



The proceedings of

The 8th Kasetart University Sriracha Campus International Conference (KUSRC-IC 2026)



**Sustainable Future Design:
The Convergence of AI and
Digital Green Technology**



The Proceedings of
The 8th
**Kasetsart University
Sriracha Campus
International Conference
(KUSRC-IC 2026)**

August 26 - 27, 2026



Subject



Science, Engineering,
Innovation and Technology



Business, Economics
and Social Sciences

Organized by

Kasetsart University Sriracha Campus
Faculty of Management Science Kasetsart University Sriracha Campus
Faculty of Engineering at Sriracha
Faculty of Science at Sriracha
Faculty of Economics at Sriracha
Faculty of International Maritime Studies

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the 8th Kasetsart university Sriracha campus
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Preface

Kasetsart University Sriracha Campus is honored to present the 8th Kasetsart University Sriracha Campus International Conference (KUSRC-IC 2026), held under the theme “Sustainable Future Design: The Convergence of AI and Digital Green Technology.” The conference was held on August 26–27, 2026, at Kasetsart University Sriracha Campus, Chonburi, Thailand, bringing together researchers, academics, professors and students to share knowledge, exchange ideas, and explore emerging developments in research and innovation.

The conference was organized with the aim of providing an international platform for the presentation and dissemination of research findings, while promoting the exchange of knowledge, perspectives, and experiences among participants. It also sought to encourage interdisciplinary dialogue and establish academic and professional networks that could foster future research collaborations and contribute to the advancement of knowledge and innovation.

The conference featured oral presentations of research, which were reviewed by distinguished experts in their respective fields. The contributions presented at the conference covered a broad range of disciplines and were organized into three major areas: Science; Engineering, Innovation and Technology; Business, Economics and Social Sciences. The diversity of these contributions reflects the multidisciplinary character of KUSRC-IC 2026 and its commitment to promoting meaningful academic exchange across disciplines.

This E-Proceedings presents a collection of selected research contributions from KUSRC-IC 2026, providing a valuable record of the knowledge during the conference. We hope that these proceedings will serve as a useful academic reference and encourage further research, innovation, and collaboration among researchers and scholars worldwide.

The Organizing Committee of KUSRC-IC 2026 would like to express its sincere appreciation to all authors, presenters, researchers, academics, and participants for their valuable contributions and active engagement throughout the conference. We are especially grateful to the distinguished experts, reviewers, and committee members for their time, dedication, and invaluable support in ensuring the academic quality and successful organization of the conference.

(Associate Professor Sathaporn Chuepeng, Ph.D.)
Vice President for Sriracha Campus
for President of Kasetsart University



Keynote speaker

ERIK PAOLO SALAYO CAPISTRANO (艾保羅), PhD.

Cesar E.A. Virata School of Business
(formerly College of Business Administration),
University of the Philippines, Diliman
+632-928-4571 to 75 loc 2132, +63998-957-3537
escapistrano@up.edu.ph



Keynote speech of

“Technology and Sustainability: Are We Really Getting There?” Commentaries on the impact of technological developments on the pursuit of sustainability.”

CURRICULUM VITAE (covering 2021-2026)

WORKEXPERIENCE

Professor, Cesar E.A. Virata School of Business, University of the Philippines, Diliman, January 2021 – present
Dean, Cesar E.A. Virata School of Business, University of the Philippines, Diliman, August – November 2025 – present
Principal Investigator, University of the Philippines Korea Research Center, 2018 – present
College Secretary, Cesar E.A. Virata School of Business, University of the Philippines, Diliman, August – November, 2019

EDUCATIONAL ATTAINMENT

GRADUATE: PhD in International Management National Cheng Kung University, Tainan, Taiwan, 2015

Master in Business Administration, Rank 5th University of the Philippines, Diliman, 2008

UNGRADUATE: BS Business Administration, Cum Laude University of the Philippines, Diliman, 2004



SCHOLARLY / CREATIVE WORK

Academic Journal Publications:

1. Wu, W-Y., Chang, W-S., Liao, Y-K., Sudjai, P., Lizares, R., Rahnama, L., Ulpindo, E., & Capistrano, E.P. (2026). Ranking mechanisms for assessing the competitiveness of the Philippines' listed companies: A comparative analysis. *Asia Pacific Management Review*. 31(3), 100394. ESCI
2. Relente, A.R.R. & Capistrano, E.P.S. (2025). Innovation self-efficacy, theory of planned behavior, and entrepreneurial intentions: The perspective of young Filipinos. *Asia Pacific Management Review*, 30(3), 100350. ESCI
3. Manuel III, M.C. & Capistrano, E.P.S. (2025). Self-efficacy and attitudes toward healthcare technology use: Empirical evidences from the Philippines. *Asia Pacific Management Review*, 30(3), 100338. ESCI
4. Lloren-Alcantara, P.S. & Capistrano, E.P.S. (2025). Determining antecedents and outcomes towards Philippine social enterprises: A theory of planned behavior perspective. *Asia Pacific Management Review*, 30(3), 100334. ESCI
5. Capistrano, E.P.S., Gomez, M.M.E., & Isleta, A.P.M. (2024). Examining trust, self-efficacy, and technology acceptance in the Philippines' e-commerce sectors. *Information Development*, 40(4), 693-717. SSCI
6. Capistrano, E.P.S., Patent, M., & Bergania-De Vega, T. (2022). Exploring fan passions driving consumer engagement: The case of Philippine K-pop and K-drama fans. *Kritika Kultura*. 39(1), 97-133. A&HCI
7. Relente, A.R.R. & Capistrano, E.P.S. (2022). Measuring and validating Innovation Self-Efficacy: The case of Business Management students. *Asia-Pacific Social Science Review*. 22(4), 14-31. Scopus
8. Capistrano, E.P.S. (2022). E-social security success: Evidence from the Philippines. *Electronic Government: An International Journal*. 18(2), 198-222. Scopus
9. Capistrano, E.P.S. (2021). From K-Pop concerts to the Olympics: Scrutinizing the role of entertainment and sports in diplomatic efforts. *HanPil: Studies on Korea and the Philippines*. 5(1), 28-57.
10. Capistrano, E.P.S. (2021). Trust in e-commerce acceptance and use: The case of the Philippine online food delivery and tourism booking services. *Philippine Management Review*. 28(1), 37-56. ABI-INFORM
11. Ha, Q.A., Chen, J.V., Ha, U.U., & Capistrano, E.P.S. (2021). Exploring the privacy concerns in using intelligent virtual assistants under perspectives of information sensitivity and anthropomorphism. *International Journal of Human-Computer Interaction*. 37(6), 512-527. SSCI

Books and Book Chapters:

1. Capistrano, E.P.S. & Ramirez, K. (2023). Into the new world: From the objectification to the empowerment of Girls' Generation. In S.J. Lee, K. Korroch, & K.K. Liew. *Women we love: Femininities and the Korean Wave* (pp. 201-227). Hong Kong: Hong Kong University Press.



2. Daway, R.J.S. & Capistrano, E.P.S. (2023). Natasha's e-commerce journey amidst the pandemic. In A.S. Cayanan, C.R. Estrella, & H.A. Valderrama. Cases in risk management (pp. 465-503). Quezon City, Philippines: UP Business Research Foundation, Inc. and Development Center for Finance, Inc.
3. Capistrano, E.P.S. (2021). From the region and beyond: ASEAN intra and inter-regional cooperation. In B.P.B. Gutierrez, R.M. Lizares, & R.A. Rodriguez. Cases and readings in international business (pp. 845-892). Quezon City, Philippines: UP Business Research Foundation, Inc.
4. Capistrano, E.P.S. (2021). Revisiting the BPO industry in the Philippines. In B.P.B. Gutierrez, R.M. Lizares, & R.A. Rodriguez. Cases and readings in international business (pp. 691-734). Quezon City, Philippines: UP Business Research Foundation, Inc.
5. Capistrano, E.P.S. (2021). South Korean beauty brands in the Philippines. In B.P.B. Gutierrez, R.M. Lizares, & R.A. Rodriguez. Cases and readings in international business (pp. 399-442). Quezon City, Philippines: UP Business Research Foundation, Inc.

Papers Presented:

1. Capistrano, E.P.S. & Rahnema, L.C. (2025). Philippine competitiveness: Commentaries on the Enterprise Competitiveness Index results. 2025 University Education and Enterprise Competitiveness Forum, National Cheng Kung University, Tainan City, Taiwan, September 10 to 12, 2025.
2. Relente, A.R.R. and Capistrano, E.P.S. (2025). An attribution theory-approach to deep-dive into young Filipinos' entrepreneurial intentions. 26th Asia Pacific Management Conference, University of Economics and Law (UEL) - Vietnam National University, Ho Chi Minh City, Vietnam, July 15 to 17, 2025.
3. Manuel, M.C. III and Capistrano, E.P.S. (2025). Diffusion of innovation and self-efficacy: A deep-dive into Filipino users' attitudes towards healthcare technology use. 26th Asia Pacific Management Conference, University of Economics and Law (UEL) - Vietnam National University, Ho Chi Minh City, Vietnam, July 15 to 17, 2025.
4. Capistrano, E.P.S. (2025). What's next for the Korean Pop industry: A stakeholder theory perspective. 10th Philippine Korean Studies Symposium, University of the Philippines, Diliman, Quezon City.
5. Lloren-Alcantara, P.S. & Capistrano, E.P.S. (2024). Determining antecedents and outcomes towards Philippine social enterprises: A theory of planned behavior perspective. 25th Asia Pacific Management Conference, Kasetsart University, College of Management, National Cheng Kung University and Department of Industrial Engineering, Kasetsart University, Bangkok, Thailand.
6. Relente, A.R.R. & Capistrano, E.P.S. (2024). Innovation self-efficacy, theory of planned behavior, and entrepreneurial intentions: A Philippine perspective. 25th Asia Pacific Management Conference, Kasetsart University, College of Management, National Cheng Kung University and Department of Industrial Engineering, Kasetsart University, Bangkok, Thailand.



7. Manuel III, M.C. & Capistrano, E.P.S. (2024). Self-efficacy and attitude towards healthcare technology use: Empirical evidences from the Philippines. 25th Asia Pacific Management Conference, Kasetsart University, College of Management, National Cheng Kung University and Department of Industrial Engineering, Kasetsart University, Bangkok, Thailand.
8. Shim, D. & Capistrano, E.P.S. (2024). Digital technologies and innovation in the global Korean Wave: A case study approach, 9th Philippine Korean Studies Symposium, University of the Philippines, Diliman, Quezon City.

GUEST SPEAKER

1. Digital Trust: Building Confidence in the Digital Age”, Innovation Summit 2024, KPMG R.G. Manabat & Co., 2024
2. “Taking that Next Step in Going International”, Series of Economics Expo 2024 International Webinar, Faculty of Economics, Universitas Negeri Jakarta, 2024
3. “Between Trust and “Bilib sa Sarili”: How Filipino -E-Commerce Users Behave, 30th EdukCircle International Convention on Business, EdukCircle, 2024

ACADEMIC AWARDS

1. Commercial Bank and Trust Co. Professorial Chair Award, January – December, 2026
2. University of the Philippines Scientist I, January 2023 – December 2025
3. BSBA Class of 1960 Professor of Business Administration Professorial Chair Award, January – December 2025
4. 2000 Manila East Asian Insurance Corporation Professorial Chair Award, January – December 2024



Keynote speaker

HOANG-DUNG NGUYEN, Ph.D.

Date of Birth: Nov. 20, 1979
Gender: Male
Nationality: Vietnamese
Email: hoangdung@ctu.edu.vn



Keynote speech of
“AI for engineering: research and real-world
applications”

EXECUTIVE SUMMARY

Dr. Hoang-Dung Nguyen received the master degree in automation engineering from HCM University of Technology and the Ph.D. degree in cogno-mechatronics engineering from Pusan National University, Republic of Korea in 2009 and 2017, respectively. He is Director of MIS and Dean of the Faculty of Automation Engineering, Can Tho University (CTU), Vietnam. He is also a distinguished adjunct professor with ITENAS, Indonesia. He is a session chair and keynote speaker of several international conferences such as IEEE ICCUBEA (2022, India), BME11 (2026, Vietnam), and ICoISSEE (2026, Indonesia). He published the hundreds of journal and conference papers. His current research interests include control engineering, IoT, Robot engineering, AI (machine learning and deep learning), biomedical engineering, BCI, brain engineering, and brain imaging.

RESEARCH INTERESTS

- fNIRS based 3D human brain imaging.
- Brain engineering (Modelling the brain hemodynamic response)
- Intelligent control systems (Neural network, fuzzy logic, AI)
- System identification (Recursive least squares, Subspace)
- IoT
- Renewable energy (Solar energy)
- Control engineering (Sliding mode controller, adaptive control, state-space model)

PUBLICATIONS (Selected)

Books

1. Nguyen Chi Ngon and **Nguyen Hoang Dung**, Control System Engineering, Can Tho University Publishing House, 2012, 291 pages. (2nd Edition, 2023, 373 pages).
2. Tran Thanh Hung and **Nguyen Hoang Dung**, Programmable logic controller, Can Tho University Publishing House, 2012, 415 pages.



3. **Nguyen Hoang Dung**, Dai Tien Trung, and Tran Le Trung Chanh, SCADA: Analysis and Design, Can Tho University Publishing House, 2025, 246 pages.
4. **Nguyen Hoang Dung, Nguyen Van Khanh, and Huynh The Hien, IoT Technologies and Applications**, Can Tho University Publishing House, 2025, 226 pages.

Projects

International Projects

1. ANGEL (ASEAN Network for Green Entrepreneurship and Leadership): 2020-2024
2. ECORED (European quality COurse system for Renewable Energy Development): 2015-2018

National Projects

1. National project “A method for translating from national news into signal language utilized for deaf people” (ID: B2013-16-31)
2. University project “Designing automatic wet flour cutter” (ID: T2017-94).
3. University project “Adaptive sliding mode control for synchronization of coupled Fitzhugh-Naguno neurons” (ID: T2026-64)



Conference program



THE 8TH KASETSART UNIVERSITY SRIRACHA CAMPUS INTERNATIONAL CONFERENCE (KUSRC-IC 2026)

**“Sustainable Future Design :
The Convergence of AI and Digital Green Technology”**

 August 26 - 27, 2026

 At PAK PI-RUN Hotel,
Kasetsart University Sriracha Campus



DAY 1 | WEDNESDAY, AUGUST 26, 2026

TIME (THAILAND TIME)	SCHEDULE OF ACTIVITIES
 13.00 – 13.30	Registration and Collection of Souvenirs, Refreshment Boxes, Programs, and Name Badges (Grand Conference Room, 3 rd Floor, PAK PI-RUN Hotel)
 13.30 – 14.00	The 8th Kasetsart University Sriracha Campus International Conference (KUSRC-IC 2026) ceremony - Briefing by Assistant Professor Natthapon Pannurat, PhD., Assistant to the President for Research, Social Missions and Digital Sriracha Campus - Welcome speech by Associate Professor Sathaporn Chuepeng, PhD., Vice President for Sriracha Campus - Opening remarks by Assistant Professor Dr. Kanet Katchasuwanmananee, PhD., Vice President for Administration
 14.00 – 15.00	Keynote Speaker : Professor Erik Paolo Capistrano / Professor and Dean at Cesar E.A. Virata School of Business - University of the Philippines Diliman. Title of speech “Technology and Sustainability: Are We Really Getting There?” Commentaries on the impact of technological developments on the pursuit of sustainability.
 15.00 – 15.15	Coffee Break
 15.15 – 16.15	Keynote Speaker : Dr. Hoang-Dung Nguyen / Dean of the Faculty of Automation Engineering at Can Tho University (CTU) in Vietnam Title of speech: AI for engineering: research and real-world applications
 16.30 – 17.00	Participation in the 31st Anniversary Celebration of Kasetsart University Sriracha - Tram tour around the campus, visiting various buildings and enjoying the university surroundings. Visit “The Premium KU @ Sriracha” Shop.
 17.30 – 22.00	Networking Night & Certificate Awarding Ceremony (BEST PAPER AWARDS) (Dockayds Room, 6 th Floor, Holiday Inn & Suites Sriracha Laemchabang Hotel)

**The schedule may be subject to change as appropriate.*





Conference program

DAY 2

THURSDAY, AUGUST 27, 2026

SCHEDULE OF ACTIVITIES

Oral Presentation (PAK PI-RUN Hotel)

Session 1 : Science, Engineering, Innovation and Technology Grand Conference Room, 3 rd Floor		Session 2 : Business, Economics and Social Sciences Conference Room, 2 nd Floor	
08.30 – 09.00		Registration	
Time (Thailand Time)	Paper ID	Time (Thailand Time)	Paper ID
09.00 – 09.15	ID008F	09.00 – 09.15	ID002F
09.15 – 09.30	ID011F	09.15 – 09.30	ID007A
09.30 – 09.45	ID012F	09.30 – 09.45	ID016F
09.45 – 10.00	ID017F	09.45 – 10.00	ID020F
10.00 – 10.15	ID018F	10.00 – 10.15	ID003F
10.15 – 10.30		Coffee break	
10.30 – 10.45	ID003A	10.30 – 10.45	ID021F
10.45 – 11.00	ID005A	10.45 – 11.00	ID019F
11.00 – 11.15	ID009A	11.00 – 11.15	ID004A
11.15 – 11.30	ID004F	11.15 – 11.30	ID005F
11.30 – 11.45	ID007F	11.30 – 11.45	ID014F
11.45 – 12.00	ID013F	11.45 – 12.00	
12.00 – 13.00		Lunch	
13.00 – 13.15	ID022F		
13.15 – 13.30	ID006A		
13.30 – 13.45	ID008A		
13.45 – 14.00	ID001F		
14.00 – 14.15		Coffee Break	
14.15 – 14.30	ID006F		
14.30 – 14.45	ID015F		
14.45 – 15.00	ID024F		
15.00 – 15.15	ID010A		

*The schedule may be subject to change as appropriate.





Conference Committee

Honorary advisor

Associate Professor Sathaporn Chuepeng, Ph.D.

Vice president of Kasetsart University Sriracha Campus, Thailand.

Honorary Co - advisor

Associate Professor Nattapon Chantarapanich, Ph.D.

Dean of the Faculty of Engineering at Sriracha
Kasetsart University Sriracha Campus, Thailand.

Asstistant Professor P, Pungboon Pansila, Ph.D.

Dean of Faculty of Science at Sriracha
Kasetsart University Sriracha Campus, Thailand.

Asstistant Professor Parichat Tengsuwan, Ph.D.

Dean of Faculty of Economics at Sriracha
Kasetsart University Sriracha Campus, Thailand.

Asstistant Professor Prachakon Kaewkhiaw, Ph.D.

Dean of Faculty of International Maritime Studies
Kasetsart University Sriracha Campus, Thailand.

Mr. Jumpoth Boriraj, Ph.D.

Dean of Faculty of Management Sciences
Kasetsart University Sriracha Campus, Thailand.

General chair

Asstistant Professor Natthapon Pannurat, Ph.D.

Assistant to the President for Research, Social Missions and Digital Sriracha Campus
Kasetsart University Sriracha Campus, Thailand.



Conference Committee

Organizing Committee

Associate Professor Tongsai Jamnongkan, Ph.D.

Kasetsart University Sriracha Campus, Thailand.

Professor Cherdvong Saengsupavanich, Ph.D.

Kasetsart University Sriracha Campus, Thailand.

Asstistant Professor Pat Pattanarangsun, Ph.D.

Kasetsart University Sriracha Campus, Thailand.

Asstistant Professor Nantawut Sriariyawat

Kasetsart University Sriracha Campus, Thailand.

Mr. Sitthikarn Benjasupattananun

Kasetsart University Sriracha Campus, Thailand.

Technical program committee

Associate Professor Abdullah Açık, Ph.D.

Dokuz Eylül University, Turkey

Associate Professor Ut Dong THACH, Ph.D.

Ton Duc Thang University, Vietnam.

Quoc Phong Luu, Ph.D.

University of Economics Ho Chi Minh City, Vietnam.

Associate Professor Yung-Kuei Liang, Ph.D.

Tatung University, Taiwan.

Associate Professor SAFAA NAJAH SAUD AL-HUMAIRI, Ph.D.

Universiti Teknologi Malaysia, Malaysia.

Viet Hoang, Ph.D.

Ho Chi Minh City University of Science, Vietnam.



Conference Committee

Technical program committee

Assistant Professor Fida Majdoub, Ph.D.

ECAM School of Engineering, Lyon (ECAM), France.

Assistant Professor Jakkrapan Kittinorarat, Ph.D.

Phranakhon Rajabhat University, Thailand.

Somsawat Nindam, Ph.D.

Kasetsart University Sriracha Campus, Thailand.

Associate Professor Supaporn Baiya, Ph.D.

Kasetsart University Sriracha Campus, Thailand.

Associate Professor Chonlatis Darawong, Ph.D.

Sripatum University, Thailand.

Assistant Professor Teetut Tresirichod, Ph.D.

Rajamangala University of Technology Thanyaburi, Thailand.

Assistant Professor Waranan Tantiwat, Ph.D.

Lincoln University, New Zealand.



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The 8th Kasetsart University
Sriracha Campus
International Conference 2026
(KUSRC - IC 2026)

Subject :

Science, Engineering, Innovation and
Technology

(Abstract only)



Seaports and livelihoods of local coastal communities

Ariyata Suvarnabhumi, Dollaya Suwanruangsri, Phakawadee Jaroon, and
Cherdvong Saengsupavanich^{1*}

¹*Faculty of International Maritime Studies, Kasetsart University, Sri Racha Campus, Thailand*

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ABSTRACT

Seaports serve as critical nodes in global trade and economic growth, yet their expansion significantly alters the livelihoods of adjacent coastal communities. This study investigates the socio-economic and environmental impacts of Thailand's Laem Chabang (LCB) mega port on three neighboring villages: Laem Chabang Gao, Ban Na Gao, and Bantunggrad. Utilizing a survey-based methodology with 75 residents, the research captures the perspectives of long-term inhabitants, predominantly elderly, who have witnessed the port's evolution over decades. Findings reveal a complex duality of impacts. Economically, while average household incomes have risen to 22,013 THB, benefits remain concentrated among a minority, leaving many households without direct port-related income while facing new indirect costs for healthcare and property maintenance. Socially and environmentally, the port has triggered a drastic rise in traffic congestion and persistent air, noise, and water pollution. Based on the interview results, these environmental stressors may be linked to prevalent health issues in the community, including chronic respiratory ailments, hypertension, and skin allergies. The study concludes that while the port fosters national economic development, it may impose significant burdens on local quality of life. Consequently, future port expansions must prioritize comprehensive mitigation strategies, including improved environmental management, infrastructure planning, and equitable economic distribution, to ensure the sustainable coexistence of industrial operations and coastal communities

Keywords: Blue economy; Coastal management; Ports; Sustainable development



Human elements of port digital transformation: workforce, organizational, and institutional dimensions

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ABSTRACT

Ports are one of the crucial elements of the maritime industry, which is undergoing digital transformation. However, much of the literature remains predominantly technology-centric, while the human element, including port workers, management level, and institutions through which transformation must be accomplished, remains fragmented in attention. This study reviews the human management of port digital transformation through a socio-technical perspective and a micro-meso-macro analytical framework, encompassing workforce skills and technology acceptance (micro-level), organizational and human resource management (meso-level), and institutional and policy arrangements (macro-level). The synthesis presents that human challenges are not isolated barriers but symptoms of misalignment across levels, meaning the transformation succeeds when national strategy, organizational capacity, and worker acceptance reinforce one another without being neglected. The review found systematic gaps in worker-level acceptance and the absence of reskilling program evaluations, which are crucial for human capital that is most binding for digital transformation and green transition in the maritime industry that must be managed simultaneously.

Keywords: Digital Transformation; Socio-technical systems; Smart port; Workforce; Human resource management



Optimization of streptavidin immobilization on graphene electrodes for electrochemical detection of biotinylated LAMP products

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ABSTARCT

Diagnostic technologies frequently require expensive and complex laboratory infrastructure. As a step toward developing a low-cost, user-friendly electrochemical platform for tuberculosis diagnosis, screen-printed graphene electrodes were investigated for the detection of DNA products generated by loop-mediated isothermal amplification (LAMP). This study aimed to optimize streptavidin coating conditions on graphene electrodes to bind biotin-labeled LAMP products derived from wild-type and mutant sequences of *Mycobacterium tuberculosis*. Biotin and Alexa Fluor 488-labeled LAMP products were immobilized on the coated electrodes and evaluated using confocal laser scanning microscopy and quantitative image analysis. Electrochemical responses were recorded by cyclic voltammetry in the presence of Hoechst 33258 as an electroactive DNA-binding indicator. The binding efficiency of biotin-labeled LAMP products to the coated Graphene varied depending on the composition and pH of the immobilization buffers. Among the tested conditions, 100 µg/mL streptavidin in Tris-HCl buffer at pH 7.0 produced the highest fluorescence intensity and the clearest current (µA) distinction between positive and negative samples. Biotin-labeled LAMP products produced higher signals than non-biotin-labeled products under identical coating conditions, indicating streptavidin-biotin interaction. These findings demonstrate that optimizing streptavidin coating conditions improves the capture and electrochemical detection of biotin-labeled LAMP products on graphene electrodes. The optimized coating protocol provides a foundation for the future development of portable graphene-based electrochemical platforms for LAMP product detection.

Keywords: LAMP 1; Graphene 2; Streptavidin 3; Biotin 4; Mycobacterium 5



Comparative study of open-source SIEM solutions

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ABSTARCT

The growing volume and complexity of cyber threats create a need for effective and affordable security monitoring platforms. This study compares three open-source Security Information and Event Management (SIEM) solutions: Graylog, Wazuh, and the ELK Stack, to determine their suitability for cybersecurity monitoring. Each platform was installed in a controlled virtual-machine environment and configured to collect Ubuntu system logs and Docker container logs. An SSH brute-force attack was generated from Kali Linux, and the platforms were assessed using five criteria: performance, scalability, usability, detection capability, and integration. Performance measurements were repeated across 10 trials. All three platforms successfully collected the selected log sources, detected brute-force activity, supported rule-based detection and event correlation, and provided multi-node scalability and multiple ingestion methods. Graylog produced the fastest mean alert detection time (3.17 s) and search visibility time (2.87 s), but recorded the highest average CPU usage (23.7%). Wazuh provided balanced performance and the lowest average memory usage (3.26 GB), while also offering pre-built security dashboards, predefined detection rules, and endpoint monitoring features. The ELK Stack recorded the lowest average CPU usage (2.6%) but required the most memory (11.2 GB) and had the slowest mean alert detection time (18.21 s). Overall, Wazuh achieved the highest evaluation score and is suitable for security-focused deployment with minimal configuration, whereas Graylog is preferable for rapid log analysis and the ELK Stack for flexible, large-scale analytics.

Keywords: Security Information and Event Management; open-source SIEM; threat detection; log management; cybersecurity

Modelling and performance analysis of a PV-based DC microgrid for electric vehicle charging with battery and hydrogen energy storage

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ABSTARCT

This paper presents the modeling and performance analysis of a standalone photovoltaic (PV)-based DC microgrid for electric vehicle (EV) charging incorporating hybrid battery–hydrogen energy storage. The proposed system integrates a PV generation unit, a lithium-ion battery, and a hydrogen storage subsystem comprising a proton-exchange membrane (PEM) electrolyzer, compressed-hydrogen storage, and a PEM fuel cell. The PV array is interfaced with a 600 V DC bus through a DC/DC boost converter controlled by a Perturb-and-Observe (P&O) maximum power point tracking (MPPT) algorithm, while a bidirectional buck–boost converter connects the 400 V battery to the DC bus. A rule-based energy management system (EMS) is developed to coordinate power flow among the PV source, EV charging demand, battery, electrolyzer, and fuel cell according to the available power, battery state of charge, hydrogen storage level, and component power constraints. Representative solar-resource and EV-charging demand profiles for Si Racha, Thailand, are used to evaluate the proposed system in MATLAB/Simulink. Simulation results show that the battery provides fast bidirectional power balancing under normal operating conditions, while the hydrogen subsystem provides complementary long-duration energy management by absorbing excess PV generation through electrolysis and supplying additional power through the fuel cell during periods of high demand. The DC-bus voltage is maintained close to its 600 V reference under variations in PV generation and EV charging load. These results demonstrate the effectiveness of coordinated battery–hydrogen energy storage in improving power balance and maintaining stable DC-bus operation in PV-based EV charging microgrids.

Keywords—photovoltaic system, DC microgrid, electric vehicle charging, battery energy storage, hydrogen energy storage, PEM electrolyzer, PEM fuel cell, energy management system, MPPT.

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Generational Differences and Decision Drivers in Pet Ownership and Veterinary Service Utilization

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ABSTARCT

Understanding generational differences, species preferences, and veterinary care utilization patterns is essential for optimizing animal healthcare management and clinical service delivery. To evaluate generational shifts, acquisition behaviors, financial expenses, and clinic selection criteria among cat and dog owners, a structured cross-sectional survey collected primary data from 221 pet owners comprising 32 from Generation Z, 98 from Generation Y, and 91 from Generation X, representing 101 cat and 120 dog owners. Generational preferences varied significantly, with Generation Z favoring cats at 75%, Generation Y holding a balanced mix at 44.9% cats and 55.1% dogs, and Generation X preferring dogs at 63.74%. Despite these shifts, companionship and compassion served as universal acquisition motivators across all cohorts. Visit frequencies were similar across species, with bi-annual visits most common, as supported by a Kruskal Wallis test showing an H statistic of 3.174 ($p = 0.075$). However, dog owners incurred significantly higher annual expenses, yielding an H statistic of 5.272 ($p = 0.022$), with most dog owners spending 1501 to 3000 Baht at 45% compared to 501 to 1500 Baht for 54.46% of cat owners. Primary clinic selection drivers were proximity at 75.6%, reasonable pricing at 53.8%, and attentive care at 49.8%. Ultimately, while generational differences appear to be associated with species choice and dogs tend to require higher medical spending, core acquisition motives, visit frequencies, and clinic selection priorities suggest a notable pattern of relative uniformity across groups.

