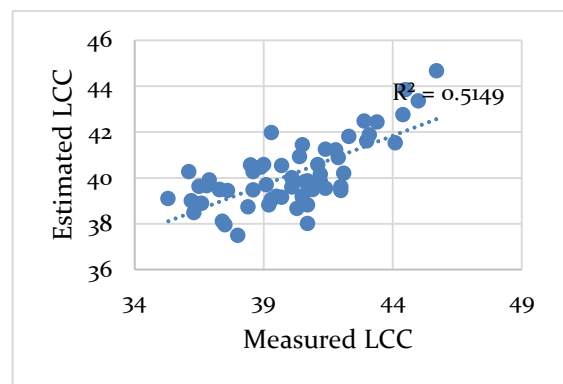


Figure 7. The scatter plot of measured LCC and estimated LCC

Thus, NDVI3, GNDVI, and NDRE were selected for LCC estimation model. The Table 3 shows the results of MLR for LCC estimation. Among the three vegetation indices included in the MLR model, only NDRE showed a significant positive relationship with LCC ($t = 4.57$, $p < 0.01$), indicating its strong predictive power. In contrast, NDVI3 and GNDVI were not significant ($p > 0.05$), suggesting limited

contribution to LCC estimation. The insignificant intercept ($p = 0.14$) implies that the baseline prediction is not statistically different from zero. Overall, NDRE proved to be the most effective variable for predicting leaf chlorophyll content in this study.

The final regression equation is expressed as:

$$LCC = 21.48 + 4.55(NDVI_3) + 0.65(GNDVI) + 27.34(NDRE) \quad (7)$$

The model achieved an R^2 of 0.55 (Fig.7), explaining about 55% of the variation in LCC, with an RMSE of 1.55, indicating a satisfactory prediction accuracy. Overall, NDRE was identified as the most influential variable for estimating leaf chlorophyll content in rice.

Table 3. the results of MLR in rice LCC estimation

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	21.48	14.59	1.47	0.14	-7.35	50.32	-7.35	50.32
NDVI3	4.55	17.54	0.26	0.80	-30.10	39.21	-30.10	39.21
GNDVI	0.65	9.70	0.07	0.95	-18.52	19.81	-18.52	19.81
NDRE	27.34	5.99	4.57	0.00	15.51	39.17	15.51	39.17

DISCUSSION

The results of this study demonstrate that hyperspectral vegetation indices, particularly those incorporating the red-edge and near-infrared (NIR) spectral regions, can effectively estimate leaf chlorophyll content (LCC) in rice. Among the 19 tested indices, NDRE exhibited the highest predictive power, followed by NDVI₃ and GNDVI. This finding aligns with previous studies indicating that indices exploiting the red-edge region are particularly sensitive to chlorophyll variation due to the sharp increase in reflectance between 680–740 nm (Anatoly Gitelson, 1994; Pengphorm et al., 2024). The strong relationship between NDRE and LCC suggests that NDRE provides a robust indicator of chlorophyll concentration, especially under varying canopy and illumination conditions.

The superior performance of NDRE can be attributed to its sensitivity to subtle changes in chlorophyll absorption that are less affected by background noise and soil reflectance compared to traditional NDVI-based approaches (de Lima et al., 2021). Although NDVI₃ was optimized for rice by selecting the most correlated red and NIR bands (B₆₆ and B₁₁₄), its correlation ($r = 0.54$) remained moderate. This result highlights that NDVI₃ remains a reliable indicator of vegetation vigor,

its sensitivity to high chlorophyll levels. GNDVI also demonstrated a positive but weaker correlation with LCC, consistent with previous findings that green-based indices capture chlorophyll variation more effectively during early growth stages but become less sensitive in mature rice canopies (Pengphorm et al., 2024).

Among the tested indices, NDRE outperformed NDVI and GNDVI, particularly in the rice canopy conditions of the study area. NDRE's superior performance can be attributed to its sensitivity to the red-edge region (680–740 nm), which is highly responsive to chlorophyll absorption, especially in crops like rice that undergo significant changes in canopy structure and chlorophyll content during growth stages. Unlike NDVI, which is limited by saturation effects at high chlorophyll concentrations, NDRE is more capable of detecting subtle variations in chlorophyll content, even in dense canopies with high chlorophyll levels.

Moreover, the specific optical properties of rice, including leaf structure and reflectance characteristics, favor the use of red-edge bands for chlorophyll estimation. In comparison, GNDVI, which emphasizes the green band, showed weaker performance because it is more sensitive during early growth stages and less effective under mature canopy conditions.

Therefore, NDRE provides a more reliable and consistent estimation of LCC, especially under the complex and variable conditions present in rice fields.