Keywords: Animal Healthcare; Generational Differences; Pet Ownership; Veterinary Service Utilization



Macroeconomic Dynamics Following the Generative AI Era Onset in ASEAN: Country-Level Evidence from Local Projections

Thu Maung Zaw^{1*}

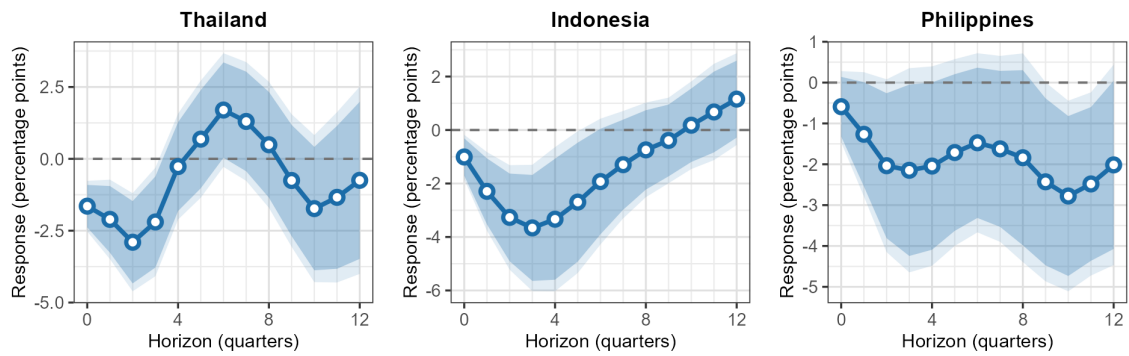
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ABSTARCT

This study documents macroeconomic dynamics in Thailand, Indonesia, and the Philippines associated with the onset of the generative AI period, using country-specific Local Projection regressions (Jorda, 2005). Quarterly data come from CEIC and national statistical agencies, covering Thailand (2000Q2-2025Q4), Indonesia (2005Q3-2025Q4), and the Philippines (2002Q1-2025Q4). The AI period is proxied by a binary step dummy equal to zero before 2022Q4 and one from 2022Q4 onward, coinciding with ChatGPT's public release. This is a descriptive rather than causal strategy: the dummy marks the start of the generative AI era but may also capture other persistent post-2022 macroeconomic changes not fully absorbed by the controls, namely global oil prices, US policy rates and their first difference, a COVID-19 indicator, and China's quarterly GDP growth. Output and inflation gaps are HP-filter deviations ($\lambda = 1,600$) from trend GDP and from each central bank's official target midpoint, respectively. Impulse responses span zero to twelve quarters, estimated with Newey-West HAC standard errors and reported at 90% and 95% confidence. Thailand and Indonesia follow a J-curve pattern: output contracts on impact, then expands significantly from around the seventh quarter. The Philippines contracts persistently with no recovery; one plausible explanation is its large business process outsourcing workforce's disproportionate exposure to AI-related task displacement, though this cannot be established from aggregate data alone. Inflation is largely unaffected in Thailand, falls in Indonesia at horizons four to five, and declines sharply in the Philippines from horizon six through twelve; this may reflect a supply-side cost channel, though other post-2022 structural changes cannot be ruled out. All three economies show current account deterioration at medium horizons, possibly reflecting rising imports of AI-related capital goods. Exchange rates appreciate in Thailand and Indonesia; the Philippines shows a delayed monetary tightening response. The three countries respond differently, and differences in sectoral composition, inflation history, and business process outsourcing dependence offer plausible, though not definitively identified, explanations.

Keywords: artificial intelligence shocks; local projections; ASEAN macroeconomics; output gap; exchange rate



Notes: Solid line = LP point estimate. Dark shading = 90% CI; light shading = 95% CI (Newey-West HAC s.e.).
Shock: step dummy = 1 from Q4 2022 (ChatGPT release). Controls: oil price, US policy rate, COVID-19, China GDP growth.

Figure 1 Inflation gap response to AI announcement shock

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Utilization of Al₂O₃-based Spent CO₂ Sorbent in Sustainable Cellular Lightweight Concrete Using Response Surface Methodology

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Abstract

This study investigated the feasibility of utilizing Al₂O₃-based spent sorbent as a partial replacement for cement and sand in Cellular Lightweight Concrete (CLC) using Response Surface Methodology (RSM) based on a Box–Behnken Design (BBD). The effects of the water-to-cement ratio (A), sand-to-cement ratio (B), cement replacement (C), and sand replacement (D) on dry density, compressive strength, and water absorption were evaluated. Dry density ranged from 0.795 to 1.424 g/cm³, compressive strength ranged from 0 to 3.759 MPa, and water absorption ranged from 14.87 to 35.57%. The water-to-cement ratio primarily affected compressive strength, whereas the sand-to-cement ratio had the greatest influence on dry density and water absorption. Compared with the corresponding control mixtures, Al₂O₃-based spent sorbent did not significantly reduce the compressive strength or water absorption and maintained comparable dry density. The sorbent could be incorporated at up to 10% cement and 10% sand replacement without a significant performance penalty, demonstrating its potential for sustainable CLC production.

Keywords: Cellular Lightweight Concrete; Carbon Capture; Al₂O₃ -based Spent Sorbent; Response Surface Methodology; Waste Utilization

1. Introduction

The increasing deployment of Carbon Capture, Utilization and Storage (CCUS) technologies has generated large quantities of Al₂O₃-based spent CO₂ sorbent, creating a growing challenge for sustainable waste management [1]. Although the spent sorbent gradually loses its CO₂ adsorption capacity after repeated carbonation–regeneration cycles, it retains chemically stable Al₂O₃ together with a mesoporous structure and high specific surface area, making it a promising secondary raw material rather than a waste requiring disposal [2]. However, previous studies have mainly focused on sorbent regeneration and CO₂ capture performance, whereas the beneficial utilization of Al₂O₃-based spent sorbent in construction materials has received little attention.

Non-autoclaved Cellular Lightweight Concrete (CLC) is a lightweight cement-based material produced by incorporating preformed foam into a cementitious matrix. Compared with autoclaved aerated concrete, CLC is manufactured under ambient curing conditions, resulting

in lower energy consumption [3,4]. Its engineering properties, including dry density, compressive strength, and water absorption, are primarily influenced by the water-to-cement ratio, sand-to-cement ratio, and incorporated replacement materials [5]. Previous studies have shown that suitable mineral replacement materials can maintain satisfactory compressive strength while reducing cement consumption [6]. Therefore, the chemical stability and porous structure of Al_2O_3 -based spent sorbent suggest its potential as an alternative replacement material for CLC [7].

Despite this potential, the effects of Al_2O_3 -based spent sorbent on the engineering properties of CLC have not been systematically investigated. Response Surface Methodology (RSM) is an effective statistical tool for simultaneously evaluating the influence of multiple mixture variables while reducing the number of experimental trials required [8]. Therefore, this study aims to (1) investigate the feasibility of utilizing Al_2O_3 -based spent sorbent as a partial replacement material for cement and sand in CLC, and (2) evaluate the effects of the water-to-cement ratio, sand-to-cement ratio, cement replacement, and sand replacement on the dry density, compressive strength, and water absorption of CLC using RSM based on a Box–Behnken Design (BBD).

2. Research Methodology

This study investigated the feasibility of utilizing Al_2O_3 -based spent sorbent as a partial replacement for cement and sand in CLC. The materials included Ordinary Portland Cement (Type I) (OPC), sand, tap water, Al_2O_3 -based spent sorbent obtained from a carbon capture process, and a commercial synthetic foaming agent. The sand was sieved through a 2 mm sieve before mixing to ensure a uniform particle size distribution. The foaming agent dosage was fixed at 120 mL for all mixture proportions to maintain a consistent air-void system.

The experimental program was designed using RSM based on BBD to evaluate the effects of mixture variables on the engineering properties of CLC. Compared with the conventional one-factor-at-a-time (OFAT) approach, BBD enables the simultaneous evaluation of multiple variables and their interactions using fewer experimental runs than a full factorial design. In addition, BBD develops second-order polynomial models to describe the relationships between mixture variables and engineering responses, making it an effective approach for analyzing cement-based composites [8–10].

The experimental design consisted of four numerical factors, as summarized in Table 1. The investigated factors were the water-to-cement ratio (A), sand-to-cement ratio (B), cement replacement by Al_2O_3 -based spent sorbent (C), and sand replacement by Al_2O_3 -based spent sorbent (D). The levels of factors A and B were selected based on previous studies of CLC, while factors C and D represented the percentage of cement and sand replaced by Al_2O_3 -based spent sorbent, respectively.

Table 1. Experimental factors and levels used in the Box–Behnken Design (BBD).

Factor	Symbol	Unit	Low (-1)	Center (0)	High (+1)
Water-to-cement ratio	A	-	0.3	0.4	0.5
Sand-to-cement ratio	B	-	0.5	1.0	1.5
Cement replacement by spent sorbent	C	%	0	5	10
Sand replacement by spent sorbent	D	%	0	5	10

CLC mixtures were prepared according to the experimental design by mixing OPC, sand, tap water, and Al_2O_3 -based spent sorbent, followed by the incorporation of a preformed synthetic foaming agent. The fresh mixtures were cast into 5 cm cubic molds and cured in the

molds for 5 days. After demolding, the specimens were sealed with plastic film and cured for an additional 3 days to minimize moisture loss during early hydration. Compressive strength was evaluated at this age because, under ambient curing, the early-age strength of foamed cement systems develops rapidly, and subsequent strength gain is comparatively small; the 8-day value was therefore considered representative for the comparative evaluation in this study.

The cured specimens were tested for compressive strength, dry density, and water absorption. Compressive strength was determined using a YES-300 Digital Compression Testing Machine. Dry density was determined from the oven-dry mass after drying at 105 ± 5 °C for 24 h, while water absorption was measured after immersing the oven-dried specimens in tap water for 24 h. The experimental results were analyzed using ANOVA to evaluate the statistical significance of the developed response surface models.

3. Results and Discussion

This study evaluated the feasibility of utilizing Al_2O_3 -based spent sorbent as a partial replacement material for cement and sand in CLC through a Box–Behnken Design (BBD) consisting of 27 experimental mixtures and 9 corresponding control mixtures.

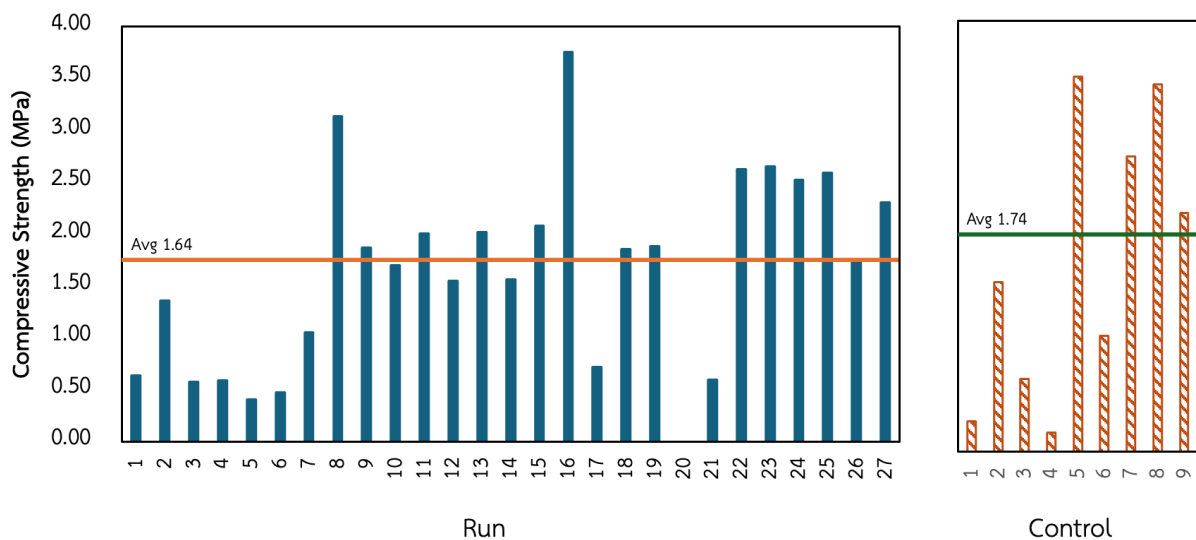


Figure 1. Comparison of the compressive strength of Al_2O_3 -based spent sorbent-incorporated CLC and the corresponding control mixtures.

Figure 1 compares the compressive strength of CLC incorporating Al_2O_3 -based spent sorbent with the corresponding control mixtures. The average compressive strength of the spent sorbent mixtures was 1.64 MPa, compared with 1.74 MPa for the control mixtures. Although several experimental mixtures exhibited higher compressive strengths than corresponding controls, the overall average compressive strength of the spent sorbent mixtures was slightly lower.

Figure 2 compares the water absorption of CLC incorporating Al_2O_3 -based spent sorbent with the corresponding control mixtures. The average water absorption of the spent sorbent mixtures was 21.95%, slightly lower than that of the control mixtures (22.34%). Although some mixtures exhibited higher water absorption than the controls, the overall average water absorption of the spent sorbent mixtures was slightly lower.

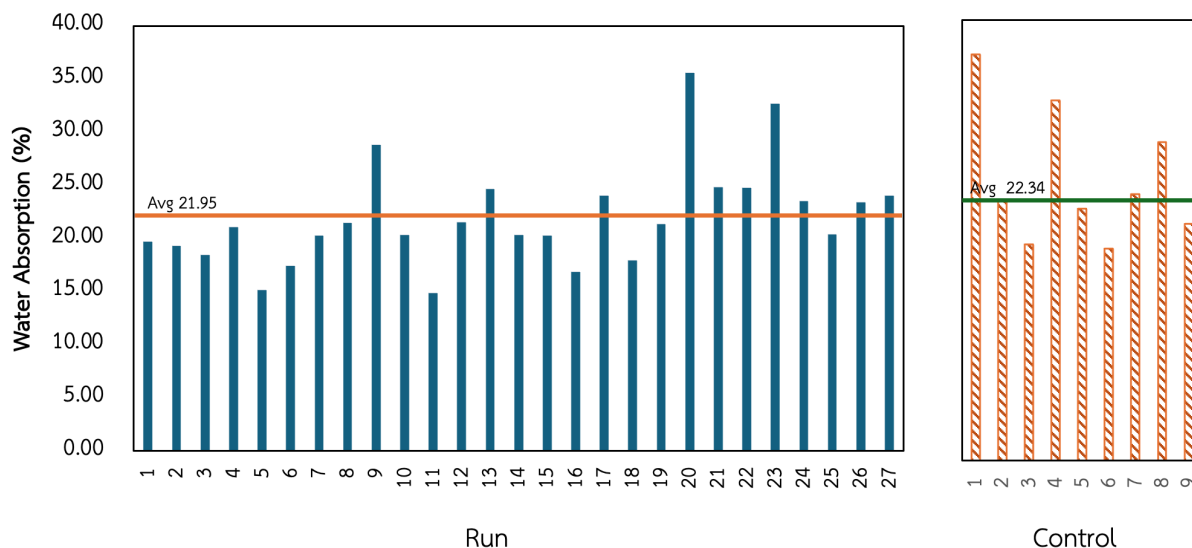


Figure 2. Comparison of the water absorption of Al₂O₃-based spent sorbent-incorporated CLC and the corresponding control mixtures.

Effect of Mixture Parameters on Dry Density

The ANOVA results for the developed dry density model are presented in Table 2. The model was significant ($F = 45.34$, $p < 0.0001$), with $R^2 = 0.854$ and adjusted $R^2 = 0.835$, and a non-significant lack of fit ($F = 1.95$, $p = 0.324$), confirming its adequacy. In terms of coded factors, the fitted model was: Dry density = $1.097 + 0.170B - 0.014D + 0.064BC + 0.063D^2$. The sand-to-cement ratio (B) was identified as the most influential factor affecting the dry density of CLC ($F = 158.90$, $p < 0.0001$). In addition, the interaction between the sand-to-cement ratio and cement replacement by Al₂O₃-based spent sorbent (BC) and the quadratic effect of sand replacement by Al₂O₃-based spent sorbent (D^2) were also statistically significant ($p < 0.01$). In contrast, the linear effect of sand replacement by Al₂O₃-based spent sorbent (D) was not statistically significant ($p = 0.2613$).

Table 2. ANOVA for the developed Dry Density model.

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	0.4765	4	0.1191	45.34	< 0.0001
B	0.4175	1	0.4175	158.90	< 0.0001
D	0.0034	1	0.0034	1.31	0.2613
BC	0.0329	1	0.0329	12.54	0.0013
D ²	0.0312	1	0.0312	11.89	0.0016
Residual	0.0815	31	0.0026		
Lack of Fit	0.0772	28	0.0028	1.95	0.3239
Pure Error	0.0042	3	0.0014		

$R^2 = 0.8540$; Adjusted $R^2 = 0.8352$; lack of fit not significant.

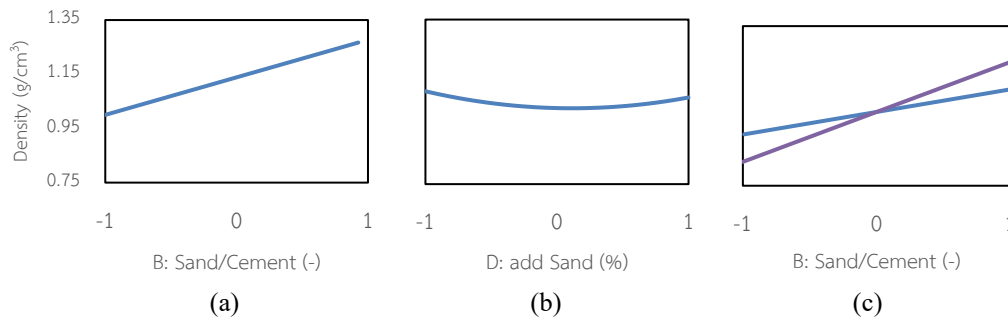


Figure 3. Significant effects of mixture variables on the dry density of CLC (a) main effect of the sand-to-cement ratio (B), (b) interaction effect between the sand-to-cement ratio (B) and cement replacement Al₂O₃-based spent sorbent (C), and (c) quadratic effect of sand replacement by Al₂O₃-based spent sorbent (D²).

As shown in Figure 3(a), the dry density of CLC increased with increasing the sand-to-cement ratio because the higher solid fraction improved particle packing while reducing the relative proportion of the foamed cement paste. Consequently, the air-void content decreased, resulting in a denser hardened matrix [11].

Figure 3(b) indicates that the effect of cement replacement by Al₂O₃-based spent sorbent depended on the sand-to-cement ratio, whereas Figure 3(c) shows a quadratic response to sand replacement. However, the absence of a significant linear effect of spent sorbent replacement (Table 2) indicates that incorporating Al₂O₃-based spent sorbent within the investigated range had only a limited influence on the dry density of CLC. This finding suggests that the spent sorbent mainly affected the internal pore structure rather than the bulk density of the composite, which is consistent with previous studies reporting that supplementary cementitious materials primarily modify the pore system while producing only minor changes in the dry density of foamed concrete [12,13].

Effect of Mixture Parameters on Compressive Strength

The ANOVA results for the developed compressive strength model are presented in Table 3. In terms of coded factors, the fitted model was: Compressive strength = 1.545 + 0.901A + 0.213B – 0.116C – 0.355D, with R² = 0.517, adjusted R² = 0.455, and a non-significant lack of fit (F = 3.46, p = 0.167). The developed model was statistically significant (F = 8.29, p = 0.0001), indicating that the selected mixture variables adequately explained the variation in the compressive strength of non-autoclaved Cellular Lightweight Concrete (CLC). Among the factors investigated, only the water-to-cement ratio (A) had a statistically significant effect on compressive strength (F = 26.06, p < 0.0001). In contrast, the sand-to-cement ratio (B), cement replacement by spent sorbent (C), and sand replacement by spent sorbent (D) did not significantly affect compressive strength within the investigated range (p > 0.05).

Table 3. ANOVA for the developed compressive strength model.

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	18.61	4	4.65	8.29	0.0001
A	14.62	1	14.62	26.06	< 0.0001
B	0.8192	1	0.8192	1.46	0.2360
C	0.2192	1	0.2192	0.3909	0.5364
D	2.06	1	2.06	3.67	0.0647
Residual	17.39	31	0.5609		
Lack of Fit	16.86	28	0.6023	3.46	0.1672
Pure Error	0.5227	3	0.1742		

R² = 0.5169; Adjusted R² = 0.4546; lack of fit not significant.

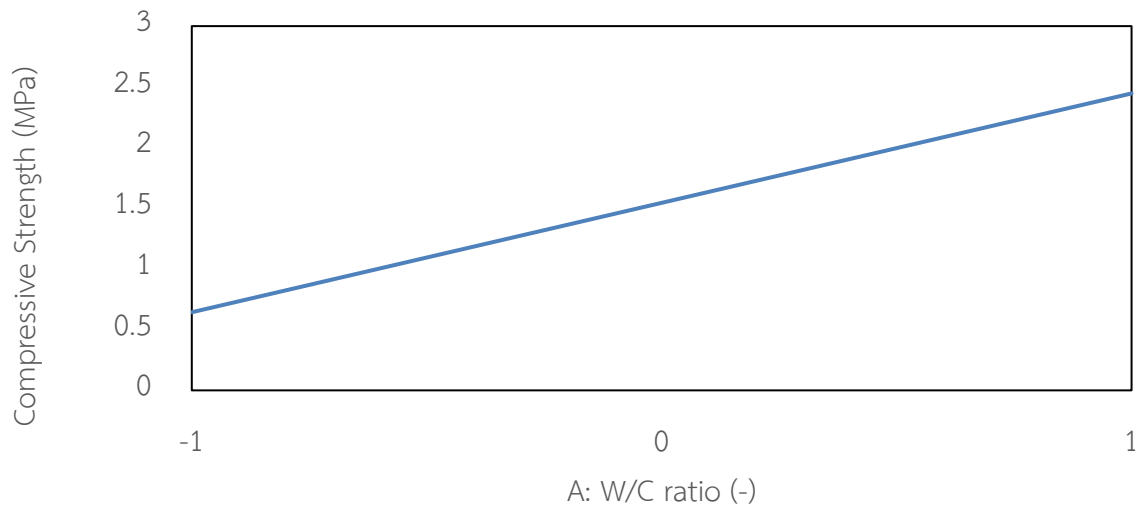


Figure 4. Significant effect of the water-to-cement ratio (A) on the compressive strength of CLC.

As shown in Figure 4, the compressive strength of CLC increased by increasing the water-to-cement ratio over the investigated range. This trend is consistent with the ANOVA results, indicating that the water-to-cement ratio was the dominant factor governing the compressive strength of CLC.

The increase in compressive strength can be attributed to the availability of sufficient water for cement hydration. At the lowest water-to-cement ratio (0.30), the available water may not have been sufficient to fully hydrate the cement particles, resulting in incomplete hydration and limited strength development. Increasing the water-to-cement ratio to 0.50 promoted the formation of hydration products and improved the continuity of the cementitious matrix, thereby enhancing the compressive strength of CLC. This beneficial effect was particularly evident at the early curing age of 8 days, when hydration was still progressing. Similar behavior has been widely reported for cementitious materials, where adequate water availability promotes hydration and early-age strength development, while improved matrix densification contributes to higher compressive strength [13].

Cement replacement and sand replacement by Al_2O_3 -based spent sorbent had no statistically significant effects on compressive strength ($p > 0.05$), indicating that the investigated replacement levels had only a limited influence on the load-bearing capacity of CLC. Considering that Al_2O_3 -based spent sorbent retains a chemically stable alumina phase after repeated carbonation–regeneration cycles, the material is likely to behave primarily as a stable mineral constituent rather than substantially altering the mechanical performance of CLC within the investigated replacement range [14].

Although the Al_2O_3 -based spent sorbent retains a mesoporous, high-surface-area alumina phase, the reactions through which alumina can contribute to strength—namely the consumption of calcium hydroxide and the formation of additional calcium–aluminate and calcium–silicate hydrates—develop mainly at later curing ages. Because the specimens in this study were tested at an early age of 8 days and the replacement levels were low ($\leq 10\%$), the spent sorbent behaved predominantly as a fine mineral filler that modified the pore and air-void structure rather than as a chemically active binder (Iskra-Kozak & Konkol, 2021). This interpretation is consistent with the present results, in which the spent sorbent influenced the dry density only through the pore-related BC interaction and D^2 quadratic terms, whereas its linear effects on compressive strength were not statistically significant.

Effect of Mixture Parameters on Water Absorption

The ANOVA results for the developed water absorption model are presented in Table 4. The model was significant ($F = 11.18$, $p < 0.0001$), with $R^2 = 0.591$ and adjusted $R^2 = 0.538$, and a non-significant lack of fit ($F = 4.21$, $p = 0.131$), confirming its adequacy. In terms of coded factors, the fitted model was: Water absorption = $22.089 + 1.819A - 4.814B + 0.173C - 0.005D$. Among the factors investigated, the sand-to-cement ratio (B) had the greatest influence on the water absorption of CLC ($F = 39.09$, $p < 0.0001$), followed by the water-to-cement ratio (A) ($F = 5.58$, $p = 0.0246$). In contrast, cement replacement by Al_2O_3 -based spent sorbent (C) and sand replacement by Al_2O_3 -based spent sorbent (D) did not significantly affect water absorption within the investigated range ($p > 0.05$).

Table 4. ANOVA for the developed water absorption model.

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	477.23	4	119.31	11.18	< 0.0001
A	59.55	1	59.55	5.58	0.0246
B	417.12	1	417.12	39.09	< 0.0001
C	0.4906	1	0.4906	0.0460	0.8316
D	0.0004	1	0.0004	0.0000	0.9952
Residual	330.83	31	10.67		
Lack of Fit	322.63	28	11.52	4.21	0.1305
Pure Error	8.21	3	2.74		

$R^2 = 0.5906$; Adjusted $R^2 = 0.5378$; lack of fit not significant.

As shown in Figure 5, the water absorption of CLC increased by increasing both the water-to-cement ratio and the sand-to-cement ratio over the investigated range. Figure 5(a) shows that increasing the water-to-cement ratio increased water absorption, while Figure 5(b) indicates that increasing the sand-to-cement ratio also increased water absorption. These observations are consistent with the ANOVA results, which identified both variables as statistically significant, with the sand-to-cement ratio exerting greater influence.

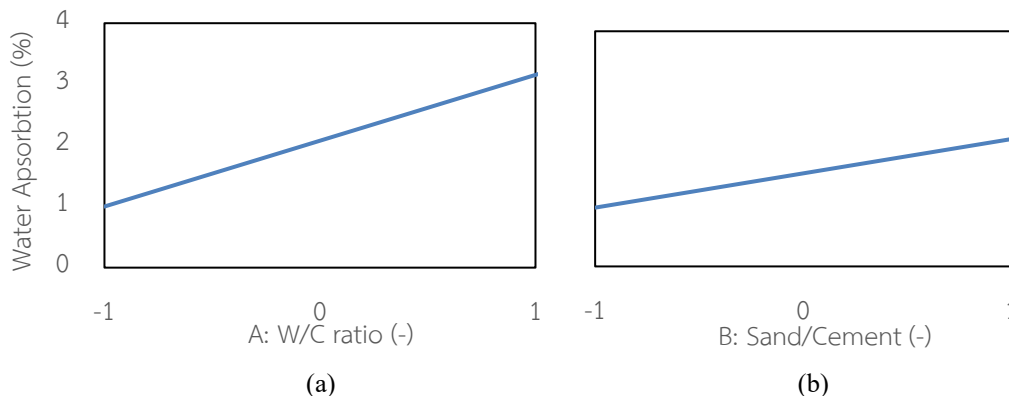


Figure 5. Significant effects of mixture variables on the water absorption of CLC (a) water-to-cement ratio (A) and (b) sand-to-cement ratio (B).

The increase in water absorption with increasing the water-to-cement ratio can be attributed to the larger amount of mixing water available during casting. Excess water that was not consumed during cement hydration subsequently evaporated, leaving interconnected capillary pores within the hardened matrix. The increased pore connectivity facilitated water penetration, resulting in higher water absorption. Similar behavior has been widely reported in cementitious

materials, where increasing the water-to-cement ratio increased capillary porosity and consequently water absorption [13,15].

Increasing the sand-to-cement ratio also increased water absorption. As the proportion of sand increased, the volume of cement pastes available to coat the aggregate particles and fill interparticle spaces decreased, resulting in a less compact cementitious matrix and more continuous pathways for water penetration. Similar observations have been reported for CLC and foamed concrete, where the mixture composition influenced the internal pore structure and consequently the water absorption [16].

The absence of statistically significant effects of cement replacement and sand replacement by Al_2O_3 -based spent sorbent indicates that, because the spent sorbent retains a chemically stable alumina phase after repeated carbonation–regeneration cycles, its incorporation within the investigated range was insufficient to substantially modify the water absorption behavior of CLC. [7]

Optimization of Mixture Proportions for Maximum Waste Utilization

To translate the response models into a practical mixture design, a numerical optimization was performed with the objective of maximizing the incorporation of Al_2O_3 -based spent sorbent. The ANOVA showed that neither cement replacement nor sand replacement had a statistically significant effect on compressive strength, dry density, or water absorption ($p > 0.05$), consistently, the average compressive strength of the spent-sorbent mixtures (1.64 MPa) was only marginally lower than that of the corresponding controls (1.74 MPa). The models therefore indicated that spent-sorbent incorporation could be increased to its maximum investigated level, 10% cement replacement and 10% sand replacement, without significantly reducing the compressive strength or otherwise compromising the engineering performance, with the properties governed mainly by the water-to-cement and sand-to-cement ratios. For example, at a water-to-cement ratio of approximately 0.45 and a sand-to-cement ratio of approximately 1.1, the maximum-replacement mixture was predicted to attain a dry density of 1.19 g/cm^3 , a water absorption of 22%, and a compressive strength of 1.5 MPa. This demonstrates that the Al_2O_3 -based spent sorbent can be valorized at its maximum investigated level without a significant performance penalty, supporting sustainable CLC production in line with Sustainable Development Goal 12. As this optimum is a model-based prediction, experimental confirmation at the predicted conditions is recommended.

The developed models were statistically significant with a non-significant lack of fit, confirming their validity. Nevertheless, the coefficients of determination for compressive strength ($R^2 = 0.517$) and water absorption ($R^2 = 0.591$) were moderate, indicating that part of the response variability was not captured by the models. This is attributed to the inherent variability of the air-void system of foamed materials, whose void size and distribution strongly govern the mechanical and transport properties and are sensitive to minor fluctuations during foam incorporation and casting (Nambiar & Ramamurthy, 2007). One mixture, in which the compressive strength fell below the measurable limit of the testing machine (reported as 0 MPa), further contributed to this scatter. In addition, all specimens were evaluated at an early curing age of 8 days because hydration and any pozzolanic contribution of the alumina phase continue beyond this age, the reported strengths should be regarded as early-age indicators, and testing at later ages (e.g., 28 days) is recommended in future work.

4. Conclusion

This study investigated the feasibility of utilizing Al_2O_3 -based spent sorbent as a partial replacement material for cement and sand in CLC using RSM. All mixtures containing Al_2O_3 -

based spent sorbent were successfully fabricated, producing CLC with dry densities ranging from 0.795 to 1.424 g/cm³, compressive strengths from 0 to 3.759 MPa (the lower-bound value of 0 MPa corresponds to a specimen whose compressive strength was below the measurable limit of the testing machine), and water absorption values between 14.87 and 35.57%.

The results demonstrated that the water-to-cement ratio was the primary factor affecting the compressive strength of CLC, whereas the sand-to-cement ratio had the greatest influence on dry density and water absorption. Compared with the corresponding control mixtures, the incorporation of Al₂O₃-based spent sorbent slightly reduced the average compressive strength (1.64 vs. 1.74 MPa) and water absorption (21.95 vs. 22.34%), while the dry density remained comparable.

In summary, Al₂O₃-based spent sorbent can be successfully utilized to produce CLC. Although a slight reduction in compressive strength was observed, the comparable dry density together with the slightly lower water absorption demonstrates that the material can be incorporated into CLC without substantially compromising its engineering performance. These findings provide a practical pathway for the beneficial utilization of carbon capture waste in support of Sustainable Development Goal 12 (Responsible Consumption and Production).

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Physiological Characterization and Generation of Auxotrophic Marker in the Xylose-Fermenting Yeast *Candida shehatae* TISTR 5843 for Bioethanol Production

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Abstract

Candida shehatae TISTR 5843 is a native pentose-fermenting yeast with significant potential for bioethanol production from lignocellulosic biomass; however, detailed insights into its substrate spectrum, fermentation kinetics under high sugar loads, and genetic marker development remain limited. This study evaluated the carbon assimilation profile, xylose fermentation kinetics, and ultraviolet mutagenesis-mediated generation of auxotrophic mutants in *C. shehatae* TISTR 5843. The strain demonstrated a broad carbon assimilation spectrum, exhibiting rapid growth on glucose and xylose, as well as utilization of sucrose, maltose, galactose, and arabinose isomers (L- and D-arabinose). Batch fermentations in YP medium supplemented with 40, 80, and 120 g L⁻¹ xylose revealed robust osmotic tolerance and superior fermentation kinetics compared to *Kluyveromyces marxianus* DMKU 3-1042. Elevating the initial xylose load from 40 to 120 g L⁻¹ progressively enhanced maximum ethanol titers (11.01 to 27.35 g L⁻¹) and ethanol productivities (0.42 to 0.61 g L⁻¹ h⁻¹), achieving the highest productivity of 0.61 g L⁻¹ h⁻¹ under 120 g L⁻¹ xylose with a theoretical yield of 44.60%. Furthermore, UV exposure (45 s; ~5% survival) successfully generated red-pigmented adenine auxotrophic mutant (*ade1/ade2*) at a frequency of 9.1×10^{-5} . These findings demonstrate that *C. shehatae* TISTR 5843 possesses excellent kinetic efficiency under high xylose concentrations, while the newly isolated adenine auxotrophic mutant provide valuable, non-antibiotic selectable markers for future protoplast fusion and genetic engineering strategies.

Keywords: *Candida shehatae*; Xylose fermentation; Ethanol production; UV mutagenesis; Genetic marker

1. Introduction

Biomass-derived bioethanol has attracted considerable attention as a sustainable alternative to fossil fuels. Currently, commercial bioethanol production mainly relies on sugar- and starch-based feedstocks, such as sugarcane, molasses, cassava, rice, and corn. However, the rising demand for these agricultural commodities for both food and fuel has raised critical concerns regarding feedstock availability and production costs. Consequently, lignocellulosic biomass, including sugarcane bagasse, corn stover, rice straw, wood residues, and other agricultural

wastes, has emerged as a promising renewable alternative due to its abundance, low cost, and non-competitive nature with food security.

Lignocellulosic biomass consists primarily of cellulose, hemicellulose, and lignin. Hemicellulose is a heterogeneous polysaccharide wherein xylose serves as the predominant pentose sugar component. Following hydrolysis, xylose is liberated and can be utilized as a carbon source for microbial ethanol fermentation. Therefore, the efficient bioconversion of xylose into ethanol is essential for improving the economic feasibility of lignocellulosic bioethanol production and maximizing the valorization of agricultural residues.

The yeast *Saccharomyces cerevisiae* is widely used for industrial ethanol production because of its high ethanol productivity from hexose sugars [1]. However, it is naturally incapable of fermenting xylose. In contrast, *Kluyveromyces marxianus* is a thermotolerant yeast capable of utilizing xylose, though its native ethanol yield from xylose is relatively low [2]. To overcome these limitations, several native xylose-fermenting yeasts, including *Pachysolen tannophilus*, *Candida shehatae* (syn. *Scheffersomyces shehatae*), *Scheffersomyces stipitis* (formerly *Pichia stipitis*) [3], and *Spathaspora passalidarum*, have been investigated for their superior natural capacity to produce ethanol from xylose [4].

Among these yeasts, *C. shehatae* has received considerable attention due to its high efficiency in converting xylose into ethanol. This yeast has demonstrated excellent potential for lignocellulosic bioethanol production from agricultural residues, such as sugarcane bagasse and rice straw hydrolysates, with previously studies reporting ethanol yields of up to 0.49 g g⁻¹, corresponding to over 90% of the theoretical yield [5]. Despite these promising traits, detailed information regarding the carbon source utilization profiles, growth kinetics, and ethanol production dynamics under varying xylose concentrations remains limited for many specific *C. shehatae* strains.

Beyond physiological characterization, strain improvement via ultraviolet (UV) mutagenesis represents a robust and classical approach for generating genetic diversity in industrial yeasts. UV-induced mutagenesis can successfully generate auxotrophic mutants, which serve as invaluable selectable genetic markers and foundational tools for protoplast fusion, genetic studies, and advanced metabolic engineering applications.

Therefore, the objectives of this study were to evaluate the carbon assimilation profile of *C. shehatae* TISTR 5843, characterize its growth and ethanol production kinetics under a range of initial xylose concentrations in comparison with other xylose-fermenting yeast strains reported previously, and generate stable auxotrophic mutant via UV mutagenesis for use as genetic marker in future strain improvement studies.

2. Materials and methods

2.1 Yeast strains and growth media

The yeast strains used in this study were *Candida shehatae* TISTR 5843, purchased from the Thailand Institute of Scientific and Technological Research (TISTR) and *Kluyveromyces marxianus* DMKU 3-1042, obtained from the Department of Microbiology, Faculty of Science, Kasetsart University. *K. marxianus* DMKU 3-1042 is also deposited in the NITE Biological Resource Center (NBRC) under the deposit numbers NITE BP-283 and NBRC 104275.

Yeasts were routinely cultivated in YM medium consisting of 3 g L⁻¹ yeast extract, 3 g L⁻¹ malt extract, 5 g L⁻¹ peptone, and 10 g L⁻¹ glucose. YNB medium consisted of 6.7 g L⁻¹ yeast nitrogen base and was supplemented with 20 g L⁻¹ of different carbon sources (glucose, galactose, xylose, L-arabinose, D-arabinose, sucrose, or maltose), depending on the assay. YPX medium contained 10 g L⁻¹ yeast extract, 20 g L⁻¹ peptone, and xylose at concentrations of 40, 80, or 120 g L⁻¹. Minimal medium contained 6.7 g L⁻¹ yeast nitrogen base without amino acids

and 20 g L⁻¹ glucose. For auxotrophic selection, minimal medium was supplemented with 12 amino acids (20 mg L⁻¹ uracil, 40 mg L⁻¹ adenine, 20 mg L⁻¹ histidine, 30 mg L⁻¹ lysine, 60 mg L⁻¹ leucine, 40 mg L⁻¹ tryptophan, 20 mg L⁻¹ methionine, 20 mg L⁻¹ arginine, 50 mg L⁻¹ phenylalanine, 200 mg L⁻¹ threonine, 155 mg L⁻¹ valine, and 30 mg L⁻¹ tyrosine). Amino acid drop-out medium was prepared by omitting specific components. Solid media were prepared by adding 15 g L⁻¹ agar [6].

2.2 Carbon assimilation profiling

A single yeast colony was suspended in sterile distilled water and vortexed. The cell suspension was streaked onto YNB agar plates containing 20 g L⁻¹ of the respective carbon source (glucose, galactose, xylose, L-arabinose, D-arabinose, sucrose, or maltose). The plates were incubated at 25°C and monitored regularly for visible colony growth to evaluate carbon assimilation capacity.

2.3 Inoculum preparation and xylose fermentation

For inoculum preparation, yeast strains were cultivated in 20 mL of YM medium in 125 mL Erlenmeyer flasks at 30°C with orbital shaking at 140 rpm for 24 h. Precultures were harvested and inoculated into 100 mL of YP medium containing 40, 80, or 120 g L⁻¹ xylose in 250 mL Erlenmeyer flasks to achieve an initial optical density at 660 nm (OD₆₆₀) of 0.5. Fermentations were performed at 30°C with shaking at 140 rpm. Cell growth was monitored periodically by measuring OD₆₆₀ [7].

2.4 Analytical methods

Fermentation samples were collected at specified time intervals and centrifuged at 6,000 rpm for 5 min. The supernatants were collected and stored at -20°C prior to analysis. Ethanol concentrations were quantified using a gas chromatograph (GC-2030; Shimadzu, Kyoto, Japan) equipped with a flame ionization detector (FID) and a DB-624 capillary column (Agilent Technologies).

2.5 UV mutagenesis and auxotrophic mutant screening

C. shehatae TISTR 5843 was grown overnight in 5 mL of YPD medium at 30°C with shaking at 160 rpm. Cells were harvested by centrifugation at 6,000 rpm for 5 min, and the resuspended in sterile distilled water. Appropriate cell dilutions were spread onto YPD agar plates to yield approximately 1,000 colonies per plate. Plates were exposed to UV irradiation at a distance of 60 cm for 45 s, achieving a survival rate of approximately 5%, followed by incubation at 30°C for 48 h. Surviving colonies were replica-plated onto amino acid drop-out medium and incubated at 30°C for 48 h. Colony capable of growing on complete minimal medium, but failing to grow on the adenine drop-out medium was identified and isolated as auxotrophic mutant. [6].

3. Results and discussion

3.1 Carbon assimilation profile of *C. shehatae* TISTR 5843

The carbon assimilation profile of *C. shehatae* TISTR 5843 is shown in Figure 1. The strain exhibited robust growth on YNB agar supplemented with 20 g L⁻¹ glucose or xylose, with visible colonies appearing after 48 h of incubation. Growth on these carbon sources was comparable to that on the YM control medium. Growth was also observed on sucrose, maltose, and galactose after 72, 96, and 96 h of incubation, respectively. Among all carbon sources tested, L-arabinose and D-arabinose supported the slowest growth, with visible colonies appearing only after 192 h of incubation. These results demonstrate that *C. shehatae* TISTR 5843 can utilize a broad range of carbon sources. Glucose and xylose supported the earliest and

most rapid growth, followed by sucrose, maltose, and galactose, whereas L-arabinose and D-arabinose were utilized more slowly than the other carbon sources under the conditions tested.

The carbon assimilation profile of *C. shehatae* TISTR 5843 was generally consistent with those reported for other established xylose-fermenting yeasts. The strain efficiently utilizes both glucose and xylose, similar to *S. stipitis*, *Pa. tannophilus* [8], *Sp. passalidarum* [9], and *K. marxianus* DMKU 3-1042 [10]. This characteristic represents a major advantage over conventional *S. cerevisiae*, which is unable to naturally assimilate xylose [11], making *C. shehatae* TISTR 5843 highly suitable for lignocellulosic bioethanol production where glucose and xylose predominate. Although *C. shehatae* TISTR 5843 assimilated both L-arabinose and D-arabinose, these pentoses required a prolonged incubation period to support detectable growth compared with the other carbon sources tested. A similar carbon assimilation pattern on arabinose has been observed in *S. stipitis* [12], whereas *Sp. passalidarum* exhibits a stronger capacity for L-arabinose utilization [13], and *K. marxianus* DMKU 3-1042 showed only weak growth [10]. Furthermore, *C. shehatae* TISTR 5843 successfully utilized galactose, sucrose, and maltose, displaying a broad substrate spectrum comparable to *S. stipitis* [14] and *Sp. passalidarum* [9, 15]. In contrast, *Pa. tannophilus* exhibits only weak galactose assimilation [8] and fails to assimilate sucrose or maltose [16]. Overall, the carbon utilization profile of *C. shehatae* TISTR 5843 closely mirrors those of top-performing native pentose-fermenting yeasts, reinforcing its strong potential for lignocellulosic biomass conversion.

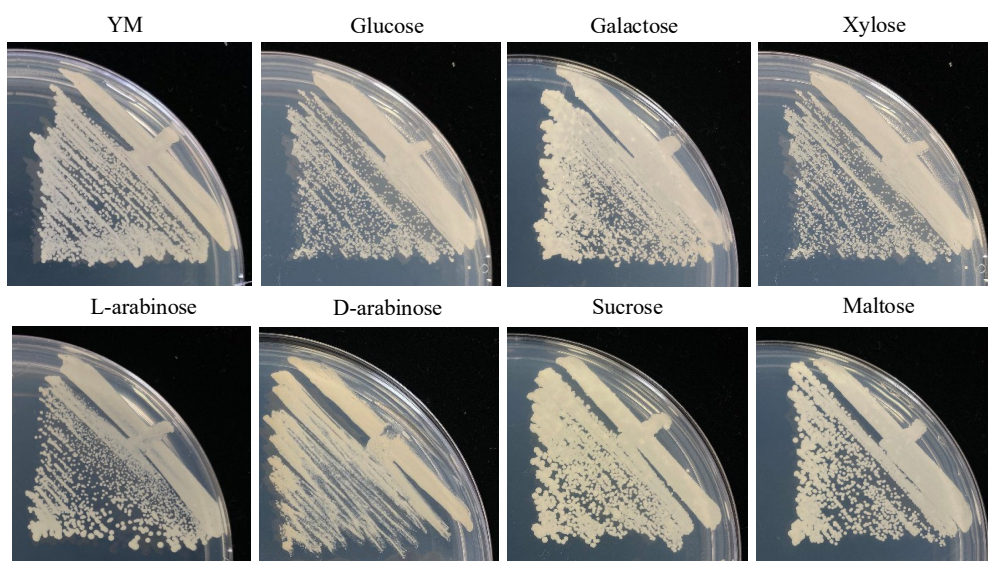


Figure 1 Carbon assimilation profile of *C. shehatae* TISTR 5843 on YNB agar supplemented with 20 g L⁻¹ of different carbon sources. Plates were incubated at 25°C until visible growth was observed: 48 h for YM, glucose, and xylose; 72 h for sucrose; 96 h for galactose and maltose; and 192 h for L-arabinose and D-arabinose. Growth on YM agar served as the positive control.

3.2 Effect of xylose concentration on the growth kinetics of *C. shehatae* TISTR 5843

The growth profiles of *C. shehatae* TISTR 5843 cultivated in YP medium supplemented with 40, 80, and 120 g L⁻¹ xylose at 30°C under shaking conditions (140 rpm) are shown in Figure 2a–c. *C. shehatae* TISTR 5843 grew successfully across all tested xylose concentrations, with cell growth increasing progressively throughout the cultivation period. Elevating the initial xylose concentration from 40 to 80 g L⁻¹ increased the maximum specific growth rate from 0.19 to 0.23 h⁻¹ (Table 1), reflecting accelerated growth during the early

exponential phase. However, when the initial xylose concentration was further increased to 120 g L⁻¹, the specific growth rate decreased slightly to 0.18 h⁻¹, although steady cell growth was maintained over time. These results demonstrate that *C. shehatae* TISTR 5843 exhibits strong tolerance to osmotic stress and maintains efficient growth kinetics across a broad spectrum of initial xylose concentrations.

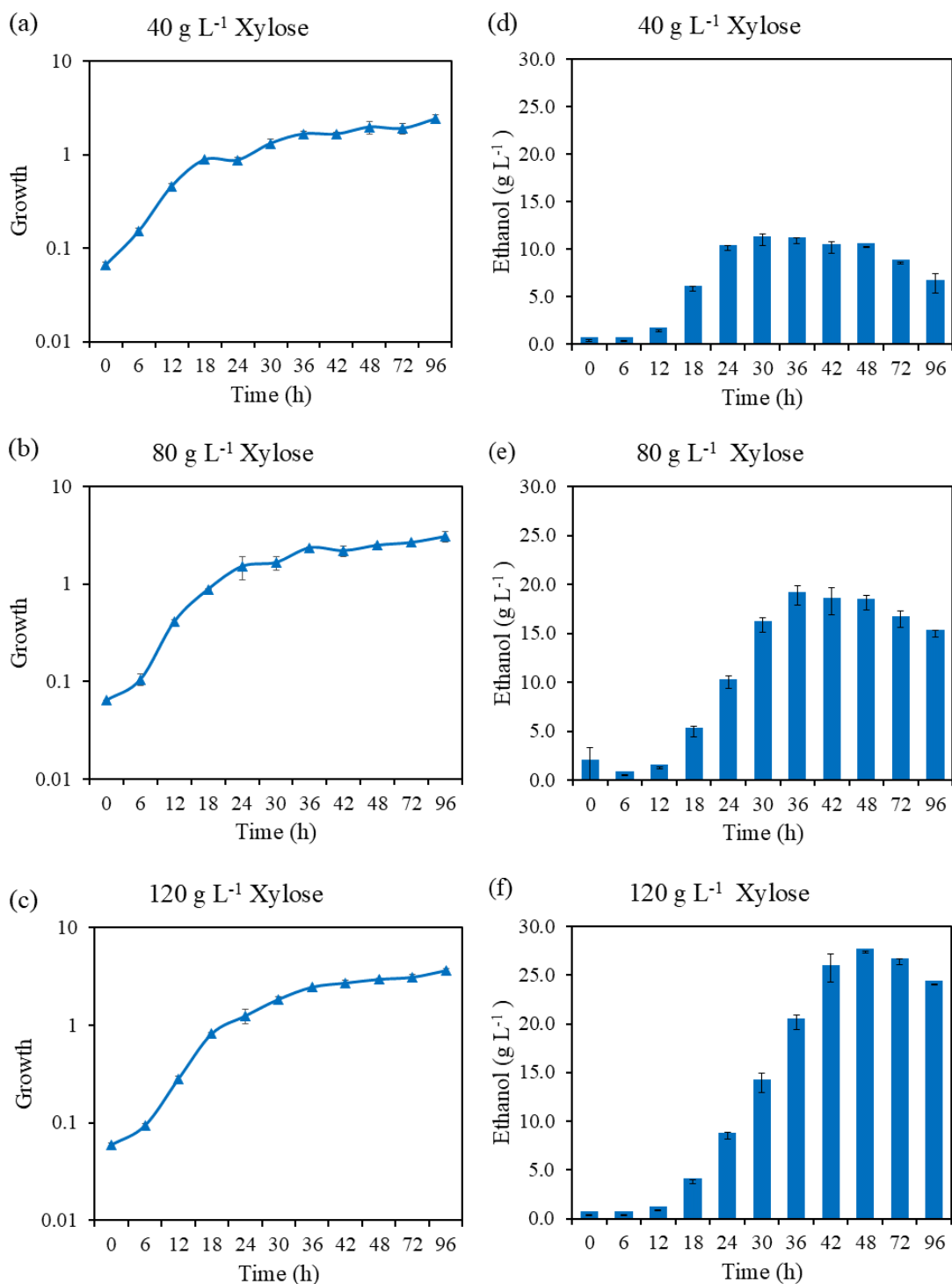


Figure 2 Growth and ethanol production profiles of *C. shehatae* TISTR 5843 cultivated in YP medium supplemented with 40, 80, or 120 g L⁻¹ xylose at 30°C under a shaking condition (140 rpm).

Table 1 Parameters obtained in YP medium supplemented with various concentrations of xylose at 30°C under a shaking condition (140 rpm).

Strain	Xylose (g L ⁻¹)	$\mu_{\max}$ (h ⁻¹)	Max ethanol concentration (g L ⁻¹)	Ethanol productivity (g L ⁻¹ h ⁻¹)	% Theoretical yield
<i>C. shehatae</i>	40	0.19 ± 0.02	11.01 ± 0.06 (30)	0.42 ± 0.01 (24)	53.86 ± 2.94
TISTR 5843	80	0.23 ± 0.03	18.84 ± 0.99 (36)	0.53 ± 0.02 (36)	46.10 ± 2.42
	120	0.18 ± 0.00	27.35 ± 0.07 (48)	0.61 ± 0.03 (42)	44.60 ± 0.12

Values in parenthesis represent cultivation times, $\mu_{\max}$, maximum specific growth rate, ±SD from three independent experiments.

3.3 Ethanol fermentation kinetics of *C. shehatae* TISTR 5843 and comparative literature analysis

The ethanol production profiles of *C. shehatae* TISTR 5843 during xylose fermentation are shown in Figure 2d–f. At an initial xylose concentration of 40 g L⁻¹ (Figure 2d), ethanol production increased rapidly during the first 18–30 h, reaching a maximum concentration of 11.01 g L⁻¹ at 30 h before gradually declining, with a productivity of 0.42 g L⁻¹ h⁻¹ and a theoretical yield of 53.86% (Table 1). At 80 g L⁻¹ xylose (Figure 2e), the maximum ethanol concentration reached 18.84 g L⁻¹ at 36 h, yielding an ethanol productivity of 0.53 g L⁻¹ h⁻¹ and a 46.10% theoretical yield (Table 1). Escalating the initial xylose concentration to 120 g L⁻¹ (Figure 2f) resulted in continuous ethanol accumulation that peaked at 27.35 g L⁻¹ at 48 h, achieving the highest ethanol productivity of 0.61 g L⁻¹ h⁻¹ with a 44.60% theoretical yield (Table 1). Evidently, increasing initial xylose concentrations positively enhanced ethanol productivity while causing a slight decline in theoretical yield percentage. In contrast, *K. marxianus* DMKU 3-1042 produced negligible amounts of ethanol across all tested conditions, with maximum ethanol concentrations remaining below 2.3 g L⁻¹ and productivities between 0.02 and 0.03 g L⁻¹ h⁻¹ (Table 2). Overall, *C. shehatae* TISTR 5843 demonstrated substantially superior ethanol production capacity and kinetic efficiency compared to *K. marxianus* DMKU 3-1042.

A comparison with published literature (Table 2) demonstrates that *C. shehatae* TISTR 5843 exhibits competitive or superior fermentation kinetics relative to many established xylose-fermenting yeasts. Among *Scheffersomyces (Pichia) stipitis* strains, CBS 6054 achieved 24.3 g L⁻¹ ethanol from 60 g L⁻¹ xylose with a lower productivity of 0.20 g L⁻¹ h⁻¹ [17], whereas NRRL Y-7124 attained 0.62 g L⁻¹ h⁻¹ from 50 g L⁻¹ xylose [18]. Notably, *C. shehatae* TISTR 5843 reached a comparable productivity of 0.61 g L⁻¹ h⁻¹ under a much higher sugar load of 120 g L⁻¹ xylose. At 40 g L⁻¹ xylose, the ethanol productivity of *C. shehatae* TISTR 5843 (0.42 g L⁻¹ h⁻¹) was also on par with *S. stipitis* CBS 5773 (0.41 g L⁻¹ h⁻¹) [19].

Compared with *Sp. passalidarum* strains, CBS 10155 produced 20.5 g L⁻¹ ethanol with a higher productivity (0.85 g L⁻¹ h⁻¹) at 40–50 g L⁻¹ xylose [20], whereas strain CMUWF1–2 yielded 8.4 g L⁻¹ ethanol with an ethanol productivity of 0.34 g L⁻¹ h⁻¹ from 20 g L⁻¹ xylose [13].

Among previously reported *C. shehatae* strains, NCL-3501 achieved higher ethanol concentrations (14.0 and 30.0 g L⁻¹) at 40 and 80 g L⁻¹ xylose, respectively [21], but exhibited lower productivities (0.29 and 0.25 g L⁻¹ h⁻¹) than TISTR 5843 (0.42 and 0.53 g L⁻¹ h⁻¹). Compared with *Scheffersomyces (Candida) shehatae* TTC79, strain TISTR 5843 exhibited a higher ethanol productivity (0.42 g L⁻¹ h⁻¹ at 40 g L⁻¹ xylose) than TTC79 (0.36 g L⁻¹ h⁻¹ at 50 g L⁻¹ xylose) [22]. At 80 g L⁻¹ xylose, *S. shehatae* TTC79 achieved a higher maximum ethanol concentration (29.0 g L⁻¹) and productivity (0.61 g L⁻¹ h⁻¹) [22] than TISTR 5843 (18.84 g L⁻¹

and 0.53 g L⁻¹ h⁻¹, respectively). However, *C. shehatae* TISTR 5843 maintained efficient kinetic performance up to a significantly higher initial sugar concentration of 120 g L⁻¹ xylose, reaching an equivalent maximum productivity of 0.61 g L⁻¹ h⁻¹ with an ethanol accumulation of 27.35 g L⁻¹. Furthermore, *C. shehatae* TISTR 5843 outperformed *Pa. tannophilus* NRRL Y-2460 (7.7 g L⁻¹ ethanol; 0.10 g L⁻¹ h⁻¹ productivity) [19]. The poor xylose fermentation performance observed for *K. marxianus* DMKU 3-1042 aligns with findings by Kwon et al. (2018) for *K. marxianus* KCTC 17694 (2.9 g L⁻¹ ethanol; 0.04 g L⁻¹ h⁻¹ productivity at 80 g L⁻¹ xylose) [23].

Taken together, these comparative findings confirm that *C. shehatae* TISTR 5843 is a highly promising candidate for the bioconversion of xylose into ethanol, offering clear kinetic advantages under high xylose concentrations.

Table 2 Comparison of ethanol production by xylose-fermenting yeasts reported in previous studies.

Strain	Xylose (g L ⁻¹)	Temperature (°C)	Shaking (rpm)	Max ethanol concentration (g L ⁻¹)	Ethanol productivity (g L ⁻¹ h ⁻¹)	Reference
<i>P. stipitis</i> CBS 6054	60	30	100	24.3	0.20	[17]
<i>S. stipitis</i> NRRL Y-7124	50	30	200	15.0	0.62	[18]
<i>P. stipitis</i> CBS 5773	40	Room temp.	200	15.1	0.41	[19]
<i>Sp. passalidarum</i> CBS 10155	40–50	30	200	20.5	0.85 ^a	[20]
<i>Sp. passalidarum</i> CMUWF1–2	20	30	160	8.4	0.34	[13]
<i>Pa. tannophilus</i> NRRL Y-2460	40	Room temp.	200	7.7	0.10	[19]
<i>C. shehatae</i> NCL-3501	40	30	150	14.0	0.29	[21]
	80	30	150	30.0	0.25	[21]
<i>S. shehatae</i> TTC79	50	30	100	17.1	0.36 ^a	[22]
	80	30	100	29.0	0.61 ^a	[22]
<i>K. marxianus</i> KCTC 17694	80	30	100	2.9	0.04 ^a	[23]
<i>K. marxianus</i> DMKU 3-1042	40	30	140	2.1	0.03	This study
	80	30	140	2.3	0.02	This study
	120	30	140	1.9	0.02	This study

^a calculated by the authors (not given directly in the references)

3.4 UV mutagenesis and isolation of adenine auxotrophic mutants

C. shehatae TISTR 5843 was subjected to UV mutagenesis with an exposure time of 45 s, resulting in a survival rate of approximately 5%. The surviving colonies were screened for auxotrophic mutants using the replica-plating method on amino acid drop-out medium. The adenine auxotrophic mutant was successfully isolated, corresponding to an auxotrophic frequency of 9.1×10⁻⁵. This mutant grew normally on the complete medium (master plate) but failed to grow on the adenine drop-out medium, confirming its auxotrophic phenotype.

In addition, this mutant characteristically accumulated a red pigment in its vacuoles, resulting in the formation of distinct red-colored colonies, a phenotype typically caused by defects in the *ADE1* or *ADE2* genes [24]. The adenine auxotrophic strain obtained in this study can serve as valuable genetic and selectable markers for advanced strain improvement. For instance, in protoplast fusion, such markers enable the efficient screening and isolation of

fusants from un-fused parental cells on selective minimal media. This strategy has been successfully applied to improve industrially important traits, such as inhibitor tolerance and ethanol productivity, in related xylose-fermenting yeasts like *Sp. passalidarum* [25]. Furthermore, this mutant can be utilized as selectable marker in genetic transformation through complementation with *ADE* marker genes. This approach provides a viable alternative to antibiotic-resistance markers, thereby improving selection efficiency in wild-type yeasts while mitigating biosafety concerns associated with antibiotic resistance [26].

4. Conclusion

This study demonstrates that *Candida shehatae* TISTR 5843 is a highly versatile and robust yeast strain with significant potential for bioethanol production from lignocellulosic biomass. The strain exhibited a broad carbon assimilation spectrum, utilizing both hexoses and pentoses with rapid growth observed on glucose and xylose, alongside the ability to assimilate sucrose, maltose, galactose, and arabinose isomers. Furthermore, *C. shehatae* TISTR 5843 displayed strong osmotic tolerance and superior fermentation kinetics across a wide range of xylose concentrations. Increasing the initial xylose load from 40 g L⁻¹ to 120 g L⁻¹ progressively enhanced both maximum ethanol titer and productivity, reaching 27.35 g L⁻¹ and 0.61 g L⁻¹ h⁻¹, respectively—a performance that competitively rivals established xylose-utilizing yeasts and substantially surpasses *K. marxianus* DMKU 3-1042. Beyond its natural kinetic advantages, UV mutagenesis successfully yielded adenine auxotrophic mutant (*ade1/ade2*) characterized by a distinctive red-pigmented phenotype at an isolation frequency of 9.1×10^{-5} . Together, these robust fermentation capabilities under high sugar loads and the development of valuable adenine auxotrophic selectable marker establish *C. shehatae* TISTR 5843 as an exceptional platform strain for future genetic modification and protoplast fusion strategies aimed at industrial bioethanol optimization.