The use of multicollinearity screening (VIF) in model development proved essential for ensuring the robustness of the regression model. Many indices such as RECI, LCI, OSAVI, and RVI exhibited very high VIF values (>100), indicating redundancy among predictors. Excluding these indices improved the stability and interpretability of the model, confirming that NDRE alone could provide satisfactory predictive performance without introducing instability or overfitting.

The integration of UAV-based hyperspectral imaging with in-situ SPAD measurements in this study provides a practical workflow for precision agriculture, enabling timely detection of nutrient stress and guiding fertilization management.

Nevertheless, several limitations should be acknowledged. The moderate model accuracy ($R^2 = 0.55$) suggests that additional factors—such as leaf structure, canopy geometry, and varying illumination—may have influenced reflectance measurements. Furthermore, environmental conditions (e.g., soil moisture and sun angle) and differences between rice varieties (TBR225 vs. Japonica 02) might have introduced variability not fully captured by the current model. Future research should consider integrating machine learning algorithms (Random Forest, PLSR) or radiative transfer modeling to improve predictive accuracy and generalizability across growth stages and cultivars (Du & Luo, 2024; H. Liu et al., 2023). The regression model achieved a moderate $R^2 = 0.55$ explaining about 55% of the variation in leaf chlorophyll content (LCC). While this result provides a reasonably strong indication of the relationship between the selected vegetation indices and chlorophyll content, the predictive accuracy may not fully meet practical thresholds for field applications, where higher precision is typically required for actionable decisions, especially in large-scale agricultural settings.

In practical terms, an R^2 of 0.55 could be considered acceptable for early-stage crop monitoring and management, particularly in fields where timely but non-invasive data collection is critical. However, for more precise applications such as nutrient management or stress detection, the accuracy may need to be improved. To improve model performance, future work could incorporate additional predictors, such as spectral bands in the shortwave infrared (SWIR) and environmental variables (e.g., soil moisture, temperature). Moreover, applying nonlinear machine learning approaches, like Random Forest or Deep Learning, could better capture the complex relationships in the data. Addressing environmental variability, such as soil properties and sun angle, could further enhance model robustness. These improvements could lead to more precise and reliable field applications.

Overall, this study confirms that hyperspectral indices, particularly NDRE, hold strong potential for accurate and non-destructive estimation of chlorophyll content in rice. By selecting optimal spectral bands and reducing model redundancy, the approach enhances the precision of crop health monitoring. These findings contribute valuable insights toward advancing UAV-based hyperspectral applications in rice phenotyping and precision nutrient management.

CONCLUSION

This study demonstrated that UAV-based hyperspectral imaging is a reliable and efficient approach for estimating leaf chlorophyll content (LCC) in rice. Among 19 tested vegetation indices, those incorporating red-edge and near-infrared spectral information exhibited the strongest correlations with LCC. In particular, the Normalized Difference Red Edge Index (NDRE) proved to be the most effective predictor, yielding a coefficient of determination indicating satisfactory predictive accuracy.

The results confirm that the red-edge spectral region provides superior sensitivity to

chlorophyll variation compared with conventional NDVI-based indices, which are often limited by saturation effects at high chlorophyll concentrations. The optimized NDVI₃ also showed consistent but moderate performance, highlighting its potential use when hyperspectral red-edge data are unavailable.

By integrating hyperspectral data with ground-based SPAD measurements, the study establishes a robust framework for non-destructive chlorophyll monitoring, offering valuable support for precision fertilization and stress diagnosis in rice production. Nonetheless, environmental factors and varietal differences may affect spectral responses, and future work should explore advanced modeling approaches such as partial least squares regression (PLSR) or machine learning to enhance predictive robustness and generalization across growth stages.

Overall, this research advances the understanding of hyperspectral vegetation indices for chlorophyll estimation and reinforces the potential of UAV-based remote sensing as a practical tool for sustainable and data-driven rice crop management.

KNOWLEGEMENT

This work is supported by the Vietnam Academy of Science and Technology and represents the pre-feasibility study for the project “Application of UAV Imagery and Machine Learning for Estimating Fresh Tea Productivity” (project code VASTo8.03/25-26).