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Sustainable Bio-Cosmetic Sheet Materials: Characterization of Mulberry Paper Across Basis Weight and Treatment Placement

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Abstract

The growing global trend toward waterless cosmetics is driving demand for sustainable, bio-based sheet materials as alternatives to conventional liquid and aerosol formats. Mulberry paper, derived from the bast fiber of *Broussonetia papyrifera*, is a renewable cellulose-based substrate with strong potential to meet this demand; however, no systematic study has yet characterized its microstructure across both basis weight and chemical treatment placement (pre- vs. post-treatment) simultaneously. This study examined mulberry paper at three basis weights (20, 25, and 30 gsm) using scanning electron microscopy (SEM) in top-view and cross-sectional views, together with attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR), to compare wet-end chemical addition with post-formation surface coating. SEM results revealed a consistent structural trade-off between fiber-network porosity and the number of overlapping fiber layers as basis weight increased, while ATR-FTIR identified consistent peak shifts in the 1600-1617 cm⁻¹ and 1500-1540 cm⁻¹ regions that may serve as candidate signature peaks for distinguishing treatment placement. Signal sensitivity decreased markedly at higher basis weight, reflecting the limited penetration depth of the ATR technique. As a preliminary, descriptive characterization, this study did not include mechanical or functional performance testing; rather, it establishes structural and spectroscopic baseline data for mulberry paper that may inform the future development of cellulose-based sheet materials, including potential applications in waterless cosmetic products.

Keywords: Mulberry paper; SEM; ATR-FTIR; Basis weight; Treatment placement

1. Introduction

Increasing awareness of sustainability in the cosmetics and personal care industry is driving a transition from liquid and aerosol-spray formats toward waterless beauty [1], which reduces the direct water footprint throughout a product's life cycle, lowers the need for preservatives, and increases active-ingredient concentration in the absence of a water diluent [1]. The global waterless cosmetics market was valued at approximately USD 10.85 billion in 2023 and is projected to reach USD 23.90 billion by 2031, driven by consumer demand for sustainable and environmentally friendly products [2]. This trend is an important driver for the search for new bio-based substrates suitable for development into sheet-based products for this growing market.

Bio-based cellulose materials derived from renewable resources have attracted increasing

interest as alternatives to synthetic materials that are difficult to biodegrade [3], particularly in sheet-based platforms that can be engineered to have multi-functional properties through chemical treatment during manufacturing. This trend has created a need to systematically understand the structure of cellulose-based substrates, both in terms of structural parameters (e.g., basis weight) and treatment-process parameters (e.g., the placement of chemical addition during production).

Mulberry paper, produced from the bast fiber of *Broussonetia papyrifera*, is a bio-based substrate with a cellulose structure well suited to development into a multi-functional sheet material, owing to its fiber network, which can be treated to achieve wet strength, tactile softness, or other surface properties as required [4]. However, although mulberry paper has long been used in handicraft and packaging contexts [5], no systematic structural analysis has yet covered both the effect of basis weight and the effect of chemical treatment placement (pre- vs. post-treatment) in this substrate.

Prior studies on mulberry paper have mostly focused on the fiber-level morphology of the raw material, such as fiber length, width, and Runkel ratio across cultivars and stem positions [4], or the feasibility of processing mulberry fiber into cotton-blended yarns [5] and its overall industrial utilization [6]. However, no study has yet analyzed the structural changes of mulberry paper at the sheet level across different basis weights, together with spectroscopic evidence of chemical treatment placement, within a single study. This represents the knowledge gap that the present study aims to address, and distinguishes this work from prior studies that examined fiber properties and utilization separately.

This study therefore aims to investigate and explain the microstructural and spectroscopic changes of mulberry paper associated with basis weight and chemical treatment placement, guided by the following research questions: RQ1 - How does the microstructure of mulberry paper (fiber-network porosity in top view and fiber-layer overlap in cross-section) change across different basis weights (20, 25, and 30 gsm)? RQ2 - Does the placement of chemical treatment during manufacturing (wet-end addition prior to sheet formation vs. surface coating after sheet formation) leave distinguishable spectroscopic evidence (ATR-FTIR), and if so, how? Answering these research questions provides preliminary, descriptive characterization data rather than quantitative functional performance testing or statistical hypothesis testing.

2. Materials and Methods

2.1 Materials and Sample Groups

The substrate used in this study was mulberry paper produced from the bast fiber of *Broussonetia papyrifera*, processed by conventional alkali scouring to remove lignin and non-cellulosic impurities [7]. Three basis weights were studied: 20, 25, and 30 grams per square meter (gsm). Two sample dimensions were analyzed: (1) the basis-weight dimension, using two SEM sample groups - pre-treatment (code pre_2, referring to paper with chemicals added in the wet-end system during sheet formation) and post-treatment (code post_3, referring to paper coated with chemicals on the surface after sheet formation); and (2) the treatment-placement dimension, using five ATR-FTIR sample groups - post_1 (untreated control), pre_1 (wet-strength agent added in the wet-end system), post_1wet_strength (the same agent coated on the surface), pre_2 (wet-strength agent combined with a softness agent added in the wet-end system), and post_3 (both agents coated on the surface). The selection of these two treatment-placement sample groups is based on the working mechanisms of wet-strength and surface-conditioning agents reported in the literature [8, 9, 10].

2.2 Scanning Electron Microscopy (SEM) Imaging

All sample groups were imaged in both top-view and cross-sectional views at 500x and 1,000x magnification to examine the overall fiber-network structure and fiber-layer overlap, and at 5,000x and 10,000x magnification to examine fine fiber-surface detail and the presence of microscale impurities. Imaging covered five areas per sample per magnification level to verify intra-sheet consistency before representative images were compared across basis weights. This imaging and fiber-bonding analysis approach is consistent with methods used in prior pulp-and-paper structural research [11, 12].

2.3 ATR-FTIR Spectroscopic Analysis

ATR-FTIR spectra of all five sample groups were compared over the wavenumber range of 1500-1800 cm^{-1} , corresponding to carbonyl ($\text{C}=\text{O}$), $\text{C}=\text{C}$, and asymmetric carboxylate functional groups [13]. Comparisons were structured in three ways to isolate confounding variables: (1) comparison of the chemical effect alone, with treatment placement held constant (e.g., post_1wet_strength vs. post_1); (2) comparison of the treatment-placement effect, with the chemical formulation held constant (e.g., pre_1 vs. post_1wet_strength); and (3) comparison of the basis-weight trend within each sample group.

2.4 Scope of Analysis

All analyses in this article are qualitative, comprising peak identification, peak-position shifts, and descriptive comparison of SEM micrographs only. No mechanical testing (e.g., tensile strength, bending stiffness), functional performance measurement, or statistical hypothesis testing was performed.

3. Results and Discussion

The instrumental characterization results in this article are presented in four parts: (1) the structural characteristics of mulberry paper across basis weight, examined by SEM; (2) spectroscopic evidence of the treatment-placement effect, examined by ATR-FTIR; (3) structural consistency supporting the above two parts; and (4) practical implications of the findings for treatment-placement selection. All results are presented descriptively to establish a structural and spectroscopic baseline for subsequent quantitative analysis.

3.1 Structure of Mulberry Paper Across Basis Weight (SEM)

Top-view SEM micrographs of mulberry paper at all three basis weights showed a clearly consistent trend: the 20 gsm sheet exhibited the most open fiber network, with the widest inter-fiber spacing and the fewest fibers crossing per field of view, while the 30 gsm sheet exhibited the densest network, with multiple overlapping fibers within the same field of view and markedly reduced spacing; the 25 gsm sheet fell between these two conditions (Figure 1). This trend can be explained by the increasing fiber content per unit area with basis weight, which increases the number of fiber intersections and overlaps within the plane. The same trend was consistently observed in cross-sectional view, where the number of overlapping fiber layers increased progressively from 20 to 25 to 30 gsm, consistent with the increasing sheet thickness (Figure 2). Because higher basis weight results from increased fiber content per unit area during sheet formation, the number of overlapping fiber layers in cross-section increases as a direct consequence of the manufacturing process, a mechanism consistent with the general relationship between basis weight and sheet density/porosity reported in the literature [14, 15, 16]. At higher magnification (10,000x), used to examine fine fiber-surface detail, longitudinal striations characteristic of bast-fiber cell walls were clearly observed at every basis weight, with no significant qualitative difference in surface striation among the three levels, except for small

particles adhering to the fiber surface in isolated areas of the 20 gsm sheet only (Figure 3). Examination of images from all five areas per sample confirmed that these trends were genuine sheet characteristics rather than artifacts of a specific selected area. A comparative summary is presented in Table 1. The observed relationship between structural porosity and basis weight is also consistent with the relationship between structure and mechanical properties of paper reported in the literature [17].

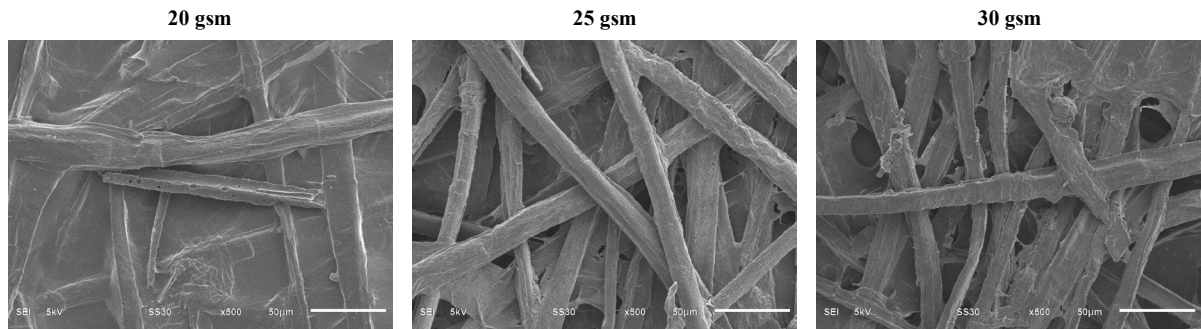


Figure 1 Top-view SEM micrographs (500x) comparing mulberry paper at 20, 25, and 30 gsm

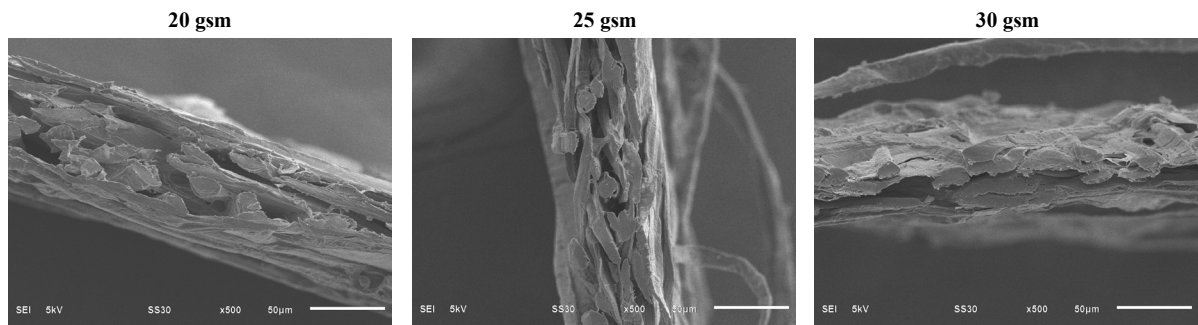


Figure 2 Cross-sectional SEM micrographs (500x) comparing mulberry paper at 20, 25, and 30 gsm

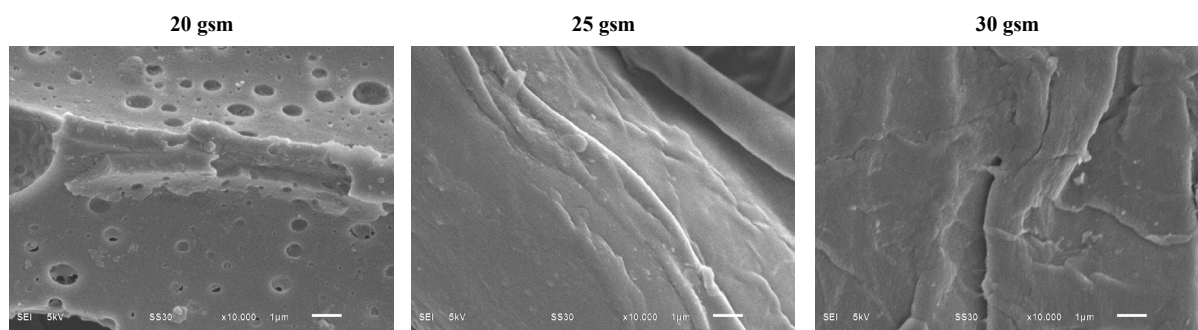


Figure 3 Fiber-surface SEM micrographs (10,000x) comparing mulberry paper at 20, 25, and 30 gsm

Table 1 Qualitative structural trend of mulberry paper across basis weight, with fiber-level literature reference values

Basis Weight (gsm)	Top View - Qualitative Trend	Cross Section - Qualitative Trend	Relative Porosity Ranking
20	Most open fiber network; widest inter-fiber spacing	Fewest overlapping fiber layers; thinnest sheet	Highest (Most porous)
25	Intermediate density; uniform across sheet	Intermediate fiber-layer overlap	Intermediate
30	Densest fiber network; narrowest inter-fiber spacing	Most overlapping fiber layers; thickest sheet	Lowest (Least porous)

Values in Table 1 represent a qualitative, relative ranking based on SEM observation only, not directly measured numerical values (e.g., pore size in μm or porosity in %). For contextual reference at the single-fiber level, prior studies on the morphology of *B. papyrifera* bast fiber report fiber lengths of 7.4-9.9 mm, fiber widths of 17-27 μm , and Runkel ratio values of 1.10-2.08 depending on cultivar and stem position [4]. These are single-fiber-level literature values and are not measurements taken from the SEM images of this sample set; they are presented solely for comparative context and are not a result of this study.

3.2 Evidence of Treatment-Placement Effect: Pre- vs. Post-Treatment (ATR-FTIR)

Spectroscopic evidence from ATR-FTIR provided additional information helping to more clearly separate the effect of treatment placement from the effect of chemical formulation. When comparing samples treated with wet-strength agent alone between the two placement modes at 20 gsm, the wet-end-treated sample showed uniformly distributed peaks at up to 11 positions within the 1500-1800 cm^{-1} range, consistent with the mechanism by which the agent penetrates the fiber structure while the fiber is swollen under wet conditions, as reported in the literature [10, 18]; whereas the surface-coated sample of the same agent showed new peaks specifically at 1506.6, 1520.8, and 1539.2 cm^{-1} , which were absent in the wet-end-treated sample (Figure 4). This surface-specific peak pattern is consistent with the thin-film formation mechanism typical of surface coatings on porous materials [19]. When the softness agent was added together with the wet-strength agent, the peak-position difference between the two placement modes became noticeably smaller (Figure 5), consistent with the observation that the softness agent may cover or modify the surface, thereby reducing the resolution of the overall ATR signal, a behavior also observed in surface coating films containing multiple conditioning agents [20].

When treatment placement was held constant to examine the chemical effect alone, a prominent negative peak at 1610-1617 cm^{-1} appeared consistently at both 20 and 25 gsm, which may indicate that this region is where the wet-strength agent affects the chemical structure of mulberry paper, consistent with the bonding mechanism between the wet-strength agent and hydroxyl groups on the cellulose surface reported in the literature [8, 9] (Figure 6). However, when considering the trend of signal magnitude across basis weight, the magnitude of the difference decreased markedly at 30 gsm, remaining at only approximately ± 0.5 -0.7 units across the wavenumber range considered (Figure 7), indicating a significant limitation of the ATR-FTIR technique in detecting chemicals distributed deep within thick paper, since this technique can only detect signal within a surface depth of a few micrometers, a limitation consistent with the general behavior of thin-film formation on porous material surfaces [19].

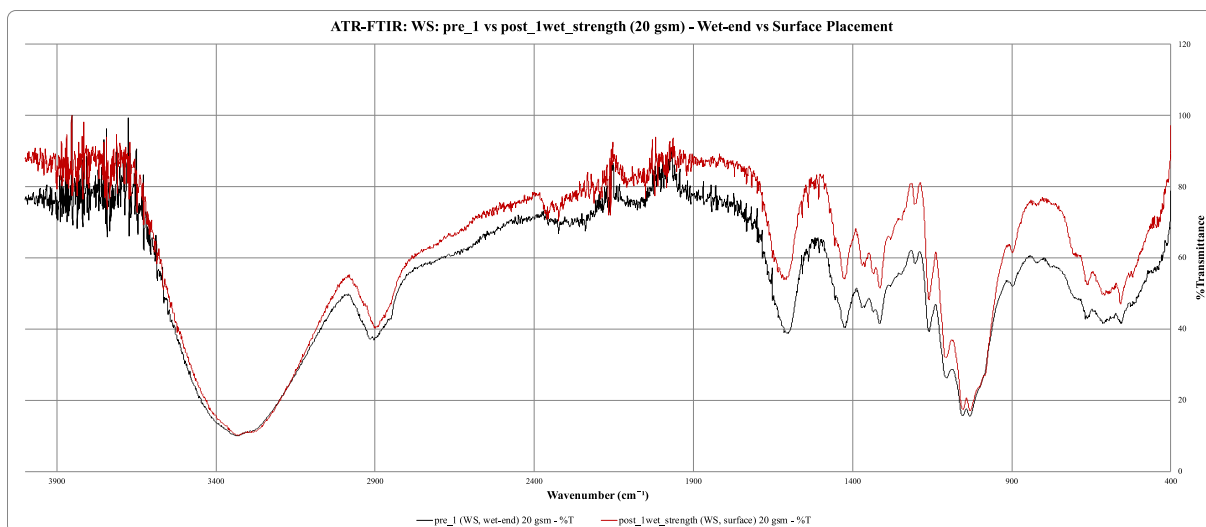


Figure 4 ATR-FTIR spectra showing the treatment-placement effect for wet-strength agent alone at 20 gsm

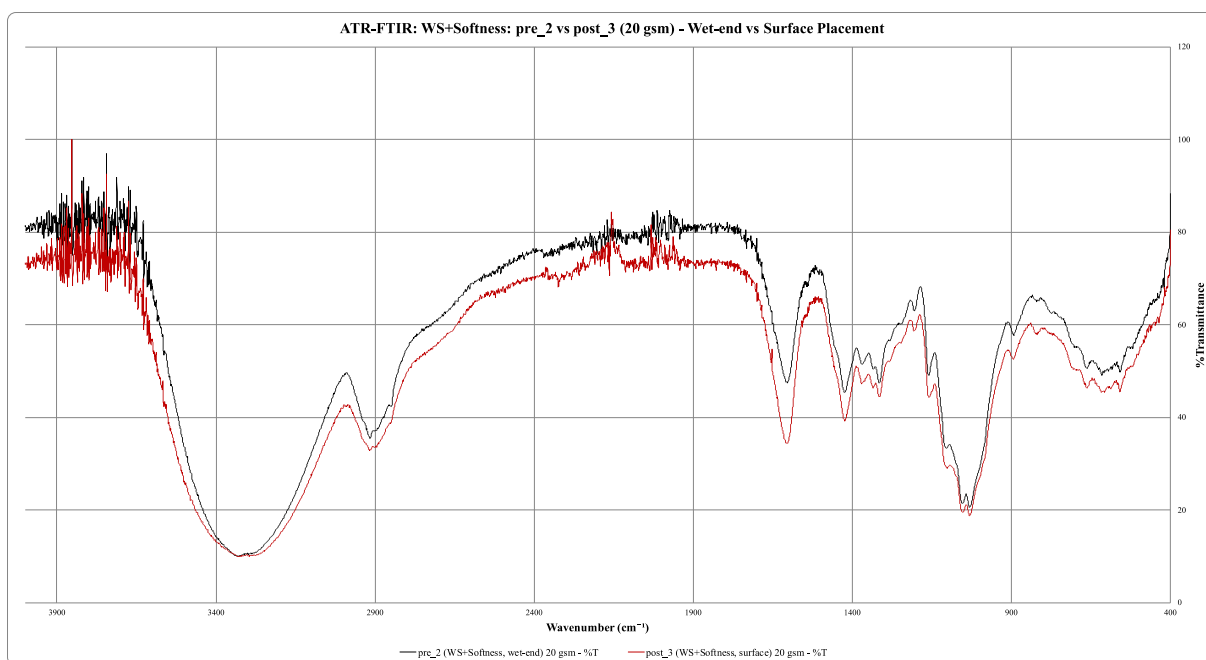


Figure 5 ATR-FTIR spectra showing the treatment-placement effect for wet-strength + softness agents at 20 gsm

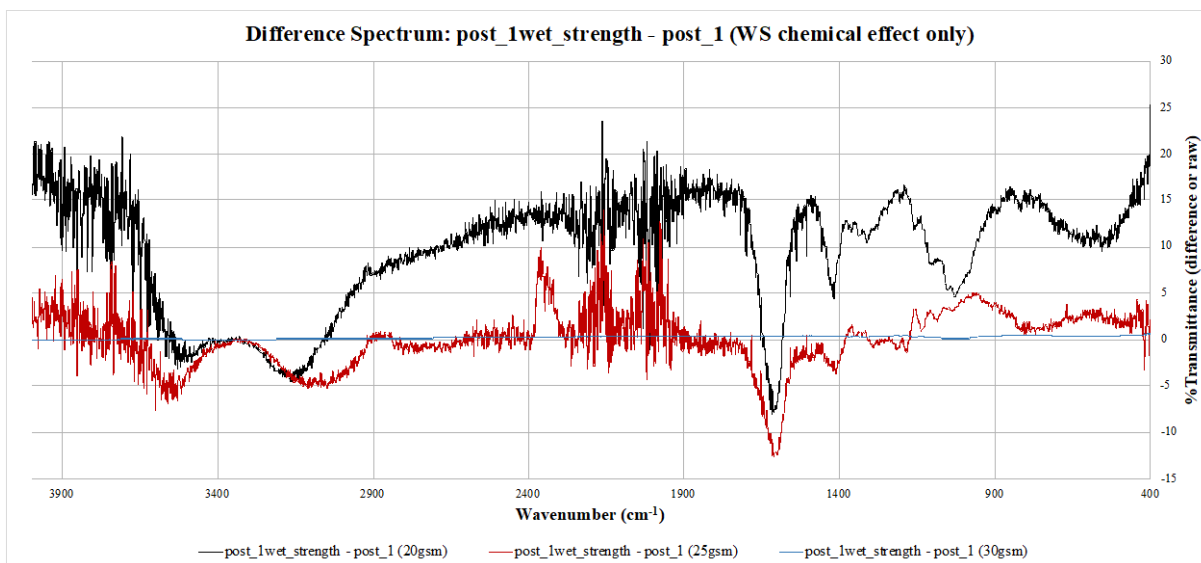


Figure 6 Difference spectrum showing the chemical effect of wet-strength agent alone

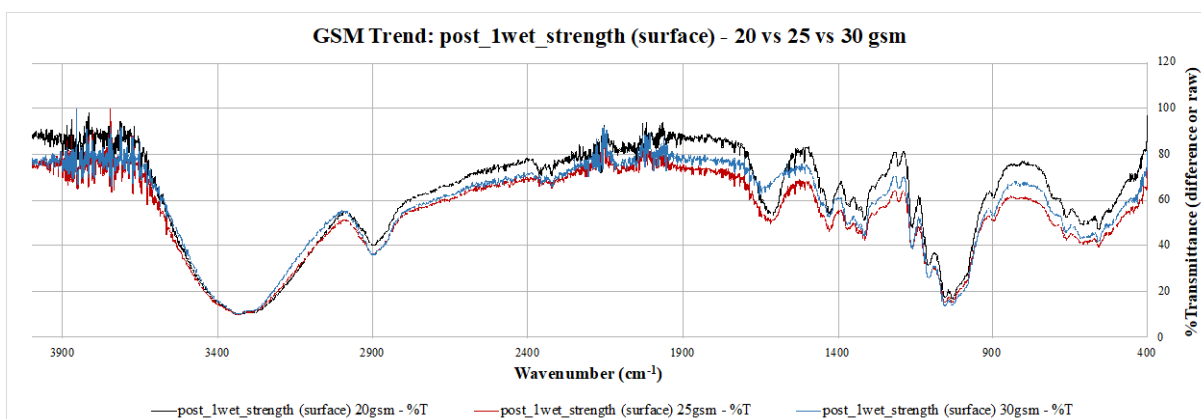


Figure 7 Basis-weight trend of the FTIR signal for the surface-coated wet-strength sample group

3.3 Structural Consistency (SEM) Supporting the FTIR Results

To examine whether the basis-weight structural trend remained consistent after chemical treatment, cross-sectional SEM micrographs of the post-treatment sample group were compared with those of the pre-treatment sample group. The underlying trend - decreasing fiber-network porosity and increasing fiber-layer overlap with increasing basis weight - appeared identical both before and after treatment (Figure 8). However, SEM alone cannot confirm whether the chemical treatment affects structure at a deeper level; this would require quantitative data from mechanical testing or higher-magnification imaging in future analysis.

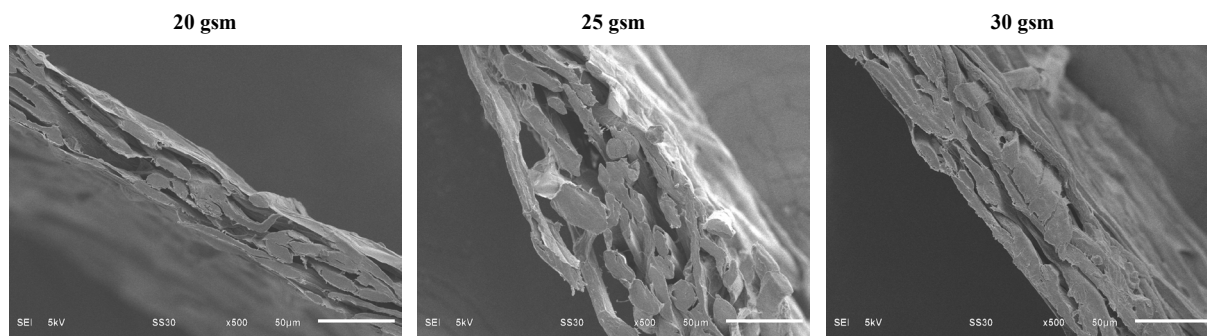


Figure 8 Cross-sectional SEM micrographs (500x) of the post-treatment group comparing 20, 25, and 30 gsm

3.4 Implications for Treatment-Placement Selection

Although the underlying structure of mulberry paper does not change direction regardless of whether the chemical is added prior to sheet formation (pre-treatment) or coated onto the surface after sheet formation (post-treatment), the differing chemical-distribution patterns found in Section 3.2 may have practical implications worth considering for further material development. Wet-end addition (pre-treatment) produced more uniformly distributed signal across all basis weights studied, which may indicate that the agent penetrates throughout the paper body rather than concentrating only at the surface [8, 10]; this approach may therefore be suitable for quality control in large-scale (scale-up) manufacturing that requires consistent chemical distribution across the sheet. Conversely, post-treatment (surface coating) produced a clearer and more concentrated signal in thinner paper, but detectability decreased markedly as basis weight increased, a limitation commonly observed in coating processes on porous materials [19, 20], which may need to be weighed against manufacturing cost and the amount of waste that may arise from a separate coating step, compared with mixing the agent during the wet-end stage, which may reduce the number of production steps [9].

4. Conclusion

The instrumental characterization presented in this article shows that the structure of mulberry paper made from the bast fiber of *Broussonetia papyrifera* changes with basis weight in a direction that is consistent in both top-view and cross-sectional views, with fiber-network porosity decreasing and the number of overlapping fiber layers increasing as basis weight increases from 20 to 30 gsm, a trend that appears consistently both before and after chemical treatment, consistent with the structure-mechanical-property relationship of paper reported in the literature [17]. In terms of spectroscopic evidence, the ATR-FTIR results identified two regions with clear potential as signature peaks for treatment placement, namely $\sim 1600\text{--}1617\text{ cm}^{-1}$ and $\sim 1500\text{--}1540\text{ cm}^{-1}$, consistent with the functional-group assignments reported in the literature [13], appearing consistently when relevant confounding variables were controlled. However, an important limitation to note is the markedly reduced sensitivity of the ATR-FTIR signal in samples with high basis weight, a limitation inherent to the technique, which can only detect a surface depth of a few micrometers.

This qualitative study provides two important pieces of baseline information for the further development of mulberry-paper-based cellulose sheet materials. First, structural evidence showing a trade-off trend between porosity and sheet density across basis weight, which serves as preliminary information for basis-weight selection in subsequent stages; however, identifying which basis weight is "optimal" would require quantitative mechanical and

functional test results, which are not available in this study. Second, peak positions that can serve as qualitative indicators of treatment placement in follow-up studies.

Future Directions: The structural and spectroscopic data presented in this article may serve as a starting point for further development of mulberry paper into a multi-functional bio-sheet material in the context of waterless cosmetics, a growing industry trend. This linkage represents only a potential future research direction and is not a conclusion drawn directly from the qualitative results of this study, since no functional performance testing relevant to actual use (e.g., oil/sebum absorption capacity, tactile feel on skin or hair) has yet been conducted. Confirming suitability for application in this product category will therefore require further research that directly measures functional performance.

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Lignin-based Hydrochar Production from Spent Coffee Grounds: Effect of Hydrothermal Carbonization Temperature and Time on Yield and Oxygenated Functional Groups of Hydrochar

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Abstract

This research aims to synthesize a lignin-based hydrochar from spent coffee grounds (SCGs) via hydrothermal carbonization (HTC) for application as a catalyst support material. The study began with lignin extraction using ammonium hydroxide solutions at concentrations of 6%, 8%, and 10%. The results revealed that the ammonium hydroxide concentration had no significant effect on the lignin yield; therefore, the 10% concentration was selected for the subsequent HTC process. The HTC started with investigating the temperature (200, 220, and 240 °C for 24 hours). The results indicated that temperature significantly affected the hydrochar yield produced from alkaline lignin solution. Consequently, the condition at 240 °C was chosen to examine the influence of reaction time (6, 12, and 24 hours). Statistical analysis confirmed that the reaction time significantly impacted the amount of oxygenated functional groups (OFGs), with the 12-hour condition yielding the highest OFG content. The methylene blue adsorption was conducted. The high MB adsorption was related to OFGs content. These results confirmed that the lignin-based hydrochar was a suitable surface properties for metal catalyst impregnation. Moreover, SEM and FTIR analysis were conducted, which confirmed a high density of OFGs that play a crucial role as anchoring sites. This study concludes that the HTC condition of 240 °C for 12 hours is the optimal condition for producing lignin-based hydrochar with the physicochemical properties ready for further development into a high-performance catalyst support.

Keywords: Lignin-based hydrochar; Lignin extraction; Spent coffee grounds; Ammonium hydroxide; Hydrothermal carbonization

1. Introduction

The development of heterogeneous catalysts is gaining significant attention in the alternative energy industry, such as biodiesel production, due to their ease of separation from the product mixture and reusability [1]. The efficiency of these catalysts largely depends on the "catalyst support." An ideal support material requires a high surface area, a porous structure that facilitates the diffusion of reactants, and a high density of surface functional groups. In particular, oxygenated functional groups (OFGs) are essential to serve as strong active anchoring sites for the desired functionalizing compounds.

Biomass-derived carbon is considered a highly promising candidate for catalyst supports [2]. Spent coffee grounds (SCGs) are an abundant organic waste rich in lignin, a natural polymer with a complex carbon structure [3, 4]. Extracting lignin from SCGs to synthesize high-value carbon materials not only aligns with the Circular Economy concept but also fosters eco-

friendly material innovation [4]. Hydrothermal carbonization (HTC) is a widely adopted green technology for converting lignin solutions into "hydrochar," as it can preserve surface OFGs much more effectively than high-temperature pyrolysis [5].

However, the physicochemical properties of the resulting hydrochar are highly sensitive and heavily dependent on the synthesis conditions. Achieving the optimal porous structure and OFG content requires systematic optimization in both the lignin extraction and HTC processes (temperature and time). Currently, studies regarding the statistical correlation of these variables in the synthesis of SCG-derived lignin-based hydrochar for catalyst support applications remain limited.

Therefore, this research aims to systematically optimize the synthesis conditions of lignin-based hydrochar from SCGs by applying statistical analysis of variance at every stage. This study ranges from varying the ammonium hydroxide concentration in the extraction process to investigating the effects of temperature and time in the HTC process. The objective is to obtain a material with an optimal balance between the percentage yield and the maximum density of OFGs. Additionally, the readiness of the material is evaluated through in-depth characterization (SEM, FTIR, and Methylene blue number) to confirm the hydrochar's potential for future application as a high-performance catalyst support.

2. Materials and Methodology

2.1 Materials and Chemicals

Spent Coffee Grounds (SCGs) were sourced from the Inthanin coffee shop on the Chulalongkorn University. The material was dried overnight at 105 °C and subsequently sieved to collect the particle fraction of approximately 60 mesh.

The chemicals used in this study were 25% Ammonium hydroxide (NH₄OH), 37% Hydrochloric acid (HCl), Sodium Hydroxide (NaOH), Sodium Hydrogen Carbonate (NaHCO₃), Sodium Carbonate (Na₂CO₃), and Methylene Blue, all of which were analytical grade.

2.2 Lignin Extraction

NH₄OH solutions were prepared at concentrations of 6%, 8%, and 10% (v/v), respectively [6]. The prepared ammonium hydroxide solutions were mixed with SCGs at a liquid-to-solid (L/S) ratio of 10:1 in 250 mL Erlenmeyer flasks. Each concentration was prepared in triplicate. The mixtures were then heated in a shaking water bath at 90 °C for 5 hours. Upon completion, the mixture was filtrate at 10,000 rpm for 15 minutes to separate the solid residue. The liquid supernatant, or lignin solution, was collected and stored in an Erlenmeyer flask at 4 °C. The concentration of NH₄OH providing the highest lignin yield will be selected for further analysis.

2.3 Polymerization of Soluble Lignin by HTC Process

The concentration of NH₄OH providing the highest lignin yield was selected. Subsequently, the lignin solution was transferred into a Teflon-lined stainless-steel autoclave and heated in a hot air oven (Binder model 400 E2) at a heating rate of 5 °C/min. The solution then underwent Hydrothermal Carbonization (HTC). The process was investigated at various temperatures (200, 220, and 240 °C) and durations (2, 12, and 24 hours). The resulting hydrochar was washed with deionized (DI) water until a neutral pH was achieved, followed by drying overnight at 105 °C. The weight of the dried hydrochar was recorded. The hydrochar obtained from the condition yielding the highest amount was selected for surface property analysis.

2.4 Physicochemical Characterization of Hydrochar

2.4.1 Oxygenated Functional Groups Analysis (OFGs)

A 0.25 g sample was weighed and individually added to 12 mL of three different alkaline solutions: 0.04 M NaOH, 0.02 M NaHCO₃, and 0.02 M Na₂CO₃. The mixtures were then agitated on a shaker at 150 rpm for 24 hours. Upon completion, the mixtures were filtered to separate the solid residues. Subsequently, a 4 mL aliquot of the filtrate was pipetted and titrated with a 0.04 M HCl standard solution.

2.4.2 Methylene Blue Number

A 0.1 g portion of the sample was added to 50 mL of Methylene Blue (MB) solution concentrations 20 mg/L. The mixtures were then agitated on a shaker at 150 rpm for 24 hours to ensure adsorption equilibrium. Upon completion of the contact time, the samples were filtered to separate the solid adsorbent from the liquid phase. The residual concentration of Methylene Blue in the filtrate was subsequently determined by measuring the absorbance at a wavelength of 664 nm using a UV-Vis spectrophotometer [7, 8].

3. Results and Discussion

3.1 Effect of Ammonium Hydroxide Concentration on Lignin Extraction

Previous studies have shown that the effect of NH₄OH concentration (6%, 8%, and 10% v/v) on the yield of lignin extracted from SCGs was evaluated. One-way analysis of variance (One-way ANOVA) revealed no statistically significant difference ($p > 0.05$) in lignin yield across the tested alkali concentrations ($F = 0.434$, p -value = 0.667), with mean yields of 0.65 ± 0.40 , 0.79 ± 0.36 , and 0.92 ± 0.29 g, respectively.

Mechanistically, the slight numerical increase in lignin yield with increasing concentration can be explained by the higher availability of hydroxide ions (OH⁻), which efficiently cleaved the ether and ester linkages connecting lignin to hemicellulose within the biomass matrix [9]. However, the lack of statistically significant differences ($p > 0.05$) indicates that the initial concentration of 6% v/v NH₄OH was already sufficient to react with the accessible lignin, reaching an extraction saturation limit. Although no significant difference was observed between treatment groups, considering experimental precision and reproducibility, the 10% v/v condition exhibited the lowest variance (Variance = 0.083) and standard deviation, reflecting superior reaction consistency alongside the highest mean lignin yield (0.924 g). Consequently, 10% v/v NH₄OH was selected as the optimal condition for lignin extraction for subsequent hydrochar synthesis.

3.2 Effect of Temperature and Time used in HTC Process

The optimization of hydrothermal carbonization (HTC) was carried out by evaluating the effects of reaction temperature (200, 220, and 240 °C) and reaction time (6, 12, and 24 h.). Regarding the temperature effect, One-way ANOVA revealed that the reaction temperature significantly influenced the hydrochar weight ($p < 0.05$). As the temperature increased from to , the hydrochar weight markedly increased from 0.1317 ± 0.0223 g (at 200 °C) to 0.1737 ± 0.0386 g (at 220 °C), reaching a maximum of 0.3716 ± 0.0117 g (at 240 °C) as show in Figure 1. This upward trend in hydrochar yield can be attributed to the enhanced repolymerization and condensation reactions of solubilized lignin fragments in the liquid phase at elevated temperatures, which promote the formation and precipitation of solid hydrochar particles [10, 11, 12]. Based on statistical significance ($p < 0.05$) and maximum yield recovery, was selected as the optimal HTC temperature.

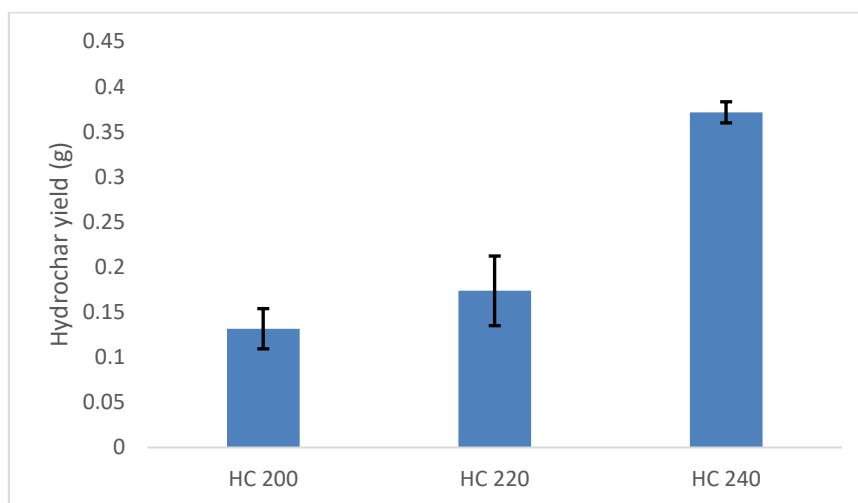


Figure 1. Effect of HTC temperature on lignin-based hydrochar yield produced from alkaline lignin solution

Fixing the reaction temperature at 240 °C, the effect of reaction time on the density of surface oxygenated functional groups was evaluated using Boehm titration. The results indicated a reduction in carboxylic group density from 0.06 mmol/g (at 200 °C) to 0.03 mmol/g (at 12 and 24 h.). Mechanistically, at elevated temperatures (> 220 °C), the lignin structure undergoes acidic depolymerization, dehydration, and decarboxylation, leading to the thermal degradation of carboxylic moieties into volatile matter and free phenolic/lactonic molecules [13]. Nevertheless, focusing on the phenolic groups—which serve as the primary active anchoring sites for chemical interaction—the reaction time of (HC-12) yielded the highest phenolic group density of 0.47 mmol/g (compared to 0.39 mmol/g at 6 h. and 0.43 mmol/g at 24 h.). Consequently, 240 °C for 12 h. was identified as the optimal HTC condition for hydrochar synthesis. In addition to achieving the highest hydrochar yield, the HC-12 condition also exhibited the maximum density of surface oxygenated functional groups (OFGs) as determined by Boehm titration, particularly the phenolic groups (Figure 2).

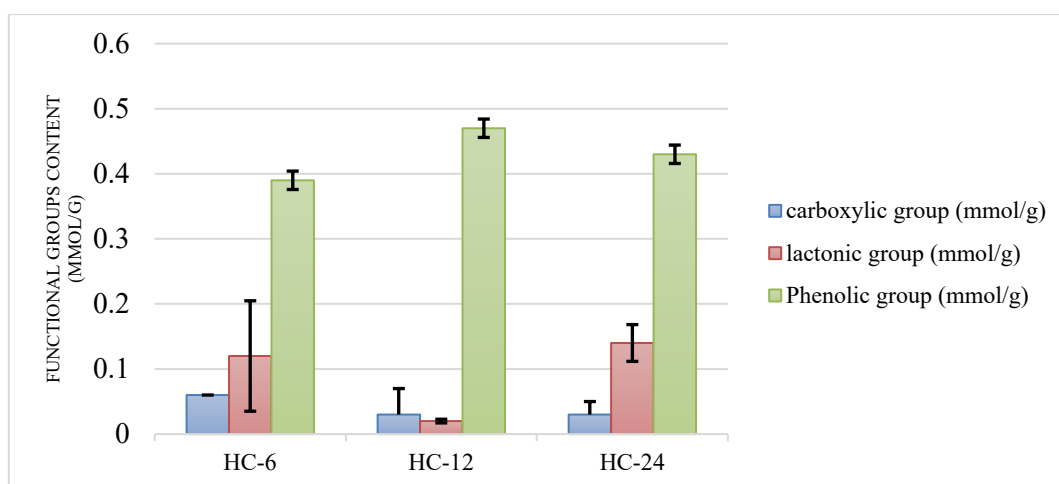


Figure 2. Effect of HTC duration on lignin-based hydrochar yield produced from alkaline lignin solution

3.3 Physicochemical Characterization of the Optimized Hydrochar

3.3.1 Morphological Characterization and Particle Size Distribution (SEM and Sieve Analysis)

The size distribution of the synthesized hydrochar under optimized conditions (HC-12) exhibited a distinct coarse-dominated profile, as shown in Figure 3. Sieve analysis revealed that the macro-fraction (>0.425 mm) constituted the vast majority of the hydrochar mass at 72.62 wt%, whereas smaller size fractions decreased sequentially: 0.212–0.425 mm (15.78 wt%), 0.106–0.212 mm (8.99 wt%), and <0.106 mm (2.61 wt%). This pronounced dominance of coarse particles reflects extensive repolymerization and cross-linking/condensation of solubilized lignin fragments during HTC at 240 °C, leading to the formation of dense carbonaceous macro-aggregates.

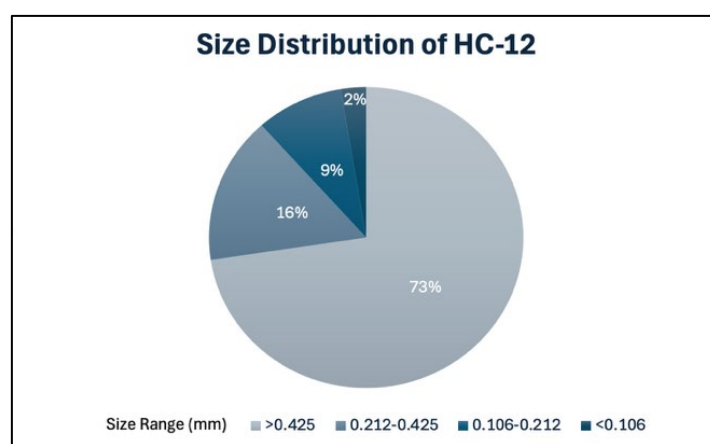


Figure 3. Particle size distribution profile of HC-12 hydrochar from sieve analysis.

The surface morphology examined by SEM (Figure 4) closely correlated with the PSD findings. The low-magnification SEM image (Figure 4a) displayed a large, irregular, blocky carbonaceous structure with sharp edges, corresponding to the predominant coarse fraction (>0.425 mm) identified in the sieve analysis. At a higher magnification of 500x (Figure 4b), the surface of these macro-blocky particles revealed a rough, stepped/layered terrace texture with spherical sub-micron secondary hydrochar particles deposited across the matrix.

This physical combination of a coarse blocky framework and a highly textured surface morphology is particularly advantageous for catalyst support applications. The structural integrity of the macro-particles provides a stable physical matrix, while the surface roughness, layered fissures, and secondary hydrochar deposits increase the effective surface area and provide abundant mechanical anchoring sites to facilitate reactant accessibility and surface functionalization for further applications.

(a) SEM-EDS profile and surface elemental composition

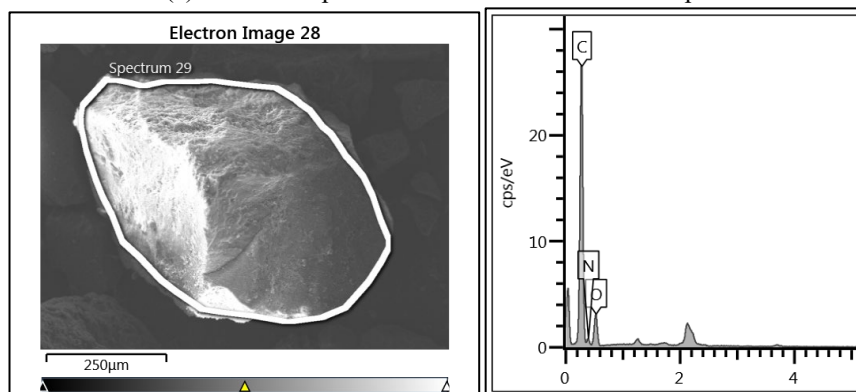


Table 1: Surface Element Ccomposites

Element	Wt%	Wt% Sigma	Atomic %
C	70.13	0.95	75.12
N	7.56	1.18	6.95
O	22.31	0.45	17.94
Total:	100		100

(b) High-magnification surface morphology

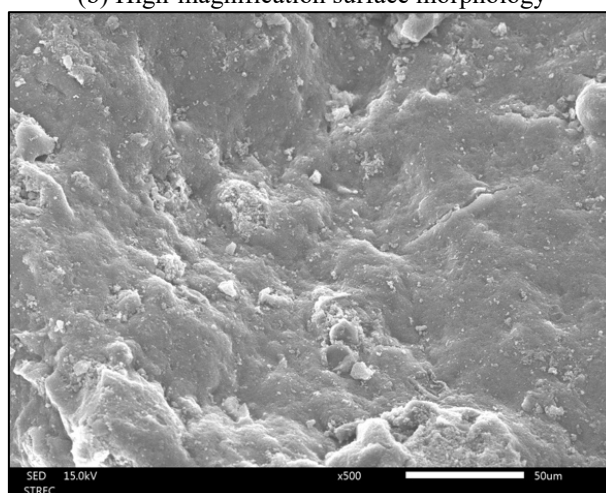


Figure 4. SEM-EDS analysis and surface morphology of HC-12 hydrochar: (a) elemental composition profile including selected area, EDS spectrum, and quantitative table, and (b) highly magnified surface texture.

3.3.2 Surface Chemical Properties and Oxygenated Functional Groups (FTIR & OFGs)

FTIR spectral analysis of the HC-12 hydrochar (Figure 5) confirmed the presence of various oxygenated and hydrocarbon functional groups on the surface. The spectrum displayed key absorption bands at $3,210\text{ cm}^{-1}$ attributed to the O–H stretching of hydroxyl groups, and peaks at $2,920\text{ cm}^{-1}$ and $2,850\text{ cm}^{-1}$ corresponding to the C–H asymmetric and symmetric stretching of aliphatic $-\text{CH}_2-$, respectively. Furthermore, the band at $1,576\text{ cm}^{-1}$ is assigned to the C=C stretching of the aromatic ring, while the peak at $1,374\text{ cm}^{-1}$ represents the C–H symmetric bending of $-\text{CH}_3$. Lastly, the absorption band at $1,070\text{ cm}^{-1}$ is associated with the C–O stretching of aliphatic groups. These results indicate that the HTC process

successfully preserved essential functional groups, including oxygen-containing species and aromatic/aliphatic structures, on the hydrochar surface.

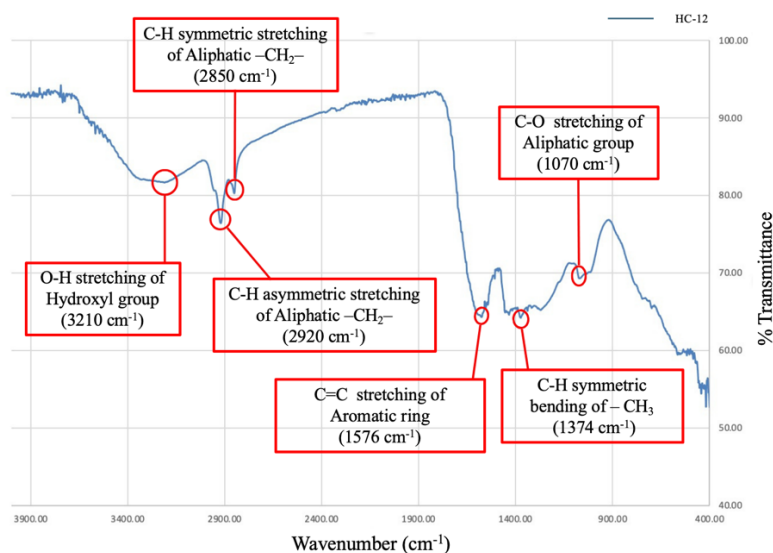


Figure5. FTIR spectrum displaying surface functional groups of HC-12 hydrochar.

For quantitative assessment, Boehm titration results demonstrated that the HC-12 hydrochar possessed a total acidic oxygenated functional group (Total acidic OFG) content of 0.524 mmol/g, comprising 0.03 mmol/g carboxylic, 0.02 mmol/g lactonic, and 0.47 mmol/g phenolic groups as shown in Figure2. The high density of acidic surface groups, particularly the predominant phenolic groups, serves as robust active chemical anchoring sites for catalyst integration in subsequent applications.

3.3.3 Evaluation of Porous Structure via Methylene Blue Adsorption (MB Number)

The Methylene Blue (MB) adsorption behavior was evaluated via a single-point adsorption test using 0.1 g of HC-12 at an initial concentration of 20 mg/L. To avoid instrumental limitations of the UV-Vis spectrophotometer—where signal saturation at highly concentrated solutions leads to high variance—this specific concentration was selected, exhibiting a removal efficiency of up to 95%. Since the MB molecule serves as a probe representative of medium-sized molecules, this adsorption behavior indicates the development of a mesoporous structure on the hydrochar matrix [8]. The presence of these mesopores is particularly crucial when applying the material as a catalyst support in reactions involving bulky reactant molecules, such as biodiesel production, as it effectively mitigates mass transfer limitations and facilitates rapid accessibility of reactants to the internal active sites. Overall, all characterization results demonstrate that the hydrochar synthesized from spent coffee ground lignin possesses both a well-developed porous architecture and a high density of surface OFGs, highlighting its remarkable potential for further development into an efficient catalyst support.

4. Conclusion

This study successfully demonstrated the synthesis of a lignin-based hydrochar catalyst support from lignin extracted of SCGs via hydrothermal carbonization (HTC). The results indicated that reaction temperature and time significantly influenced the hydrochar yield. Under

the optimal condition (HC-12), the synthesized hydrochar exhibited the highest density of surface OFGs, predominantly phenolic groups, which was firmly confirmed by FTIR analysis. The abundance of these OFGs makes the hydrochar surface highly suitable for anchoring cationic metals. This strong affinity aligns with its well-developed mesoporous architecture, as evidenced by a Methylene Blue removal efficiency of up to 95% (evaluated using 0.1 g of HC-12 at an initial concentration of 20 mg/L). Furthermore, SEM-EDS analysis revealed a substantial nitrogen content of up to 7% on the HC-12 surface, a crucial characteristic for enhancing overall catalytic performance. For further studies, given the synergistic advantages of the high OFG density and significant nitrogen doping, future work will focus on utilizing this tailored hydrochar as a carbon-supported catalyst to improve reaction efficiencies in advanced applications, such as biodiesel production.

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Carbon sphere synthesis from de-lignin spent coffee grounds: effect of acidic solution used in hydrothermal carbonization on oxygenated functional group

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Abstract

This study investigated the effects of NH_4OH delignification and acid-assisted hydrothermal carbonization (HTC) on the synthesis of carbon sphere hydrochar from spent coffee grounds (SCGs). SCGs were delignified using 6%, 8%, and 10% NH_4OH , with no statistically significant difference in lignin removal efficiency among the treatments. The 10% NH_4OH -treated SCGs, which showed the lowest experimental variance, were selected for HTC at 190 °C for 24 h using distilled water or acid-assisted conditions adjusted to pH 6 with HCl , H_2SO_4 , citric acid, or ascorbic acid. SEM-EDS confirmed successful carbon sphere formation under all conditions, likely through a hydrothermal nucleation-growth mechanism. Among the acid-assisted treatments, citric acid produced hydrochar with the highest C/O ratio (5.19), compared with 4.33–4.45 for the other acid-assisted conditions. Boehm titration and FTIR further revealed that acid-assisted HTC reduced total oxygen-containing functional groups relative to the distilled-water control while altering the distribution of surface functionalities. From a carbon-supported catalyst perspective, the oxygen-rich carbon spheres produced in distilled water may be more suitable for direct sulfonation, metal anchoring, ion exchange, and hydrophilic catalyst surfaces, whereas the more carbon-rich spheres obtained from acid-assisted HTC may be better suited as thermally stable catalyst supports for high-temperature applications.

Keywords: Spent coffee grounds; Hydrothermal carbonization; Delignification; Carbon sphere; Hydrochar

1. Introduction

Carbon spheres (CSs) are currently a class of carbon materials that have garnered significant attention due to their outstanding properties, including uniform morphology, high surface area, chemical and thermal stability, as well as customizable surface functional groups. Owing to these characteristics,[1][2] CSs are widely applied across various industries, particularly in the environmental sector as high-performance adsorbents for treating toxins, heavy metals, or dyes in wastewater; in energy storage as electrode materials for batteries and supercapacitors; [3][4] and as catalyst supports in green chemistry processes. [2]

However, current CS production still faces limitations, as it frequently relies on pure precursors such as glucose and sucrose.[5] To overcome this challenge, Hydrothermal Carbonization (HTC) has emerged as a popular approach. HTC is a thermochemical process that does not require the pre-drying of raw materials, consumes relatively low energy, and is environmentally friendly.[2] Utilizing abundant agricultural waste, such as spent coffee

grounds (SCGs), as a precursor presents a sustainable alternative that aligns with the circular economy concept. SCGs are rich in polysaccharides, such as cellulose and hemicellulose, which can undergo dehydration and polymerization during the HTC process to form spherical carbon particles. [5][6]

Despite the high potential of SCGs, the naturally complex structure of biomass, specifically the presence of lignin, often poses a major obstacle. Lignin is difficult to decompose at low HTC temperatures and can hinder the uniform formation of carbon spheres.[1] Pre-treating the feedstock via delignification using a weak alkaline solution, such as ammonium hydroxide (NH₄OH), provides an effective pathway to enhance reaction efficiency.[7] Furthermore, the addition of acid catalysts during HTC is another crucial variable that accelerates hydrolysis and controls morphology.[2][8] Nevertheless, comparative research regarding the influence of inorganic acids (e.g., HCl or H₂SO₄) and organic acids (e.g., citric acid, ascorbic acid) under strictly controlled pH conditions on the alteration of oxygen-containing functional groups (OFGs) on the surface of delignified SCG hydrochar remains limited.

Therefore, this research aims to investigate the effects of delignification using an alkaline solution and compare the influence of four types of acid catalysts (at pH 6) in the HTC process of SCGs. This study focuses on analyzing the morphological characteristics and the alteration of surface OFGs on the hydrochar. The findings will provide essential fundamental data for controlling the properties of carbon spheres, optimizing them for application as catalyst supports in green chemistry processes.

2. Methodology

2.1 Material

The raw material that will be used in this study will be spent coffee grounds (SCGs) collected from the Inthanin Coffee Faculty of Education, Chulalongkorn University. The SCGs will be dried at 105 °C overnight, sieved to obtain a particle size of 40-70 mesh, and stored in a zip-lock bag at room temperature.

The chemicals that will be used include ammonium hydroxide (NH₄OH, laboratory reagent grade), sulfuric acid (H₂SO₄, analytical grade), hydrochloric acid (HCl, analytical grade), citric acid (C₆H₈O₇ analytical grade) and ascorbic acid (C₆H₈O₆ analytical grade)

2.2 Lignin extraction

The SCGs will be mixed with alkaline solutions (NH₄OH) at concentrations of 6%v/v, 8%v/v, and 10%v/v, respectively, and deionized water at a solid-to-liquid ratio of 1:10 (g/mL). The mixture will then be heated in a water bath at 80 °C for 5 hours. After that, the extracted lignin solution will be collected and stored in plastic bottles at 4 °C. The holocellulose will be washed with 1 molar hydrochloric acid (HCl) until the pH becomes neutral, followed by washing with deionized water (H₂O). The sample will then be dried at 105 °C overnight, weighed, and the dry weight will be recorded.

The soluble lignin in the alkaline liquid fraction will be precipitated by the HCl solution. The precipitated lignin will be separated by a paper filter and dried at 105 °C overnight. The lignin recovery will be calculated using equation 1.

$$\text{Lignin Recovery (\%)} = \frac{\text{Precipitated Lignin (g)}}{\text{Total Mass of SCGs (g)}} 100\% \quad (1)$$

The alkaline type, which provides the highest lignin recovery, will be selected as the alkaline pretreatment in this work. The holocellulose samples from alkaline solutions will be used in the synthesis of carbon spheres.

2.3 Carbon sphere synthesis

One g of de-lignin SCGs will be mixed with 50 mL of H₂O, HCl, Citric, Ascorbic, and H₂SO₄ at pH 6 and will be subjected to hydrothermal carbonization (HTC) using an HTC vessel at 190 °C at a heating rate of 5°C/min for 24 hours. After the reaction, the solid product (Hydrochar) will be separated from the liquid phase by filtration, followed by washing with deionized water. Hydrochar will then be dried at 105 °C overnight, weighed, and the dry weight will be recorded. The produced hydrochar will be further analyzed using SEM, FTIR, and OFGs. Carbon sphere formation and amount of OFGs will be used as the selected criteria of carbon sphere from each acid type.

2.4 Oxygenated function group analysis

Analysis of oxygenated function group (OFGs) will be developed by using “Boehm’s Titration” method which will serve as a powerful tool for identifying and quantifying oxygenated functional groups with acid or basis properties on carbon surface and analyzed by using different base of NaHCO₃, NaOH and Na₂CO₃ that will be analyzed the carboxylic groups, lactonic groups and phenolic groups.[9]

The method will utilize 0.1 g of each sample, which will be added 12 mL of 0.04 M solution of NaOH, 0.02M solution of NaHCO₃, and Na₂CO₃ in 125 mL of flasks to determine the functional groups. The solution will be placed on the orbital shaker at 150 rpm for 24 hr. Meanwhile, 0.1 M solution of HCl will be prepared to titrate the three base solutions. After filtering the mixture by using a PTFE membrane, 4 mL of each filtrate will be pipetted, and 0.1 M of HCl solution will be used to titrate the excess of base and acid and ensure complete neutralization to pH 7 using pH meter (HANNA-HI6221.02). The numbers of oxygenated functional groups were calculated under the assumption that NaOH reacted with carboxylic, phenolic and lactonic groups on the surface, Na₂CO₃ reacted with carboxylic and lactonic groups, and NaHCO₃ reacted only with carboxylic groups. The difference between NaHCO₃ and Na₂CO₃ was considered as lactonic groups, and the difference between Na₂CO₃ and NaOH was considered as phenolic groups.