REFERENCES

- Agustín Estrada-Peña, & Fuente, A. E.-S. a. J. d. l.,2014. A global set of Fourier-transformed remotely sensed covariates for the description of abiotic niche in epidemiological studies of tick vector species. *Parasites & Vectors*, 7(1), 302. doi:https://doi.org/10.1186/1756-3305-7-302
- Anatoly Gitelson, a. M. N. M.,1994. Quantitative estimation of chlorophyll-a using reflectance spectra: Experiments with autumn chestnut and maple leaves. *Journal of Photochemistry and Photobiology B: Biology*, 22(3), 247-252.
- Ban, S., Liu, W., Tian, M., Wang, Q., Yuan, T., Chang, Q., & Li, L.,2022. Rice Leaf Chlorophyll Content Estimation Using UAV-Based Spectral Images in Different Regions. *Agronomy*, 12(11). doi:10.3390/agronomy12112832
- Broge, N. H., & Leblanc, E.,2001. Comparing prediction power and stability of broadband and hyperspectral vegetation indices for estimation of green leaf area index and canopy chlorophyll density. *Remote Sensing of Environment*, 76(2), 156-172. doi:https://doi.org/10.1016/S0034-4257(00)00197-8
- Buschmann, C., & Nagel, E.,1993. In vivo spectroscopy and internal optics of leaves as basis for remote sensing of vegetation. *International journal of remote sensing*, 14(4), 711-722. doi:10.1080/01431169308904370
- Cao, Y., Jiang, K., Wu, J., Yu, F., Du, W., & Xu, T.,2020. Inversion modeling of japonica rice canopy chlorophyll content with UAV hyperspectral remote sensing. *PLoS One*, 15(9), e0238530. doi:10.1371/journal.pone.0238530
- Chen, J. M.,1996. Evaluation of Vegetation Indices and a Modified Simple Ratio for Boreal Applications. *Canadian Journal of Remote Sensing*, 22(3), 229-242. doi:10.1080/07038992.1996.10855178
- Daughtry, C. S. T., Walthall, C. L., Kim, M. S., de Colstoun, E. B., & McMurtrey, J. E.,2000. Estimating Corn Leaf Chlorophyll Concentration from Leaf and Canopy Reflectance. *Remote Sensing of Environment*, 74(2), 229-239. doi:https://doi.org/10.1016/S0034-4257(00)00113-9
- de Lima, I. P., Jorge, R. G., & de Lima, J. L. M. P.,2021. Remote Sensing Monitoring of Rice Fields: Towards Assessing Water Saving Irrigation Management Practices. *Frontiers in Remote Sensing*, 2. doi:10.3389/frsen.2021.762093
- Deng, L., Mao, Z., Li, X., Hu, Z., Duan, F., & Yan, Y.,2018. UAV-based multispectral remote sensing for precision agriculture: A comparison between different cameras. *ISPRS Journal of Photogrammetry and Remote Sensing*, 146, 124-136. doi:10.1016/j.isprsjprs.2018.09.008
- Du, L., & Luo, S.,2024. Spectral-Frequency Conversion Derived from Hyperspectral Data Combined with Deep Learning for Estimating Chlorophyll Content in Rice. *Agriculture*, 14(7). doi:10.3390/agriculture14071186
- Gamon, J. A., Serrano, L., & Surfus, J. S.,1997. The photochemical reflectance index: an optical indicator of photosynthetic radiation use efficiency across