3. Results and discussion

3.1 Results of lignin extraction from coffee grounds using ammonium hydroxide

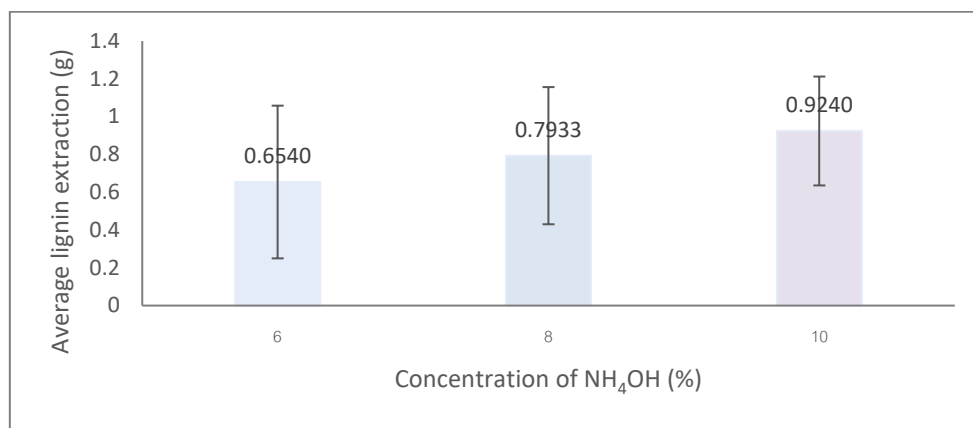


Figure 1 Effect of ammonium hydroxide concentration on the average lignin extraction yield from SCGs

A one-way analysis of variance (One-way ANOVA) was conducted to evaluate the effect of ammonia solution concentration (6%, 8%, and 10%) on delignification yield. The results indicated that the mean delignification yield tended to increase with higher concentrations, yielding values of 0.6540, 0.7933, and 0.9240, respectively. However, statistical analysis revealed that these differences were not statistically significant at the 95% ($p > 0.05$) confidence level. This lack of significance is attributed to the mean square within groups (error variance from replicates, MS_{within}) being greater than the mean square between groups ($MS_{between}$). Therefore, it can be concluded that from an operational standpoint, ammonia solution concentrations ranging from 6% to 10% result in statistically equivalent delignification efficiencies. Although there was no statistically significant difference in delignification efficiency among the three concentrations, the 10% concentration yielded the highest average efficiency (0.9240) and the lowest variance (0.0830), indicating superior process consistency. Therefore, the de-lignin SCGs extracted with 10% NH_4OH were selected as the optimal starting material to maximize lignin removal prior to HTC.

3.2 Morphological characteristics of hydrochar

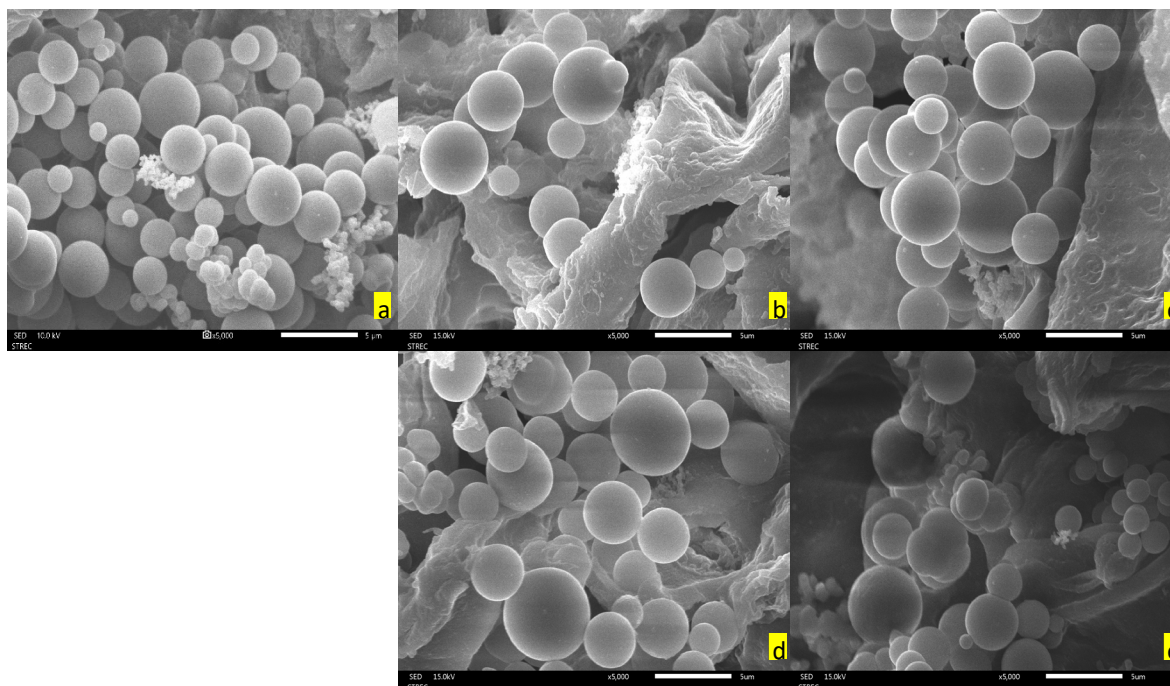


Figure 2 a) SEM image of H_2O b) SEM image of HCl c) SEM image of H_2SO_4 d) SEM image of citric e) SEM image of ascorbic

Table 1 Elements C, O and ratio C/O of carbon sphere hydrochar by SEM-EDS

samples	element C (wt%)	element O (wt%)	ratio C/O
HCl	76.95	23.05	4.45
H_2SO_4	76.49	23.51	4.33
Citric	79.58	20.42	5.19
Ascorbic	76.86	23.14	4.43

The morphological characteristics and elemental surface composition of the hydrochars synthesized under four different acid conditions were analyzed using SEM-EDS techniques, as

shown in Figures 2. The EDS analysis confirmed that the primary elements in all hydrochar samples consisted of carbon (76.49-79.58%) and oxygen (20.42-23.51%). Notably, the sample synthesized in the presence of citric acid exhibited the highest carbon content of 79.58% and the highest C/O ratio of 5.19, indicating the highest degree of carbonization. This is attributed to the more efficient catalytic enhancement of dehydration and decarboxylation reactions compared to the other conditions.

SEM images (Figures 2 a–e) revealed the formation of micrometer-sized carbon spheres across all five hydrothermal conditions, driven by the hydrolysis-dehydration-polymerization pathway of carbohydrates in spent coffee grounds, followed by nucleation and condensation. However, the choice of liquid medium and acid catalysts distinctly influenced the yield, size uniformity, and dispersion characteristics of the particles. The control sample prepared in distilled water exhibited a dense, highly populated cluster of smooth-surfaced microspheres. Among the acid-catalyzed conditions, the citric acid sample (d) produced well-defined, independent microspheres with clean, smooth surfaces and minimal inter-particle fusion. In contrast, the sulfuric acid sample (c) showed localized particle agglomeration, forming closely packed. For the hydrochloric acid (b) and ascorbic acid (e) samples, smooth spherical particles were found dispersed and partially embedded across the sheet-like/flake-like residual biomass matrix. Notably, ascorbic acid (e) displayed a wider size distribution, featuring smaller microspheres adhering to the matrix walls. These morphological differences, together with the surface oxygenated functional groups, directly dictate the available

3.3 Surface chemical analysis

3.3.1 OFGs results

Table 2 OFGs results

Functional groups	HCl	H ₂ SO ₄	Citric	Ascorbic	H ₂ O
Carboxylic group	0.14	0.20	0.17	0.14	0.89
Lactonic group	0.36	0.21	0.22	0.44	0.44
Phenolic group	0.26	0.37	0.43	0.20	0.35
Total OFGs	0.76	0.78	0.82	0.78	1.68

The quantitative analysis of surface oxygen-containing functional groups (OFGs) on the hydrochars determined by Boehm titration is presented in Table 2. The results reveal that the hydrochar prepared in DI water (control) exhibited the highest carboxylic group content at 0.89 mmol/g, with a total OFG content reaching 1.68 mmol/g. However, with the addition of acid catalysts during the HTC process at pH 6, the carboxylic group content across all samples decreased significantly to a range of 0.14 - 0.20 mmol/g. Acid-assisted HTC likely accelerated dehydration and decarboxylation reactions, leading to the removal of oxygen-containing moieties and the formation of a more carbonized hydrochar surface. The hydrochars produced in the presence of acid catalysts exhibited substantially lower carboxylic and total oxygen-containing functional groups than those prepared in deionized water. This observation is consistent with the hydrothermal carbonization mechanism described by Libra et al. (2011) [10] who reported that dehydration and decarboxylation are the dominant reactions during HTC. These reactions remove oxygen from the biomass matrix in the form of H₂O and CO₂ while condensation and aromatization reactions progressively convert the biomass into a more carbon-rich and condensed carbonaceous structure. Consequently, the abundance of oxygen-containing surface functional groups, particularly carboxylic groups, decreases after HTC.

Furthermore, the specific type of acid employed influenced the differential formation of surface functional groups. The use of ascorbic acid promoted the highest formation of lactonic

groups at 0.44 mmol/g, whereas citric acid resulted in the highest phenolic group content among the acid-treated group at 0.43 mmol/g. These variations in surface functional groups directly impact the chemical interactions and the adsorption capacity toward Methylene Blue dye in the subsequent stage.

3.3.2 FTIR results

The analysis of chemical functional groups on the hydrochar surface using FTIR spectroscopy (Figure 3) revealed that the hydrochars synthesized in the presence of HCl, citric acid, ascorbic acid, and H₂SO₄ at pH 6 exhibited similar spectral patterns, indicating that the major surface functional groups were preserved regardless of the acid catalyst employed. A broad absorption band at 3334–3338 cm⁻¹ was assigned to the O–H stretching vibration of hydroxyl groups. Prominent peaks at 2916 and 2848 cm⁻¹ corresponded to the stretching vibration of aliphatic C–H bonds, while the band at 1697–1703 cm⁻¹ was attributed to C=O stretching of carboxylic and lactonic groups. In addition, the absorption band observed at 1031–1054 cm⁻¹ was assigned to C–O and C–O–C stretching vibrations. These results indicate that the hydrochars produced under mildly acidic HTC conditions contained abundant oxygen-containing functional groups, including hydroxyl, carbonyl, and ether functionalities. Although no substantial shifts in the FTIR peak positions were observed among the different acid-assisted HTC conditions, quantitative Boehm titration revealed noticeable differences in the abundance of oxygen-containing functional groups. This finding suggests that the acid catalysts primarily influenced the relative abundance of surface functional groups rather than the types of functional groups present. Compared with the hydrochar prepared in deionized water, all acid-assisted HTC samples exhibited markedly lower carboxylic group contents and total OFGs. This trend is consistent with the hydrothermal carbonization mechanism described by Libra et al. (2011), in which dehydration, decarboxylation, condensation, and aromatization reactions progressively convert biomass into a more condensed carbonaceous structure while reducing the oxygen content of the solid product. Nevertheless, characteristic oxygen-containing functional groups remained on the hydrochar surface, These surface functionalities are expected to contribute to the adsorption performance observed in the methylene blue adsorption experiments discussed in the following section.

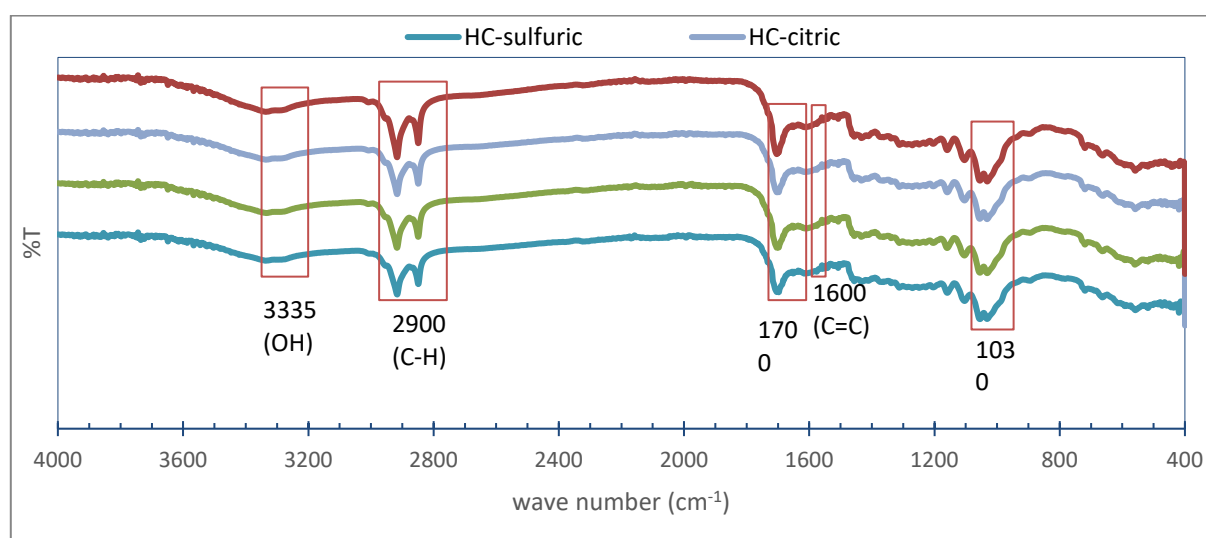


Figure 3 FTIR image

4. Conclusion

This study demonstrates that spent coffee grounds can be converted into carbon sphere hydrochar through NH_4OH delignification followed by hydrothermal carbonization. Although varying the NH_4OH concentration from 6% to 10% did not significantly affect lignin extraction efficiency, the 10% NH_4OH treatment provided more consistent results and was therefore selected for subsequent HTC experiments. The successful formation of spherical hydrochar under all HTC conditions confirms the suitability of delignified SCGs as a precursor for carbon sphere synthesis.

The reaction medium played a critical role in controlling the surface chemistry of the resulting hydrochar. While all samples retained oxygen-containing functional groups such as hydroxyl, carbonyl/carboxyl, and ether groups, acid-assisted HTC reduced the total abundance of these functionalities compared with the deionized-water condition. This suggests that acidic media promoted dehydration, decarboxylation, and condensation reactions, leading to more carbon-rich hydrochar surfaces. Therefore, HTC conditions can be used to tune carbon sphere hydrochar toward different catalyst-support properties: oxygen-rich hydrochar from deionized water may be advantageous for direct sulfonation, metal anchoring, and hydrophilic catalyst surfaces, whereas carbon-rich hydrochar from acid-assisted HTC may provide improved structural and thermal stability for high-temperature catalytic applications.

Further study should evaluate the performance of these two hydrochar types as carbon-supported catalysts for biodiesel production. In particular, oxygen-rich and carbon-rich carbon sphere hydrochars should be sulfonated and compared in terms of $-\text{SO}_3\text{H}$ density, acidity, catalytic activity, and reusability in esterification or transesterification of low-quality oil feedstocks. This comparison will clarify whether higher oxygen functionality or higher carbonization degree is more beneficial for developing stable and reusable biomass-derived solid acid catalysts.

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An Application of the Mixed Reality Technology in M60A3 Main Battle Tank Maintenance Operation

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Abstract

This study presents a Mixed Reality (MR) simulator for maintenance training of the main gun and turret systems of the M60A3 main battle tank. Three dimensional models were reconstructed from physical components through reverse engineering and implemented as guided, step-by-step disassembly and reassembly training content using the Unity real-time engine and the Microsoft HoloLens head-mounted display. The main components consist of two main systems; the M68 main gun system, which consists of three subsystems: the combination gun mount, the gun cannon, the main gun elevation mechanism and the turret system, which consists of five subsystems: the power pack control, the hand elevating pump, the main hydraulic accumulator, the traverse mechanism lock, and the hydraulic system tubes. The simulator was evaluated with 100 army armored-vehicle maintenance personnel, who completed guided disassembly/reassembly tasks while task completion time, procedural accuracy, and user satisfaction were recorded. Results indicate a mean task completion time of 18.5 minutes per subsystem, a procedural accuracy of 91.4% against the reference sequence, and a mean user satisfaction rating of 4.35/5, indicating that the simulator is a practical training tool for the cannon and turret systems of the M60A3. The approach can be extended to other armament systems to further strengthen the sustainment of the defense industry in the near future.

Keywords: Mixed Reality; M60A3; Main Battle Tank; Maintenance Training.

1. Introduction

Main battle tanks such as the M60A3 remain in active service within the Royal Thai Army, despite the original manufacturers having discontinued production and, in many cases, formal technical and logistics support. The sustainment of these platforms depends heavily on the knowledge of experienced maintenance personnel, printed technical manuals of varying completeness, and training aids. The cannon and turret systems, comprising the M68 main gun system and the hydraulic turret system, are among the most safety-critical and mechanically complex subsystems to maintain, yet they are also the subsystems most exposed to training bottlenecks, since repeated hands-on disassembly and reassembly practice on operational hardware risks wear and damage to components.

Mixed Reality (MR) technology encompassing the continuum from Augmented Reality (AR) to Virtual Reality (VR) offers a means of decoupling maintenance training from the physical availability of hardware while preserving, and in some respects enhancing, procedural fidelity through visualization of otherwise concealed internal mechanisms. Head-mounted AR devices such as the Microsoft HoloLens, combined with a real-time 3D engine such as Unity, allow trainees to interact with accurately dimensioned, part-level digital models overlaid on or

substituting for the physical vehicle. MR/AR/VR-based maintenance training has been studied extensively in manufacturing, aerospace, and healthcare contexts; however, its application to armored combat vehicle maintenance such as the M60A3, for which original technical data packages are incomplete or no longer available, has not previously been reported.

Therefore, this paper presents the development of an MR-based maintenance training simulator for the cannon and turret systems of the M60A3 main battle tank. Three-dimensional models of the M68 main gun system and turret system components were constructed at part and assembly level, and step-by-step training content covering disassembly and reassembly operations was designed and implemented using Unity and the Microsoft HoloLens headset. The objectives of this study are to construct detailed, dimensionally accurate 3D models of the target cannon and turret subsystems, to design and develop MR-based training content that guides trainees through disassembly and reassembly procedures; and to evaluate the resulting simulator as a practical maintenance training tool with active maintenance personnel.

2. Literature Review

MR/AR/VR technologies have been increasingly investigated as tools for maintenance training across manufacturing, aerospace, healthcare, and facilities management. This section reviews recent journal literature on MR/AR/VR-based maintenance and vocational training in order to position the contribution of this study, which applies MR technology to the maintenance training of the M60A3 main battle tank turret and cannon systems.

Daling and Schlittmeier [1] conducted a scoping review of MR/AR/VR-based training studies for manual assembly tasks, comparing objective performance measures with subjective evaluations, and providing a widely cited basis for methodological choices in immersive-training evaluation. Bödding, Schriek, and Maier [2] performed a systematic review and meta-analysis of mixed reality in vocational education and training, examining behavioral, cognitive, and affective outcomes and their moderators. Leite and Vieira [3] mapped current trends and proposed a research agenda for VR in human training, offering a useful frame for situating future extensions of MR-based training research.

Alam et al. [4] reviewed the role of extended reality (XR) technologies in maintenance operations, summarizing trends, adoption challenges, and integration pathways within Industry 4.0. Mao, Scheffer, and Majumdar [5] proposed the DILEAF framework for AR-enabled knowledge management in industrial maintenance, addressing how procedural knowledge can be captured and delivered through AR overlays, a design consideration directly relevant to structuring step-by-step disassembly and reassembly content. Di Pasquale et al. [6] conducted a systematic literature review of VR applications specifically for training in assembly and disassembly tasks, consolidating evaluation metrics and training-design patterns used across studies.

Ibarra Kwick et al. [7] systematically reviewed extended reality applications for CNC machine training, a comparable case of complex mechanical-system operation and maintenance instruction. Tătaru et al. [8] provided an up-to-date review of HoloLens platform applications in healthcare simulation training and education, documenting hardware capabilities, pedagogical framing, and adoption patterns for HoloLens-based instruction outside industrial settings, which supports the technical rationale for selecting HoloLens as the development platform in this study.

Steven et al. [9] conducted a PRISMA-based systematic review of twenty-five studies on VR applications in tactical and combat operations, concluding that research on practical military VR remains limited relative to other sectors due to restricted data availability and institutional access. De Armas, Tori, and Netto [10] systematically reviewed VR simulators

used in security and defense training programs more broadly, cataloguing simulator design approaches across military and law-enforcement contexts. Fan and Wen [11] presented an early but frequently cited VR soldier simulator integrating body-area-network hardware for squad-level team training, illustrating the hardware-integration challenges relevant to fielding immersive systems in operational units. Boyce et al. [12] examined how terrain-representation fidelity in an extended-reality mission-planning tool affected soldiers' comprehension of military tactics, a human-factors question relevant to calibrating visual fidelity in MR training content.

Across the reviewed literature, MR/AR/VR maintenance-training research clusters predominantly around manufacturing assembly lines, aerospace maintenance, facilities management, and healthcare simulation, with comparatively few studies addressing heavy mechanical or defense equipment, and none identified that address armored combat vehicle maintenance specifically. Consequently, this study addresses that gap by applying MR technology to the turret and cannon maintenance training of the M60A3 main battle tank, extending existing MR training design principles to a previously unstudied domain.

3. Methodology

Four major steps comprising reverse engineering and 3D reconstruction of the target hardware, simulation content design, MR development and deployment, and evaluation with maintenance personnel were implemented as follows:

3.1 Reverse Engineering & 3D Reconstruction

Detailed three-dimensional models of M68 main gun system and turret system components were constructed, capturing part geometries and dimensions as well as assembly-level relationships between mating components. This digital asset base provides the geometric foundation for the MR training content and preserves an accurate reference of subsystems for which complete original technical data packages are no longer available. Hardware digitization through data acquisition of physical tank components from M60A3 platform using high-accuracy measurement instruments was used. CAD reconstruction through solid modeling was then performed to capture exact part geometries, critical clearances, and spatial configurations.

3.2 Armored Subsystem Integration and Simulation Content Design

Simulation content was designed and developed using the Unity real-time 3D engine, targeting deployment on the Microsoft HoloLens head-mounted AR device. Digital replication was carried out for two systems, comprising eight subsystems in total: 1) The M68 105 mm main gun system - three subsystems: combination gun mount, gun cannon, and main gun elevation mechanism and 2) the turret system - five subsystems: power pack control, hand elevating pump, main hydraulic accumulator, traverse mechanism lock, and the multi-branch hydraulic system tubes. The training content was structured around step-by-step disassembly and reassembly procedures for each subsystem, allowing a trainee to follow a guided sequence of interactive steps while viewing the three-dimensional model of the corresponding components. This approach enables trainees to visualize internal mechanisms and assembly relationships that are otherwise concealed within the turret structure, without requiring access to a physical M60A3 vehicle.

3.3 MR Development & Simulation Deployment

Development and deployment onto the Microsoft HoloLens standalone headset followed three stages, summarized in Table 1. For each of the subsystems, the simulation content presents the component hierarchy, guides the trainee through the correct disassembly sequence, and then the corresponding reassembly sequence, reinforcing correct procedural order and component

identification at each step. User-experience satisfaction: performance testing with active army armored vehicle maintenance units to measure task completion times, error rates, and procedural recall was also validated.

Table 1 Stages of MR development and deployment onto the Microsoft HoloLens

Stage	Purpose	Implementation Detail
1. Asset preparation & optimization	Reduce onboard GPU workload for standalone rendering	Compiled 3D assets were optimized through material simplification, polygon-count reduction, and pre-computed (baked) light mapping, removing real-time lighting/shading computation from the HoloLens onboard GPU.
2. Interactive mechanics	Enforce correct procedural order and give real-time feedback	Sequential disassembly/reassembly logic was programmed as a step-gated state machine, so a component can only be removed or installed once its prerequisite steps are complete. Coordinate mapping between virtual components and real-time interactive transformations (drag/rotate/snap) was paired with dynamic visual and text feedback confirming correct or incorrect actions at each step.
3. Hardware deployment	Confirm stable operation on-device	The optimized application was compiled and deployed to the Microsoft HoloLens mixed-reality optical see-through headset. On-device testing was used to confirm stable frame rates and spatial tracking during interaction prior to the evaluation.

3.4 Evaluation with Maintenance Personnel

3.4.1 Participants

The simulator was evaluated with 100 active army armored-vehicle maintenance personnel (Technician Student, Technician Instructor, Technician Supervisor, and Commander) at the Cavalry Training Unit, Cavalry Center.

3.4.2 Procedure

Each participant received a brief orientation to the HoloLens headset and interface, then completed guided disassembly and reassembly of the target subsystems using the simulator.

3.4.3 Measures

During each session, task completion time and procedural accuracy (deviations from the correct reference sequence, recorded as an error count) were logged. Participants also completed a post-session questionnaire (5-point Likert satisfaction survey, from 5 as Highly Satisfied to 1 as Not Satisfied) rating ease of use, clarity of guidance, and perceived training value. These three measures - task completion time, procedural accuracy, and user satisfaction - form the quantitative basis for the results reported.

4. Results

The developed simulator successfully integrates detailed three-dimensional models of the eight target subsystems previously described with step-by-step disassembly and reassembly training content, delivered through the Microsoft HoloLens using Unity. The resulting system

allows maintenance personnel to visualize part-level geometry, assembly relationships, and correct procedural sequences for all eight target subsystems independent of the availability of physical training vehicles. The MR-based simulator addresses a practical sustainment challenge for the Royal Thai Army: the scarcity of serviceable training vehicles and instructor availability for main gun and turret systems whose original technical data and support are no longer readily available. By reconstructing accurate three-dimensional geometry of the M68 main gun system and turret subsystems, the simulator also functions as a digital preservation record of components that may otherwise depend solely on the knowledge of a shrinking pool of experienced personnel.

4.1 Quantitative Evaluation Results

Table 2 summarizes the results of the evaluation described based on 100 participants. As with any AR-based training tool, the fidelity of tactile and force-related cues remains a limitation relative to hands-on practice on physical hardware, and the simulator is best regarded as a complement to, rather than a full replacement for, supervised physical training.

Table 2 Summary of quantitative evaluation results with maintenance personnel.

Metric	Results	Notes
Participants	100	Army maintenance personnel
Mean task completion time	18.5 minutes	Per subsystem, guided mode
Procedural accuracy	91.4 %	Correct steps vs. reference sequence
User satisfaction	4.35/5	Post-session questionnaire

4.2 Simulator Figures

Figures 1-6 illustrate the development pipeline described, from the physical reference platform through to in-headset training content. Figure 1 shows the physical M60A3 main tank used as the reference platform for hardware digitization. Figure 2 also shows a mapping of the M68 main gun system and turret system subsystems onto the physical vehicle, establishing the scope of the eight target subsystems. Figure 3 demonstrates a simulator title and platform-selection screen, through which a trainee chooses M60A1/A3 configuration. Figure 4 depicts a MR scene layout, showing the reconstructed vehicle and disassembled components arranged around a virtual work surface - the interaction space in which the step-gated procedure of Table 1 is presented to the trainee. Figure 5 shows reconstructed 3D CAD models of representative main gun and turret components, illustrating the geometric fidelity achieved during reverse engineering. Figure 6 illustrates an in-headset view of the guided disassembly sequence, showing the reconstructed vehicle on a virtual work surface with the associated subsystem menu and the step timer and on-screen component labels used to reinforce correct procedural order.



Figure 1 M60A3 main tank.

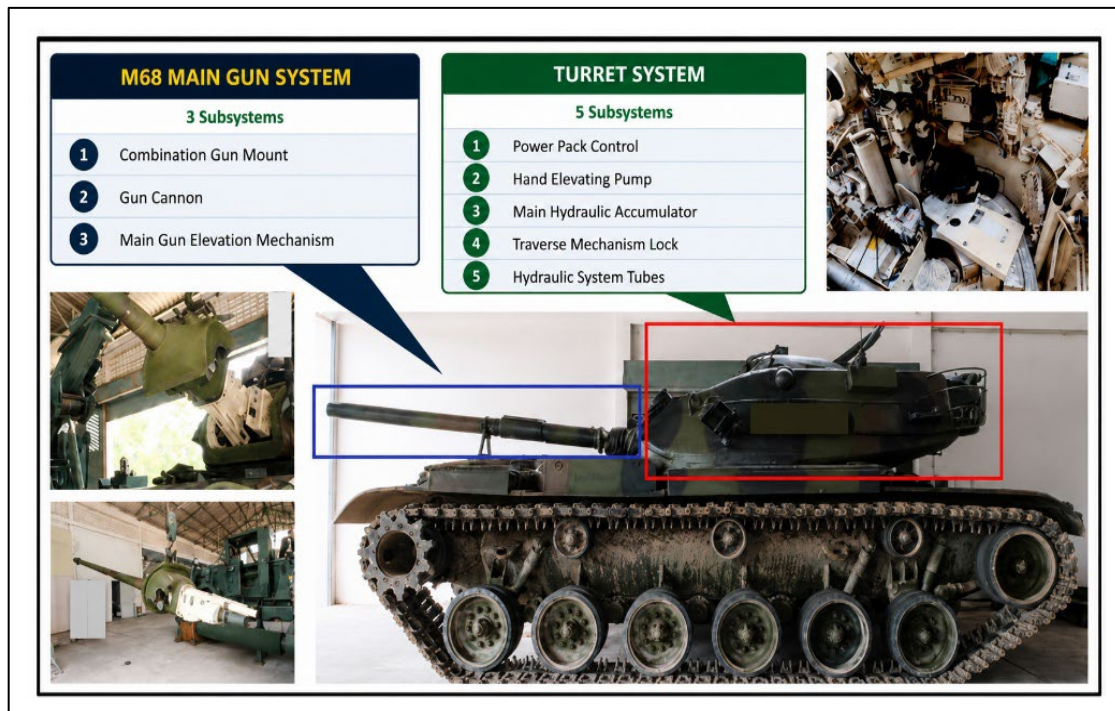


Figure 2 Main gun and turret subsystems of the M60A3 main tank.

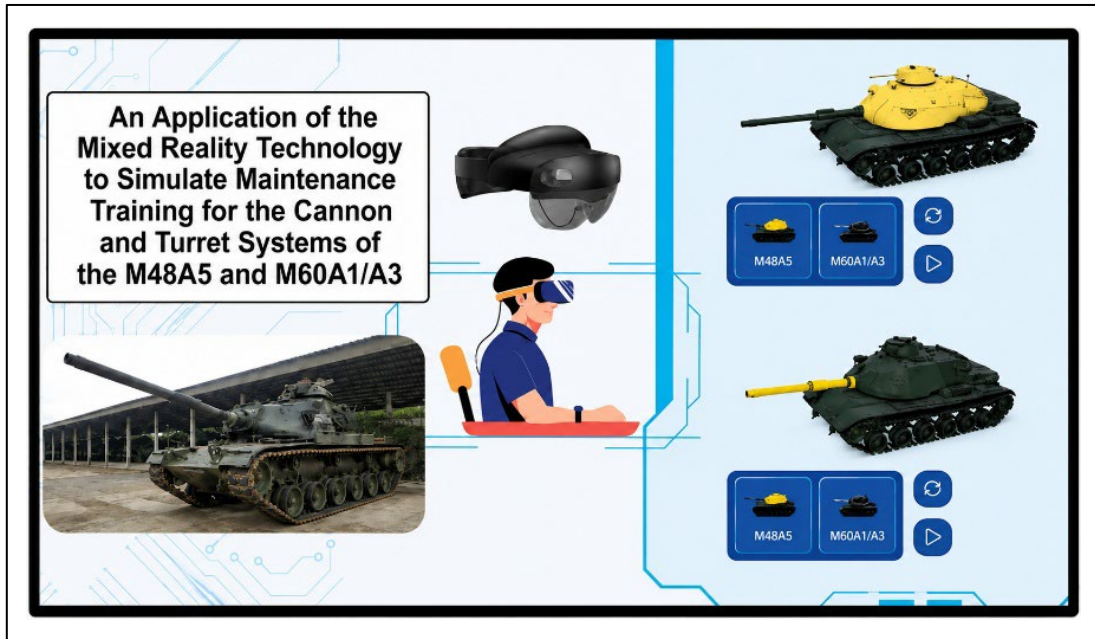


Figure 3 Platform-selection screen and configuration.



Figure 4 MR scene layout.

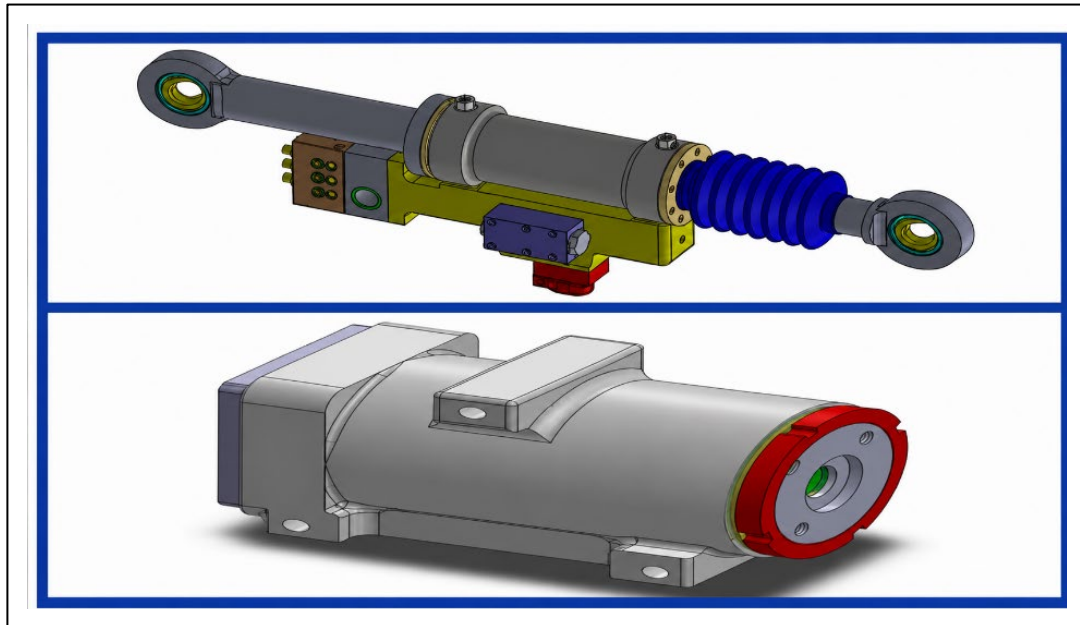


Figure 5 Reconstructed 3D CAD models of representative main gun and turret components.

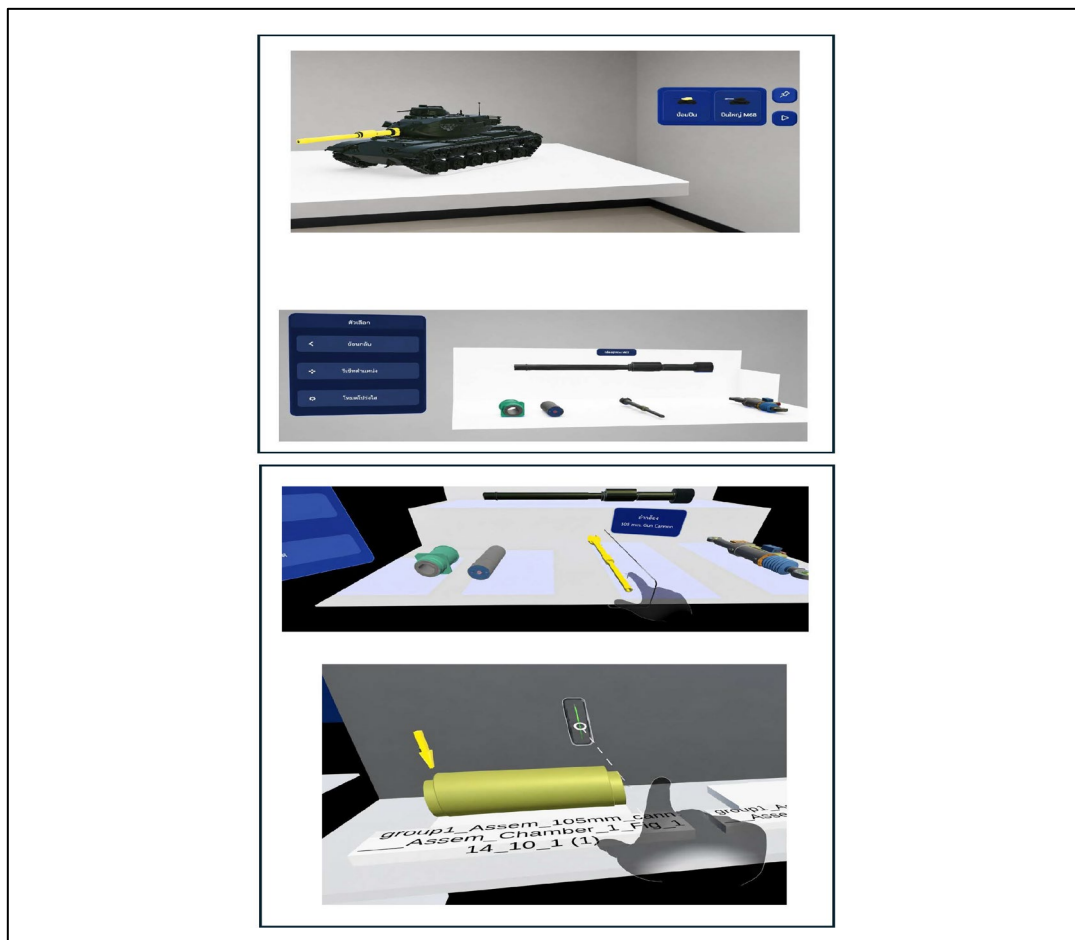


Figure 6 An in-headset view of the guided disassembly sequence.



5. Discussions

Compared with conventional on-vehicle maintenance training, the MR-based simulator offers several practical advantages. It removes the need to occupy scarce, operational hardware for repeated disassembly/reassembly practice, reducing wear and scheduling conflicts with active units. It allows trainees to visualize internal mechanisms that are normally concealed within the turret structure, and it provides consistent, step-gated guidance that structures practice around a verified reference sequence rather than depending solely on the availability and recall of experienced instructors. Because the underlying 3D models are reconstructed to capture exact part geometry, the asset base also functions as a digital preservation record for platforms whose original technical documentation is incomplete. At the same time, the approach has limitations that should be considered before wider deployment. The fidelity of tactile and force-related cues, such as torque, resistance, weight, remains limited relative to hands-on practice on physical hardware, so the simulator is best positioned as a complement to, rather than a replacement for, supervised physical training. Field deployment introduces additional constraints not present in a controlled evaluation setting, including headset battery life and field-of-view during extended sessions, the durability of hardware in maintenance-bay or field conditions, and the availability of technical support for the HoloLens platform itself. Personnel unfamiliar with AR interfaces may also require an initial adaptation period before guided training becomes as efficient as reported. Finally, scaling the approach to additional armament systems requires proportional investment in hardware digitization and content authoring; this cost is expected to decrease for future systems as the reverse-engineering and Unity content pipelines developed in this study are reused and refined.

6. Conclusions

In this work, a Mixed Reality (MR) simulation system for maintenance training of the main gun and turret systems of the M60A3 Main Battle Tank was developed to enable military personnel to perform virtual disassembly and reassembly operations through an immersive, interactive environment (immersive training). Three-dimensional models of the eight target subsystems described in Section 3.2 were constructed, together with step-by-step disassembly and reassembly training content, built using Unity and the Microsoft HoloLens headset. Evaluation with 100 army maintenance personnel indicates the simulator can be used successfully as a practical maintenance training tool, as a mean task completion time of 18.5 minutes per subsystem, a procedural accuracy of 91.4% over the reference sequence, and a mean user satisfaction rating of 4.35/5. Future work includes formal evaluation of training outcomes against conventional on-vehicle instruction over a larger participant sample, and extension of the mixed reality approach to other armament systems to further strengthen the sustainment of the defense platforms.

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Synergizing OCR and API Orchestration for Enhanced SLA Compliance in Automotive Finance: A Hybrid Intelligence Approach

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Abstract

In the highly competitive automotive finance industry, maintaining a strict Service Level Agreement (SLA) is paramount for operational excellence and customer satisfaction. However, traditional workflows often suffer from significant delays caused by manual data entry redundancies and fragmented coordination with external partners. This study proposes an integrated digital architecture that synergizes Optical Character Recognition (OCR) and API Orchestration within a Hybrid Intelligence framework to enhance SLA compliance. Leveraging empirical data from actual production implementation and historical operational records, a Monte Carlo simulation with 10,000 iterations was conducted to evaluate the proposed target operational model. Within this enhanced framework, the redesigned architecture utilizes OCR at the initial application stage to extract full documentation, enabling a strategic bypass of subsequent manual entry steps. Simultaneously, an API-driven task management system is introduced to automate coordination with Outsource Agents (OA), effectively mitigating non-value-added "Idle Time." The simulation results project that the integrated approach could potentially lead to an estimated 39.5% reduction in average processing time at the data capture stage and a significant 65.6% reduction in the 85th percentile (P85) latency, dropping from 2.93 to 1.01 hours. These findings suggest that by balancing automated speed with a Human-in-the-Loop (HITL) verification layer, organizations can achieve a more predictable, transparent, and resilient lending ecosystem, providing a scalable roadmap for digital maturity in financial services.

Keywords: Digital Transformation; API Orchestration; SLA Compliance; OCR; Hybrid Intelligence.

1. Introduction

In the current era of Digital Transformation, organizations are increasingly implementing advanced technologies to streamline operations, reduce turnaround times, and create higher strategic value [1]. However, a significant challenge remains in high-complexity sectors like automotive finance, where workflows often span across multiple internal departments and external partners. Existing academic studies frequently focus on the isolated efficiency of individual technologies, such as the use of Optical Character Recognition (OCR) for intelligent document processing to significantly reduce manual effort [2], [3]. Despite these isolated technological advancements, a notable research gap remains in understanding how to effectively integrate Hybrid Intelligence (AI + Human) within a comprehensive workflow that

orchestrates both internal processing and external outsource coordination [4]. Specifically, the transition between internal approval and external execution often suffers from significant "Idle Time" and latency due to fragmented manual hand-over processes, such as phone calls or manual scheduling. For instance, research in business process management indicates that unstructured communication channels and manual inter-organizational hand-offs can account for a substantial portion of total process delays, severely impacting service delivery times [7]. This study fills this gap by proposing an integrated architecture, validated through actual production data, that leverages OCR for internal data entry speed at the initial application stage and an API-Orchestrated Task Management system for external orchestration. By utilizing real-time API notifications, which are proven to reduce communication errors and information asymmetry [5], the proposed model provides essential visibility to Outsource Agents (OA). Furthermore, the framework aims to improve data integrity and operational reliability through a Human-in-the-Loop (HITL) design, where human operators verify system-flagged uncertain cases to maintain data quality while minimizing overall workload [6].

2. Literature Review

2.1 Strategic Importance of SLA in Service Operations

In the financial service sector, Service Level Agreement (SLA) serves as a critical tool for measuring operational performance by defining clear service standards and expectations [7]. Effective SLA management is not merely about reactive tracking but requires proactive visibility across the entire workflow to prevent potential breaches and aims to improve customer trust [8].

2.2 Business Intelligence and Data-Driven Insights

The integration of Business Intelligence technologies allows organizations to transform vast amounts of raw operational data into actionable insights [11]. By utilizing advanced analytics, firms can identify hidden bottlenecks and shift from traditional intuition-based management to a strategic, data-driven decision-making culture [11].

2.3 Hybrid Intelligence and Human-in-the-Loop (HITL)

Hybrid Intelligence refers to the paradigm where human intelligence and artificial intelligence collaborate to achieve superior results that neither could achieve alone [4]. In high-stakes industries like finance, a Human-in-the-Loop (HITL) framework is essential to manage the "accuracy-speed trade-off." This approach allows AI to handle the bulk of "Golden Path" transactions while redirecting uncertain cases to human experts, aiming to improve data integrity, though residual errors may remain [6].

2.4 API Orchestration and Task Management

API (Application Programming Interface) orchestration is the automated coordination of multiple services to execute a larger workflow. Research indicates that API-driven integration is critical in mitigating Information Asymmetry between internal departments and external partners [5]. By automating the hand-over process, organizations can significantly reduce Idle Time, which is the period where a task is stationary awaiting manual intervention, thereby stabilizing the overall service level agreement (SLA) compliance.

3. Methodology

3.1 Process Analysis and Proposed Design

The study identifies critical bottlenecks in the automotive loan application workflow through a granular analysis of its eight distinct operational stages (summarized in Table 1). Our

analysis specifically highlighted two high-redundancy manual stages: Hop 1 (DE Short) and Hop 3 (DE Full). Hop 1 represents the initial phase where basic applicant information is manually registered to initiate the loan request. Subsequently, Hop 3 requires the comprehensive manual transcription of all supporting documents, such as income proofs and identification. To analyze these inefficiencies and support the proposed system redesign, the underlying data foundation is built upon a Cloud-based Data Mart. This architecture utilizes dimensional modeling principles to improve data integrity and efficient retrieval [9], [10].

To address these inefficiencies, the proposed redesign implements a strategic OCR Integration at Hop 1. Unlike conventional implementations, this architecture utilizes OCR to extract data from the full documentation set at the very beginning of the process. By digitizing all documents upfront, the system enables an automated bypass of Hop 3 (DE Full) immediately after Hop 2 (Appraisal) is completed. This effectively reduces redundant manual data entry, reduces processing latency, and aims to improve seamless data flow throughout the subsequent underwriting and booking stages.

Table 1 Automotive Loan Operation Process and Proposed Technology Integration

Hop	Description	Current Workflow	Proposed Technology
1. DE (Short)	Data Entry (Initial Application)	Manual	OCR Integration
2. AP	Appraisal	Manual	-
3. DE (Full)	Data Entry (Full Documentation)	Manual	By passed (via Hop 1 OCR)
4. UW	Under Writing	Manual	-
5. BO1	Booking 1 (Internal Approval)	Manual	-
6. OB	Outbound	Manual	-
7. BO2	Booking 2 (Contract Execution & OA)	Manual	API Orchestration
8. OB2 (IF)	Outbound (Optional)	Manual	-

3.2 API-Orchestrated Task Management

For external operations, an API Orchestration layer is proposed at Hop 7. This stage traditionally suffers from high cumulative latency and idle time due to manual scheduling with Outsource Agents (OA). The API acts as a digital hand-over mechanism, triggering an automated task notification to the OA system immediately upon internal approval. This ensures that OA partners have real-time visibility into the "Task Management" queue, allowing them to initiate vehicle title transfers without waiting for manual prompts or offline coordination.

3.3 Simulation Framework and Parameter Validation

To accurately evaluate the proposed model, it is essential to ground the simulation in empirical data. Prior to this study, the traditional workflow relied heavily on manual data entry across multiple stages. To address this, an initial phase of the architecture was deployed into a live production environment in December 2025. This specific implementation integrated the OCR engine at the first application stage (Hop 1) to automatically extract data from applicant documents, successfully processing over 4,000 actual cases. Building upon the performance metrics gathered from this live deployment, a Monte Carlo Simulation with 10,000 iterations was subsequently executed to validate the full end-to-end "To-Be" model. This stochastic modeling approach is widely recognized for assessing operational risks and predicting system performance under uncertainty [12]. The simulation parameters are defined as follows:

- Evidence-Based Performance (OCR): Data extraction speed and accuracy rates were derived directly from the December 2025 OCR implementation. This ensures that the simulation reflects observed technical capabilities in a real-world setting rather than

theoretical assumptions.

- Strategic Proposal (API): Although the API layer is in the conceptual phase, its potential value in reducing coordination with idle time was modeled based on digital transformation literature [5], assuming a 20–30% reduction in external station latency.
- Distribution Selection: A Gamma Distribution was used to model the baseline TAT, as it effectively captures the "long tail" of extreme delays found in the historical dataset from June 2025.
- Human-in-the-Loop (HITL): An 11.3% probability ($P = 0.11$) for manual intervention was included to handle system-flagged uncertain cases, aims to improve data integrity, though residual errors may remain. During this pilot phase, the OCR engine achieved a Field-Level Extraction Accuracy of 92.4% and a Character Error Rate (CER) of approximately 4.1%. Consequently, application documents with confidence scores falling below the predefined threshold accounted for the 11.3% HITL intervention rate.

Table 2 Monte Carlo Simulation Parameters and Distribution Selection

Stage / Variable	Baseline (Manual)	Proposed (AI-HITL)	Distribution Type	Data Source
1. DE (Short)	Avg: 1.64 hrs./case	Avg: 0.99 hrs./case	Triangular (Min, Most Likely, Max)	Production Data
3. DE (Full)	Avg: 0.57 hrs./case	Avg: 0.55 hrs./case (Review)	Constant	Production Data
7. BO2 (API)	High Latency / Manual	20%–30% Time Reduction	Uniform	Strategic Proposal
Accuracy / HITL	Staff expertise	$P = 0.11$ (11.3% HITL)	Discrete / Bernoulli	Production Data
Overall Variance	Historical Records	Simulated Output	Gamma Distribution	Analysis (June-2025)

From Table 2, the simulation parameters are meticulously categorized to improve model validity. The internal efficiency gains at Hop 1 and the automation rates for the Human-in-the-Loop (HITL) framework are directly extracted from the OCR production data following the initial system implementation in December 2025. This transition from manual workflow to a live production environment, involving over 4,000 cases in a single month, provides a superior level of empirical certainty compared to theoretical assumptions. Conversely, the external orchestration impacts at Hop 7 are modeled as a Strategic Proposal based on digital transformation benchmarks to address identified Information Asymmetry and Idle Time. By utilizing a Gamma Distribution for the overall TAT baseline, the model accounts for the stochastic nature of automotive loan processing, specifically targeting the mitigation of the "long tail" of extreme delays that typically lead to SLA breaches.

Table 3 Descriptive Statistics for Initial Data Capture (Hop 1) – Pilot Implementation (N=4,152)

Variable / Operational Stage	N (Cases)	Mean (Hrs)
Baseline (Manual Data Entry)	4,152	1.64
Proposed (OCR – Overall)	4,152	0.99
OCR: Golden Path (Auto, 88.7%)	3,683	0.89
OCR: HITL Intervention (11.3%)	469	1.77

Table 3 presents the Descriptive statistics and 95% Confidence Intervals (CI) derived from the

4,152 actual production cases processed during the initial pilot phase. The observed Standard Deviation (Std. Dev.) reflects the empirical variance in processing times, highlighting that while manual intervention for complex cases (11.3% HITL) exhibits higher variance, the overall integration of OCR significantly stabilizes the mean Turnaround Time (TAT) compared to the baseline manual entry.

4. Results and Discussion

4.1 Simulation Outcomes and Efficiency Gains

The Monte Carlo simulation, executed with 10,000 iterations, reveals a substantial improvement in the operational efficiency of the automotive loan process. By integrating OCR at Hop 1—enabling the strategic bypass of Hop 3 (DE Full)—and implementing API-orchestrated task management at Hop 7, the system suggests the following quantitative gains:

- **Reduction in Mean Turnaround Time (TAT):** The average processing time for initial data capture (DE Short) decreased by 39.5%, shifting from a baseline of 1.64 hours to 0.99 hours. This specific reduction is driven directly by the transition from manual data entry to automated OCR extraction at Hop 1, while overall systemic gains are further amplified by the elimination of redundancies at Hop 3 and the mitigation of coordination idle time at Hop 7.
- **Process Elimination Impact:** The strategic decision to use OCR for full document extraction at the earliest stage (Hop 1) effectively removed the manual bottleneck previously attributed to Hop 3 (DE Full). This suggests that front-loading digital data captures create significant downstream value. The elimination of such redundant manual stages aligns with Business Process Management (BPM) best practices, which advocate for the removal of non-value-added activities to maximize process throughput [13].
- **Idle Time Mitigation:** The API orchestration at Hop 7 successfully stabilized the hand-over process to Outsource Agents (OA). By providing real-time task visibility, the simulation showed a marked decrease in the "waiting period" that typically inflates the total TAT in the C2C product line.

4.2 Risk Assessment and Sensitivity Analysis

Beyond average performance, the study evaluated the system's ability to handle extreme delays, which are the primary cause of SLA breaches.

- **P85 Risk Reduction:** The 85th percentile (P85) latency—a critical risk metric representing the maximum time required to process 85% of all loan applications—was reduced from 2.93 hours to 1.01 hours. Unlike average processing times that can obscure extreme delays, the P85 metric specifically highlights the system's resilience against worst-case operational bottlenecks. This projected 65.6% improvement in the P85 metric shows potential to reduce extreme delays, making the process more predictable and compliant with strict SLAs.
- **Sensitivity Analysis:** To identify the most critical performance drivers, a sensitivity analysis was conducted. The results indicate that the overall SLA compliance is most sensitive to OCR Accuracy at Hop 1 and API Response Latency at Hop 7. An 11.3% Human-in-the-Loop (HITL) intervention rate was observed in the production phase, highlighting the importance of maintaining high OCR accuracy to minimize manual workload.

4.3 Strategic Discussion: Hybrid Intelligence and Digital Maturity

The synergy between AI-driven automation (OCR) and API orchestration represents a shift towards Hybrid Intelligence. Rather than attempting to achieve 100% automation, which is often impractical in complex financial services, the proposed framework leverages an 88.7% automated OCR system (reflecting the 11.3% HITL rate from production data) supported by a strategic verification layer.

This architecture addresses the sociotechnical aspect of digital transformation by reallocating human expertise from mundane data entry (Hop 3) to high-value verification and exception handling. Furthermore, the use of API as an orchestration layer transforms the relationship with external partners (OA) from a reactive, manual-based coordination into a proactive, data-integrated ecosystem. This transition is essential for organizations aiming to reach higher levels of digital maturity, where real-time reporting and automated task triggers replace legacy, intuition-based operations.

4.4 Limitations of the Study

While the Monte Carlo simulation provides robust projections grounded in initial production data, several limitations must be acknowledged. First, the efficiency gains at the external coordination stage (Hop 7) are based on theoretical API orchestration models rather than live production data. The actual latency reduction may fluctuate depending on the technical readiness and system constraints of third-party Outsource Agents (OA). Second, the simulation assumes a static 11.3% Human-in-the-Loop (HITL) intervention rate; however, in a full-scale deployment, this rate may vary dynamically based on the complexity and quality of incoming physical documents. Furthermore, the current simulation framework evaluates the proposed Hybrid Intelligence model solely against the traditional manual baseline. It does not incorporate comparisons with other isolated technological interventions, such as RPA-only, OCR-only workflows, or comprehensive BPM redesigns. Consequently, while the proposed architecture demonstrates significant potential, further comparative analysis is required to establish its relative superiority over these specific single-technology deployments. Finally, the simulated outputs represent potential operational ceilings. Empirical validation through a complete, end-to-end live system deployment is required in future works to definitively confirm these projected SLA improvements.

5. Conclusion and Future Work

5.1 Conclusion

This study suggests that achieving a competitive Service Level Agreement (SLA) in the automotive loan industry requires more than just isolated automation. By integrating OCR-driven front-end automation with an API-orchestrated task management system, the proposed architecture effectively bridges the gap between internal processing and external coordination.

The simulation results, grounded in actual production data, confirm that the strategic use of OCR to extract full documentation at Hop 1 can substantially reduce significant manual redundancies, while API integration mitigates the non-value-added "Idle Time" in outsource coordination. This synergy suggests a potential 39.5% reduction in average processing time and, more importantly, a 65.6% reduction in P85 operational risk at the critical data capture stage. The Human-in-the-Loop (HITL) framework further helps maintain high accuracy and data integrity, providing preliminary evidence that a hybrid intelligence approach is effective compared to manual or fully automated systems in high-complexity financial environments.

5.2 Future Work

While this research provides a robust conceptual and simulated framework, the next phase

involves the full-scale deployment of the API Orchestration Layer to replace manual scheduling with Outsource Agents (OA). Future studies should explore:

1. **Real-time Performance Monitoring:** Implementing the cloud-based data mart and real-time dashboard as proposed in the broader digital transformation roadmap to monitor live API latency and SLA compliance at the OA hand-off (Hop 7). By visualizing operational bottlenecks in real-time, the system can trigger automated alerts when OA response times exceed predefined thresholds, allowing for dynamic task reallocation before SLA breaches occur.
2. **Advanced AI Integration:** Exploring the use of Large Language Models (LLMs) or specialized Machine Learning models to further reduce the 11.3% HITL verification rate. Specifically, LLMs can be trained to contextually interpret non-standard or low-quality documents (e.g., complex income proofs or handwritten notes) that currently trigger human intervention at Hop 1. This targeted AI deployment could potentially resolve edge cases autonomously, driving the manual verification rate down without compromising data integrity.
3. **Ecosystem Expansion:** Extending the API-driven task management to include other third-party partners, such as insurance providers and credit bureaus. For our specific automotive loan workflow, integrating a National Credit Bureau (NCB) API at the Underwriting stage (Hop 4) or auto insurance APIs during the initial Booking phase (Hop 5) would facilitate Straight-Through Processing (STP). This would transform the current architecture into a fully automated, end-to-end digital lending ecosystem, effectively eliminating the remaining manual verification of touchpoints.
4. **Comparative Baseline Analysis:** To robustly validate the relative performance of the Hybrid Intelligence approach, future studies should conduct a systematic sensitivity analysis encompassing multiple operational baselines. Evaluating the proposed architecture against alternative single-technology configuration specifically RPA-only and OCR-only deployments—will provide deeper empirical insights into the optimal technology mix for mitigating delays in complex financial workflows.

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Development of an Artificial Intelligence-Based Solar Photovoltaic Power Generation Forecasting System

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Abstract

This study develops an AI-based solar photovoltaic power generation forecasting system using the Light Gradient Boosting Machine (LightGBM) algorithm and evaluates its forecasting accuracy. Two models — for solar power generation and electricity load — were trained on 524,810 records of one year of operational data from an actual PV site, combined with weather data from the Open-Meteo Archive API. Accuracy was assessed using RMSE and MAPE, with an adaptive daily retraining mechanism to improve predictions over time. The solar model achieved an average MAPE of 6.13% (RMSE 4.28 kW), while the load model achieved an average MAPE of 20.02% (RMSE 12.02 kW), showing a consistent downward trend across cross-validation folds. Predicted values were compared with actual output to detect equipment anomalies, and used to estimate carbon emission reductions (tCO₂e) for ESG reporting. A cloud-edge architecture with a React-based web dashboard supports real-time monitoring and decision-making. Results confirm LightGBM's suitability for time-series solar forecasting and demonstrate a practical framework for intelligent energy management, fault detection, and sustainability reporting.

Keywords: Solar power forecasting; LightGBM; Fault diagnosis; Edge-cloud architecture

1. Introduction

The global transition toward renewable energy is an urgent worldwide agenda, with solar energy widely recognized as a key future energy source for driving a low-carbon economy. However, the high variability of solar power — driven by weather conditions, irradiance, and other environmental factors — remains a major challenge for forecasting accuracy and power grid management. Integrating solar power into the electricity grid is essential to advancing a low-carbon economy, yet accurate forecasting remains difficult because of the inherent variability of solar power output [1].

Over the past decade, artificial intelligence (AI) and deep learning techniques have played an increasingly important role in improving the accuracy of solar power forecasting. A systematic literature review analyzing 242 studies found that hybrid models combining Convolutional Neural Networks (CNN) and Long Short-Term Memory (LSTM) networks reduced the Mean Absolute Error (MAE) by 15–30% compared with single models. Deep learning models were found to perform particularly well for short-term forecasting, while ensemble methods performed better for day-ahead forecasting. These findings highlight the substantial potential of AI to significantly improve the reliability of solar power forecasting systems [2].

Beyond forecasting, fault diagnosis and equipment health monitoring have become equally important, as the power generation efficiency of PV systems often deteriorates under complex

operating conditions. The rapid expansion of PV installations has led both academia and industry to place greater emphasis on damage prediction and equipment health management, requiring intelligent operational maintenance strategies to preserve system integrity. A widely adopted approach compares power output predicted from actual weather-based models with values measured directly from equipment, as demonstrated in prior research proposing a learning-based method to detect potential anomalies in PV systems by comparing measured AC power output with predicted values, enabling system operators to plan preventive maintenance. This principle is directly aligned with the fault-diagnosis concept that the present study seeks to further develop [3], [4].

In light of these challenges, the researchers propose the development of an AI-based forecasting system for solar photovoltaic power generation that predicts the electrical energy expected from a PV installation using AI technology together with environmental data such as irradiance, cloud cover, and temperature, with the predicted values then compared against actual measured output to help detect system anomalies. The study further develops a supporting database for the overall system alongside a website that presents the analyzed data through dashboards and automated reports to support decision-making, performance monitoring, and future system improvement, with the primary objectives being to develop an Artificial Intelligence-Based Solar Photovoltaic Power Generation Forecasting System and to test and evaluate the accuracy of the proposed forecasting models.

Unlike previous studies that mainly focus on forecasting model accuracy, this research proposes an integrated intelligent photovoltaic management framework. The novelty of this work lies in integrating adaptive daily retraining, edge–cloud deployment, anomaly detection, and ESG reporting into a unified AI-driven photovoltaic forecasting framework. This integrated approach enables not only accurate forecasting but also continuous model adaptation, real-time system monitoring, intelligent fault diagnosis, and sustainability assessment within a single operational platform.

2. Literature Review

Research on AI-based solar power forecasting has advanced rapidly between 2023 and 2026. A systematic literature review analyzing 242 studies indicates that hybrid models combining CNN and LSTM can reduce the mean absolute error by 15–30% compared with single models, with deep learning techniques performing well for short-term forecasting and ensemble methods more suitable for day-ahead forecasting [2].