- species, functional types, and nutrient levels. *Oecologia*, 112(4), 492-501. doi:10.1007/s004420050337
- Gamon, J. A., & Surfus, J. S.,1999. Assessing leaf pigment content and activity with a reflectometer. *New Phytologist*, 143(1), 105-117. doi:https://doi.org/10.1046/j.1469-8137.1999.00424.x
- Gitelson, A., & Merzlyak, M. N.,1994. Quantitative estimation of chlorophyll-a using reflectance spectra: Experiments with autumn chestnut and maple leaves. *Journal of Photochemistry and Photobiology B: Biology*, 22(3), 247-252. doi:https://doi.org/10.1016/1011-1344(93)06963-4
- Gitelson, A. A., Gritz †, Y., & Merzlyak, M. N.,2003. Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves. *Journal of Plant Physiology*, 160(3), 271-282. doi:https://doi.org/10.1078/0176-1617-00887
- Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G.,2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, 83(1), 195-213. doi:https://doi.org/10.1016/S0034-4257(02)00096-2
- J.W. Rouse, J., & R.H.Hass, J. A. S. a. D. W. D.,1974. Monitoring vegetation systems in the Great Plains with ERTS. Vol. 351, *NASA Special Publication*, 309-317.
- Jang, Y. H., Park, J. R., Kim, E. G., & Kim, K. M.,2022. OsbHLHq11, the Basic Helix-Loop-Helix Transcription Factor, Involved in Regulation of Chlorophyll Content in Rice. *Biology (Basel)*, 11(7). doi:10.3390/biology11071000
- Jia, Y., Zhang, H., Zhang, X., & Su, Z.,2022. Quantitative Analysis and Hyperspectral Remote Sensing Inversion of Rice Canopy Spad in a Cold Region. *Engenharia Agrícola*, 42(4). doi:10.1590/1809-4430-eng.agric.v42n4e20220030/2022
- Jiang, J., Cai, W., Zheng, H., Cheng, T., Tian, Y., Zhu, Y., . . . Yao, X.,2019. Using Digital Cameras on an Unmanned Aerial Vehicle to Derive Optimum Color Vegetation Indices for Leaf Nitrogen Concentration Monitoring in Winter Wheat. *Remote Sensing*, 11(22), 2667.
- Jordan, C. F.,1969. Derivation of Leaf-Area Index from Quality of Light on the Forest Floor. *Ecology*, 50(4), 663-666. doi:https://doi.org/10.2307/1936256
- Liu, H., Lei, X., Liang, H., & Wang, X.,2023. Multi-Model Rice Canopy Chlorophyll Content Inversion Based on UAV Hyperspectral Images. *Sustainability*, 15(9). doi:10.3390/su15097038
- Liu, L.-y., Huang, W.-j., Pu, R.-L., & Wang, J.-h.,2014. Detection of internal leaf structure deterioration using a new spectral ratio index in the near-infrared shoulder region. *Journal of Integrative Agriculture*, 13(4), 760-769.
- Minh Khanh Luong, Tong Si Son¹, Huong Mai, Huong Thi Mai To, Giang Son Tran, Binh Pham-Duc, . . . Ai, T. T. H.,2024. UAV hyperspectral image acquisition and processing, an application for nutrient estimation of rice in Vietnam. *Vietnam Journal of Earth Sciences*, 46(4), 533-552.
- Nio, S. A., Ludong, D. P. M., & Siahaan, R.,2022. Short communication: Pattern of chlorophylls content declined during partial submergence for rice varieties cultivated in North Sulawesi at the vegetative stage. *Biodiversitas Journal of Biological Diversity*, 23(5). doi:10.13057/biodiv/d230524
- Pengphorm, P., Thongrom, S., Daengngam, C., Duangpan, S., Hussain, T., & Boonrat, P.,2024. Optimal-Band Analysis for Chlorophyll Quantification in Rice Leaves Using a Custom Hyperspectral Imaging System. *Plants (Basel)*, 13(2). doi:10.3390/plants13020259
- Peñuelas, J., Gamon, J. A., Fredeen, A. L., Merino, J., & Field, C. B.,1994. Reflectance indices associated with physiological changes in nitrogen- and water-limited sunflower leaves. *Remote Sensing of Environment*, 48(2), 135-146. doi:https://doi.org/10.1016/0034-4257(94)90136-8
- Qi, J., Chehbouni, A., Huete, A. R., Kerr, Y. H., & Sorooshian, S.,1994. A modified soil adjusted vegetation index. *Remote Sensing of Environment*, 48(2), 119-126. doi:https://doi.org/10.1016/0034-4257(94)90134-1
- Rondeaux, G., Steven, M., & Baret, F.,1996. Optimization of soil-adjusted vegetation indices. *Remote Sensing of Environment*, 55(2), 95-107. doi:https://doi.org/10.1016/0034-4257(95)00186-7
- Salmerón Gómez, R., García García, C., & García Pérez, J.,2020. Detection of Near-Multicollinearity through Centered and Noncentered Regression. *Mathematics*, 8(6). doi:10.3390/math8060931
- Thi, L. P., & Van, C. L.,2025. Estimating chlorophyll content in rice leaves using vegetation indices derived from multispectral UAV imagery (in

- vietnamese). *Journal of Hydro-meteorology*, 05(773), 88-102. doi:10.36335/vnjhm.2025(773).88-102
- Wang, J., Zhou, Q., Shang, J., Liu, C., Zhuang, T., Ding, J., . . . Huo, Z., 2021. UAV- and Machine Learning-Based Retrieval of Wheat SPAD Values at the Overwintering Stage for Variety Screening. *Remote Sensing*, 13(24). doi:10.3390/rs13245166
- Wang, L., Duan, Y., Zhang, L., Rehman, T., Ma, D., & Jin, J., 2020. Precise Estimation of NDVI with a Simple NIR Sensitive RGB Camera and Machine Learning Methods for Corn Plants. *Sensors (Basel)*, 20(11). doi:10.3390/s20113208
- Wang, Y., Tan, S., Jia, X., Qi, L., Liu, S., Lu, H., . . . Ma, X., 2023. Estimating Relative Chlorophyll Content in Rice Leaves Using Unmanned Aerial Vehicle Multi-Spectral Images and Spectral-Textural Analysis. *Agronomy*, 13(6). doi:10.3390/agronomy13061541
- Zhang, S., Zhao, G., Lang, K., Su, B., Chen, X., Xi, X., & Zhang, H., 2019. Integrated Satellite, Unmanned Aerial Vehicle (UAV) and Ground Inversion of the SPAD of Winter Wheat in the Reviving Stage. *Sensors (Basel)*, 19(7). doi:10.3390/s19071485