Among algorithms most closely related to this study, Yang et al. [5] proposed a LightGBM model for medium-term PV power forecasting that integrates meteorological data with historical generation data, using Recursive Feature Elimination for variable selection and Bayesian optimization for hyperparameter tuning. Their model achieved MAE = 37.49, RMSE = 64.67, and $R^2 = 0.89$, confirming that LightGBM is well suited to tabular, time-series solar-energy data — consistent with the rationale for adopting the same algorithm in this research.

Based on the recent literature, LightGBM has demonstrated competitive performance for photovoltaic power forecasting using tabular meteorological and operational datasets while offering fast training speed, efficient memory usage, and suitability for edge deployment. These characteristics make LightGBM an appropriate algorithm for the proposed intelligent forecasting framework.

Nourollahi Hokmabad, Husev, and Belikov [6] proposed a day-ahead hybrid forecasting framework for photovoltaic systems that combines a physics-based model with machine learning techniques — including a self-attention-based encoder–decoder network — to improve forecast reliability under data-limited conditions. Their work highlights a key limitation of

purely data-driven approaches, which is directly relevant to the limitation of the present study, whose models are still trained on data from a single site.

Other related studies — including explainable AI-based forecasting [7], machine-learning-based fault classification using random forest [8], survey work on AI approaches for solar forecasting [9], and AI-based smart-grid management frameworks [10] — further reflect the breadth of ongoing research supporting the direction of this research.

3. Methodology

3.1 Research Design

This study adopts a Developmental Research methodology to design, implement, and evaluate an integrated AI-driven photovoltaic forecasting framework. Unlike conventional forecasting studies that primarily focus on prediction accuracy, the proposed framework incorporates adaptive daily retraining, edge–cloud deployment, anomaly detection, and ESG reporting into a unified operational platform for intelligent photovoltaic energy management.

3.2 Data Sources

The primary dataset used to develop and test the models consists of primary data collected from an actual operating site of a case-study company, comprising generated electrical energy, electricity consumption, and equipment temperature values, totaling 524,810 records over a one-year period. This dataset was combined with external weather data — solar irradiance (GHI), temperature, and cloud cover — obtained from the Open-Meteo Archive API.

3.3 Research Tools

Table 1 Research tools and technologies.

Category	Tool / Technology	Role
Programming languages	Python, JavaScript (Node.js, React)	AI, backend, and frontend development
AI model development	LightGBM	Time-series forecasting of solar power and load
Data management	Pandas, NumPy	Data cleaning; IQR / outlier calculation
Model evaluation	Scikit-learn	MAPE, RMSE computation; time-series cross-validation
Theoretical solar irradiance calculation	pvlib	Clear-sky GHI and Clear-Sky Index (kt) calculation
Database	MySQL (Cloud + Edge)	Time-series data storage

3.4 Model Development Process

- Data preparation: External weather features were merged with internal field-sensor features, including calculation of the Clear-Sky Index (kt) to distinguish cloud-covered periods from nighttime periods.

- Model training: Two LightGBM models were developed — one for solar power forecasting and one for electricity load forecasting — using 5-fold time-series cross-validation with an early-stopping mechanism to prevent overfitting.
- Accuracy evaluation: Model accuracy was assessed using RMSE (kW) and MAPE (%), with MAPE calculated only during daylight hours to avoid division by near-zero values at night.

$$RMSE = \sqrt{[(1/n) \sum_{i=1}^n (y_i - \hat{y}_i)^2]} \quad MAPE = (100/n) \sum_{i=1}^n |(y_i - \hat{y}_i) / y_i| \quad (1)$$

The solar power forecasting model achieved an average MAPE of 6.13% and an average RMSE of 4.28 kW during 5-fold cross-validation, meeting the accuracy criteria and reflecting a good level of forecasting performance. After evaluation, the complete dataset was used to retrain a final model so that it could learn from every available record before being saved as a deployable model file for use on the edge device.

```
2026-05-02 04:49:48,596 [INFO] Fold 1: Train=2,644 | Val=2,640
2026-05-02 04:49:51,228 [INFO] Fold 1: MAPE=6.40% | RMSE=4.15 kW
2026-05-02 04:49:51,229 [INFO] Fold 2: Train=5,284 | Val=2,640
2026-05-02 04:49:51,407 [INFO] Fold 2: MAPE=5.33% | RMSE=3.36 kW
2026-05-02 04:49:51,407 [INFO] Fold 3: Train=7,924 | Val=2,640
2026-05-02 04:49:51,661 [INFO] Fold 3: MAPE=5.41% | RMSE=3.76 kW
2026-05-02 04:49:51,661 [INFO] Fold 4: Train=10,564 | Val=2,640
2026-05-02 04:49:51,885 [INFO] Fold 4: MAPE=6.36% | RMSE=4.50 kW
2026-05-02 04:49:51,885 [INFO] Fold 5: Train=13,204 | Val=2,640
2026-05-02 04:49:52,133 [INFO] Fold 5: MAPE=7.13% | RMSE=5.65 kW
2026-05-02 04:49:52,134 [INFO]
>>> Solar Average MAPE: 6.13% | RMSE: 4.28 kW
```

Figure 1 Solar forecasting model cross-validation results

The electricity load forecasting model produced an average MAPE of 20.02% and an average RMSE of 12.02 kW across the 5-fold cross-validation. While the overall MAPE remained slightly above the target threshold, a progressive reduction in forecasting error was observed across successive folds, with the final validation fold achieving a MAPE of 15.33%. This trend suggests that the model's predictive capability improves as more historical observations are incorporated into the training process, consistent with the general behaviour of data-driven machine learning models, where larger and more representative datasets typically enhance generalization and forecasting performance. This cross-validation trend is distinct from, and should not be conflated with, the separate seven-day forecast evaluation reported in Section 4.2.

```
2026-05-02 04:49:52,896 [INFO] Fold 1: Train=5,444 | Val=5,444
2026-05-02 04:49:53,036 [INFO] Fold 1: MAPE=26.13% | RMSE=13.07 kW
2026-05-02 04:49:53,036 [INFO] Fold 2: Train=10,888 | Val=5,444
2026-05-02 04:49:53,195 [INFO] Fold 2: MAPE=22.03% | RMSE=14.38 kW
2026-05-02 04:49:53,195 [INFO] Fold 3: Train=16,332 | Val=5,444
2026-05-02 04:49:53,522 [INFO] Fold 3: MAPE=18.48% | RMSE=12.45 kW
2026-05-02 04:49:53,522 [INFO] Fold 4: Train=21,776 | Val=5,444
2026-05-02 04:49:53,756 [INFO] Fold 4: MAPE=18.13% | RMSE=10.97 kW
2026-05-02 04:49:53,756 [INFO] Fold 5: Train=27,220 | Val=5,444
2026-05-02 04:49:54,155 [INFO] Fold 5: MAPE=15.33% | RMSE=9.22 kW
2026-05-02 04:49:54,156 [INFO]
>>> Load Average MAPE: 20.02% | RMSE: 12.02 kW
```

Figure 2 Load forecasting model cross-validation results

- Adaptive retraining mechanism: The system automatically retrains new models every day at midnight, comparing the MAPE/RMSE of the new model with the currently deployed model. The new model is deployed to the edge device only if it demonstrates superior performance.
- Carbon and ESG calculation: Accumulated energy (kWh) is converted into avoided carbon emissions (tCO₂e) using Thailand's national emission factor (0.4999 tCO₂e/MWh for on-grid systems).
- Anomaly detection: Predicted values are compared with actual measured values. If the actual value falls significantly below the predicted value beyond a defined threshold (e.g., strong sunlight but low power output), the system interprets this as an equipment anomaly.

3.5 Testing Period

Following offline evaluation using historical datasets, the proposed framework was further validated through a shadow deployment in a real-world operational environment from 1–7 May 2026. During this period, the edge device continuously acquired real-time measurements from the smart meter and photovoltaic inverter via the Modbus/RTU protocol at 15-minute intervals, and the deployed models generated 24-hour-ahead forecasts in parallel with the live system without affecting production operations. The forecast values generated during this shadow deployment were retained and subsequently compared against the actual measured values recorded over the same period; this day-by-day comparison is reported in Section 4.2. No data loss or communication interruption was observed during the deployment, demonstrating the robustness of the data acquisition pipeline and the reliability of the proposed architecture for continuous real-time photovoltaic monitoring and forecasting.

3.6 System Analysis and Design (System Architecture)

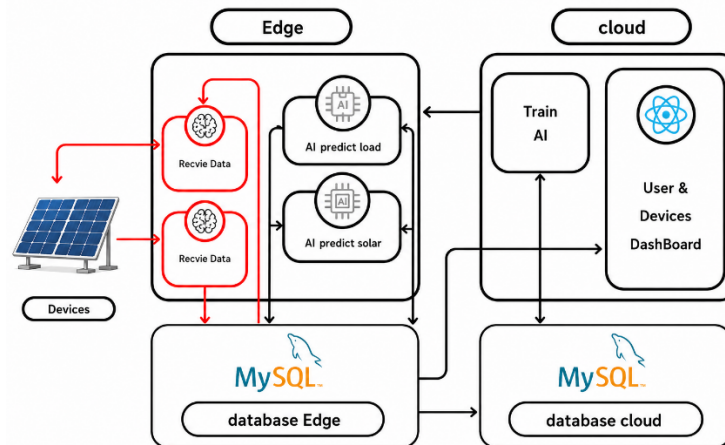


Figure 3 Overall system architecture

AI Model component: This component consists of two AI models running on the edge side — the Load forecasting model (AI Predict Load) and the Solar power forecasting model (AI Predict Solar). Both models were developed using the LightGBM framework and trained on the system's actual accumulated energy data stored in the cloud database.

Edge component: The edge device is installed on-site and is responsible for receiving raw data from solar panels and related equipment through the Receive Data module. The data is averaged every 15 minutes and sent to both AI models to generate a 24-hour-ahead forecast.

The resulting predictions are stored in the edge database, and the 15-minute averaged data is simultaneously transmitted to the cloud database

Cloud component: The cloud component collects and stores data received from the edge into the cloud database and uses this data to automatically retrain new AI models every day at midnight. Once retraining is complete, the system compares the MAPE and RMSE of the new model with those of the currently deployed model; if the new model performs better, it is sent back down to the edge device to replace the existing model.

Web Dashboard component: This platform, developed using React, allows system administrators to monitor and verify the energy status of the system. It retrieves data from both the edge database and the cloud database to display predicted and actual power generation and consumption, equipment operating data, and historical energy-use records, enabling administrators to plan energy management effectively.

4. Results

4.1 System Development Results

Users can manage company data as shown in the figure below, including adding new company information into the system, updating existing company records, and verifying data accuracy, ensuring that stored data remains complete and can be used effectively.

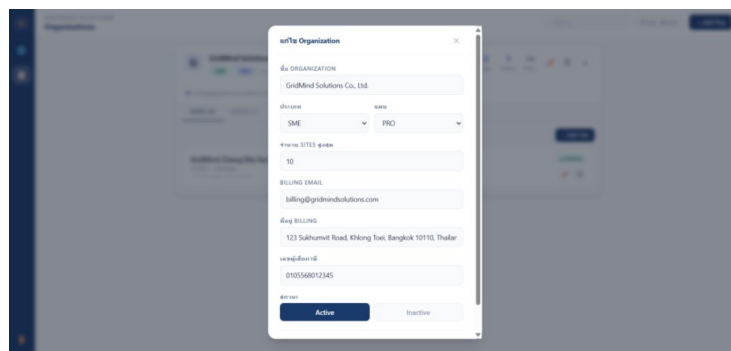


Figure 4 Company data management interface

Users can manage company and site data through this interface, which displays customer company information such as the number of users and the number of sites associated with each company.

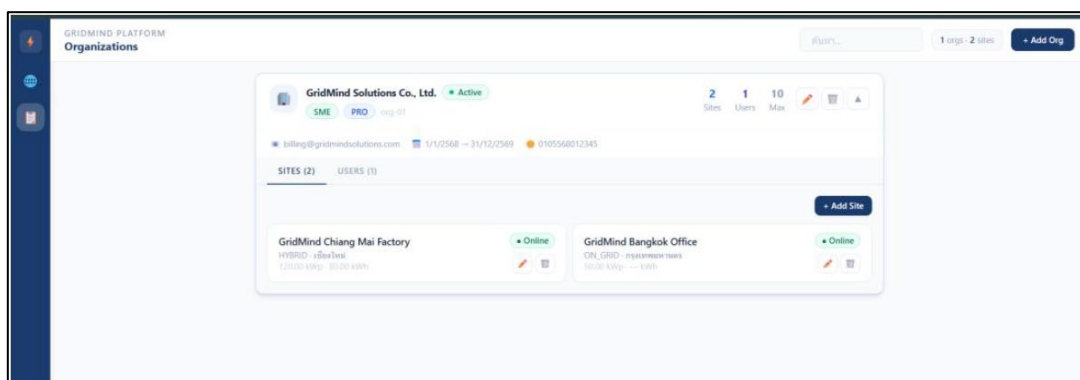


Figure 5 Company and site management interface

Users can view a system overview through a dashboard that presents site-level data such as energy values updated every minute, predicted power generation and consumption over the next 24 hours displayed at 15-minute intervals, predicted electricity output, carbon-footprint reduction values, and comparison graphs between predicted and actual values.

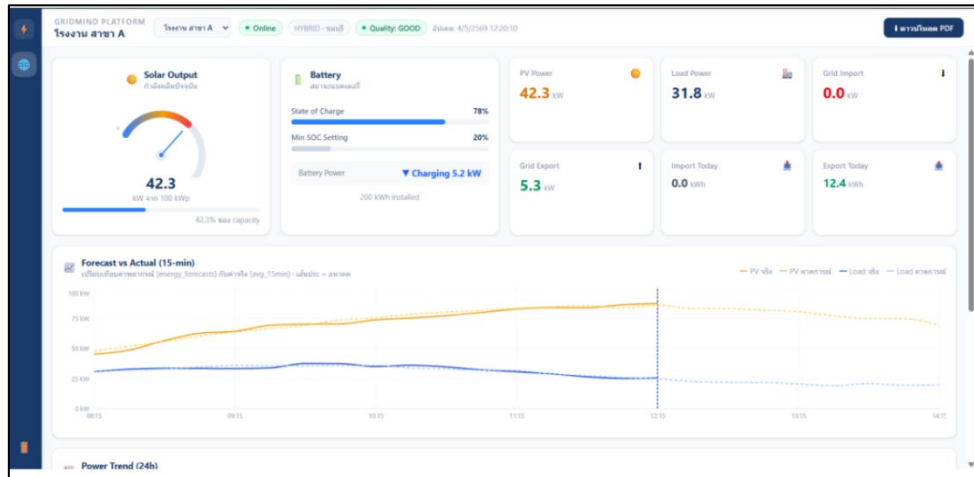


Figure 6. System overview dashboard

4.2 Forecast Accuracy Test Results

The AI forecasting models were evaluated over the shadow-deployment period of 1–7 May 2026 (see Section 3.5) to assess how many actual measured values per day fell within the model's predicted range and how many fell outside it. The Solar dataset contains a maximum of 48 values per day, while the Load dataset contains a maximum of 96 values per day. The results are presented in Tables 2 and 3 below.

Table 2 Solar power forecasting model test results (1–7 May 2026)

Forecast Date	Avg. MAPE	RMSE	Actual Within Range	Actual Outside Range	Accuracy (%)
1 May 2026	6.13%	4.28 kW	44	4	91.7%
2 May 2026	6.20%	4.21 kW	43	5	89.6%
3 May 2026	6.13%	4.21 kW	45	3	93.8%
4 May 2026	6.14%	4.23 kW	43	5	89.6%
5 May 2026	6.12%	4.23 kW	44	4	91.7%
6 May 2026	6.09%	4.26 kW	45	3	93.8%
7 May 2026	6.11%	4.27 kW	43	5	89.6%
Overall average accuracy					91.4%

Table 3 Load forecasting model test results (1–7 May 2026)

Forecast Date	Avg. MAPE	RMSE	Actual Within Range	Actual Outside Range	Accuracy (%)
1 May 2026	20.02%	12.02 kW	67	29	69.79%
2 May 2026	19.94%	12.03 kW	72	24	75.00%
3 May 2026	19.72%	11.98 kW	79	17	82.29%
4 May 2026	19.52%	11.96 kW	71	25	73.96%
5 May 2026	19.52%	11.96 kW	66	30	68.75%
6 May 2026	19.04%	11.89 kW	72	24	75.00%
7 May 2026	18.76%	11.67 kW	68	28	70.83%
Overall average accuracy					73.66%

From Tables 2 and 3, the Solar model achieved an average MAPE ranging from 6.09% to 6.20%, significantly below the target threshold of 15%, reflecting a good level of accuracy. The Load model, in contrast, achieved an average MAPE ranging from 18.76% to 20.02%, still above the target threshold, but showing a consistent downward trend over the seven-day period (from 20.02% to 18.76%), consistent with the automated retraining mechanism that allows the model to improve as additional data accumulates.

5. Conclusion

5.1 Conclusion

The results confirm that the LightGBM framework is well suited to time-series solar power forecasting, consistent with the findings of Yang et al. [5], who reported an R^2 as high as 0.89 using a similar model. The accuracy of the Solar model in this study (MAPE $\approx$ 6%) can therefore be considered acceptable by international standards. In contrast, the Load model's accuracy, which has not yet met the target threshold, reflects the limitation previously identified by Hokmabad et al. [6], who noted that purely data-driven approaches tend to underperform when training data is insufficient — consistent with the situation in this research, where electricity-consumption behavior is highly volatile and the training data is drawn from a single site.

The adaptive retraining mechanism, designed to retrain the model automatically every day at midnight, represents a key strength that enables the system to achieve self-learning in line with the conceptual framework, and helps explain why the Load model's MAPE showed a continuous downward trend throughout the testing period.

In terms of ESG, the system demonstrates that AI's potential extends beyond numerical forecasting to environmental-impact analysis. This is consistent with the broader trend of applying LightGBM to carbon-emission-related problems beyond power forecasting itself, as illustrated by Zhou et al. [11], who used a LightGBM-SHAP framework to model and interpret carbon emissions from building energy variables.

5.2 Future Work

The adoption of Federated Learning would enable co-training of models across multiple solar power sites while maintaining data privacy by avoiding the exchange of raw operational data. Furthermore, integrating physics-based models with data-driven approaches such as LightGBM, as suggested by Hokmabad et al. [6], would improve the robustness and reliability

of forecasts, particularly in situations with limited training data or rapidly changing environments. Expanding the framework to include data from geographically distributed solar installations would be beneficial.

6. Acknowledgement

LEONICS CO.,LTD and Huachiew Chalermprakiet University for their support throughout this research.

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Design and Development of a Prototype Semi-Autonomous Hexacopter for Real-Time Wild Elephant Detection and Deterrence

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Abstract

This study aimed to design and develop a prototype semi-autonomous hexacopter for real-time wild elephant detection and deterrence. The system integrated a 450-mm hexacopter frame, Pixhawk flight controller, GPS and telemetry modules, Raspberry Pi 5, 12-megapixel camera, 60-W LED module, USB speaker, relay module, and ground control station. The prototype was designed to support manual flight, waypoint-based autonomous navigation, aerial monitoring, and light- and sound-based deterrence. Its performance was evaluated through structural assembly, manual flight, autonomous waypoint flight, and detection–deterrence tests. The prototype achieved an overall structural assembly performance of 80.00% and manual flight performance of 90.00%. Autonomous flight across five planned waypoints achieved an average performance of 96.00%. The detection–deterrence test achieved an overall performance of 76.67%, comprising 80.00% for target detection, 80.00% for deterrence-system operation, and 70.00% for ground control station data display. The results indicate that the prototype can integrate aerial monitoring, semi-autonomous navigation, and real-time deterrence within a single platform. Further evaluation under diverse outdoor conditions is required to verify its operational reliability.

Keywords: Semi-autonomous hexacopter; Unmanned aerial vehicle; Wild elephant detection; Elephant deterrence; Real-time monitoring

1. Introduction

Human–elephant conflict is a continuing problem in areas where agricultural land and human settlements overlap with elephant habitats. Habitat loss, land-use change, and the reduction of natural food sources have encouraged elephants to move into agricultural areas, resulting in crop damage, economic loss, and safety risks for local communities [1]–[5]. In Thailand, changes in agricultural land use and the reduction of suitable habitat have also contributed to increased crop-raiding incidents by wild Asian elephants [6]. Several methods have been used to reduce human–elephant conflict, including fences, community patrols, warning systems, fire, light, and sound-based deterrents [2], [7]–[10]. However, many of these methods require continuous maintenance or place personnel close to elephants. Their effectiveness may also vary according to the location, environmental conditions, elephant behavior, and response time. Therefore, a flexible system that can support rapid monitoring and deterrence from a safer distance is needed. Unmanned aerial vehicles (UAVs) provide an alternative platform for wildlife monitoring because they can operate above difficult terrain and collect information over a relatively wide area [11]–[13]. UAVs can also reduce the need for ground personnel to approach areas where elephants are present. Previous field research in Tanzania reported that UAVs were able to encourage elephants to leave crop fields and settlement areas during conflict situations [14]. Nevertheless, drone operations near wildlife

must be carefully controlled because flight altitude, distance, speed, noise, and approach direction may affect animal behavior [15].

This study presents the design and development of a prototype semi-autonomous hexacopter for real-time wild elephant detection and deterrence. The prototype combines a hexacopter airframe, Pixhawk flight controller, ArduPilot firmware, Raspberry Pi 5, camera, LED module, USB speaker, relay module, and ground control station. The system is designed to support manual flight, waypoint-based navigation, aerial observation, deterrence activation, and system-status reporting. The work focuses on the construction and functional evaluation of the prototype under controlled testing conditions.

2. Methodology

The prototype was developed through four connected stages: structural design, control-unit design, prototype fabrication and assembly, and operational configuration. The work focused on integrating a semi-autonomous hexacopter platform with an on-board detection unit and a deterrence mechanism.

2.1 Structural Component Design of the Prototype Semi-Autonomous Hexacopter

The structural components of the prototype were designed using computer-aided design (CAD) software. The airframe was arranged as a hexacopter to accommodate the propulsion system, flight-control components, battery, camera, on-board processing unit, and deterrence devices within a single platform. The structure was divided into four main sections. The upper section consisted of the top cover, GPS mounting support, side covers, and upper arm mounting components. The middle section served as the main equipment compartment and included the control-unit support, aluminum arm mounts, BLDC motor covers, ESC supports, locking components, and battery support with a protective cover. The lower section functioned as the landing structure. It included upper and lower carbon-fiber mounting parts, carbon-fiber rods, and landing supports. A separate mounting section was designed for the deterrence devices, including a support for the LED module, a USB speaker mount, and a housing for the LED control components. This modular arrangement allowed individual parts to be adjusted or replaced during prototype development. The structural design and the main component groups are shown in Fig. 1. In the figure, labels 1–4 refer to the upper section, middle section, lower section, and deterrence-system mounting structure, respectively.

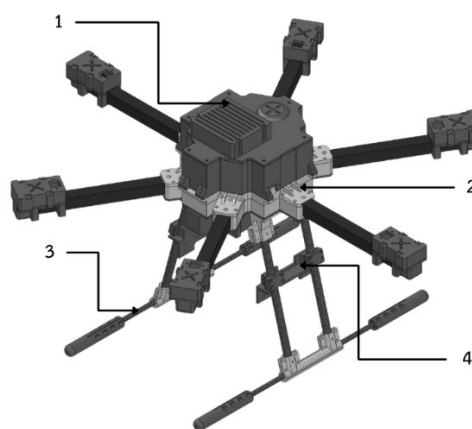


Figure 1 Overall structural design and main component groups of the hexacopter prototype.

2.2 Control Unit Design of the Prototype System

The control unit was designed as two interconnected parts: the flight-control unit and the detection-and-deterrence unit. The flight-control unit was responsible for aircraft movement, stabilization, navigation, and waypoint-based operation. It consisted of a Pixhawk flight controller, telemetry module, receiver module, GPS module, ESC power-management unit, ESC signal-control unit, ESCs, and BLDC motors. The Pixhawk flight controller was configured using ArduPilot firmware. During operation, it received navigation and sensor information for flight stabilization and position control. The controller transmitted signals to the ESCs, which regulated the rotational speed of the six motors. The telemetry module and receiver module supported communication between the aircraft, the remote controller, and the ground control station. The detection-and-deterrence unit was built around a Raspberry Pi 5. A 12 MP camera module was connected to the Raspberry Pi 5 to capture images from the operating area. The unit also included a three-channel relay module, a 12 V 60 W LED module, and a USB speaker. When the detection process identified the target under the specified operating condition, the Raspberry Pi 5 sent a control signal to the relay module to activate the visual and acoustic deterrence devices. The arrangement of the flight-control and detection-and-deterrence components is presented in Fig. 2. Labels 1–7 in the figure represent the telemetry module, Pixhawk flight controller, receiver module, Raspberry Pi 5, ESC signal-control unit, ESC power-management unit, and camera module, respectively.

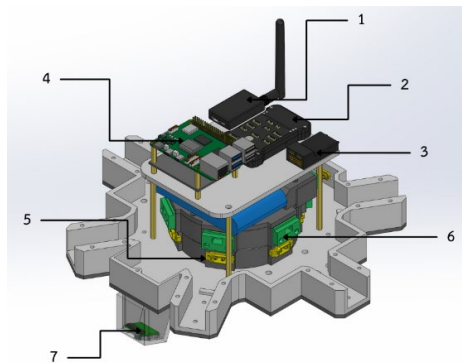


Figure 2 Configuration and internal component layout of the flight-control and detection units.

The integrated design of the structural and control components is shown in Fig. 3. This configuration illustrates how the flight-control, detection, and deterrence devices were installed on the same hexacopter prototype.



Figure 3 Integrated assembly of structural, control, detection, and deterrence subsystems.

2.3 Prototype Fabrication and Assembly

After completing the CAD design, selected structural parts were fabricated using a 3D printer. Additive manufacturing was selected because it allowed the team to produce custom mounting components and revise the design when necessary during assembly. Before fabrication, critical parts were examined through stress simulation to identify areas that could be affected by loading during operation. Printing settings were selected according to the function and installation position of each component. The simulation and fabrication process is shown in Fig. 4.

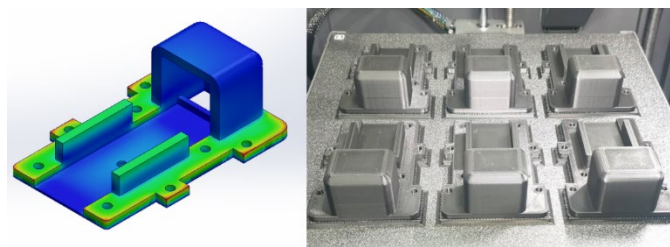


Figure 4 Stress simulation and fabrication process of structural components via additive manufacturing.

Two filament materials were used in the fabrication process: acrylonitrile butadiene styrene (ABS) and carbon-fiber-reinforced polyethylene terephthalate glycol (PETG-CF). These materials were selected for use in different structural components of the prototype. Assembly began with the middle section, followed by the lower structure, deterrence-system mounting section, and upper structure. Components were secured using screws and nuts according to the CAD design. The completed prototype had a diameter of 450.00 mm and a height of 480.00 mm. It used a six-rotor configuration with aluminum box arms measuring 25.40 mm and propellers measuring 381.00 mm. The landing gear was constructed from carbon-fiber rods with a diameter of 16.00 mm. The prototype was powered by a 22.2 V, 10,800 mAh Li-Po battery. The completed semi-autonomous hexacopter prototype is shown in Fig. 5.



Figure 5 The completed prototype of the semi-autonomous hexacopter for real-time operation.

2.4 Operational Design and Programming Configuration

The operating procedure was designed for situations in which information about possible

wild elephant activity is received from a controlled area, community area, or agricultural area. The prototype supports two operating modes based on the observed situation. In Mode 1, the system is used for location tracking and reporting. When an elephant is reported near an area but does not appear to be moving toward it, the drone is deployed to the designated location for observation and detection. The location information can then be reported to the responsible personnel through the ground control station. In Mode 2, the system is used for detection and deterrence. When the elephant is considered likely to approach a community or agricultural area, the drone is sent to the designated location. The on-board camera captures images for detection, and the deterrence devices are activated when the system detects the target according to the configured condition. The LED module and USB speaker are intended to provide visual and acoustic signals as a response mechanism. The overall operational workflow, including manual operation, semi-autonomous flight, detection, deterrence, and ground control station monitoring, is shown in Fig. 6.

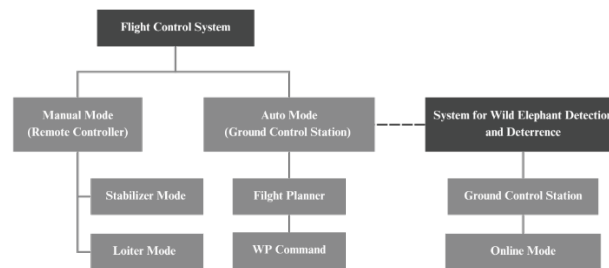


Figure 6 Operational workflow including flight modes, detection, and deterrence responses.

For flight operation, ArduPilot firmware was configured on the Pixhawk flight controller using Mission Planner software. The configuration process included hardware setup, sensor calibration, propulsion-related settings, battery monitoring, and flight-mode selection. The Flight Planner function was used to define waypoint commands and the planned flight path for semi-autonomous missions. The configuration procedure used in Mission Planner is shown in Fig. 7. The process includes mandatory hardware configuration, optional hardware configuration, software parameter settings, and waypoint planning.

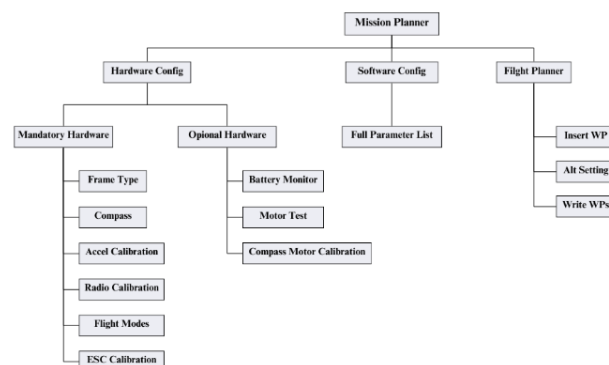


Figure 7 Flight-control configuration and waypoint planning procedure in Mission Planner.

For the detection-and-deterrence function, the camera module continuously captured images and transmitted them to the Raspberry Pi 5 for processing. The detection model was

prepared using annotated images of wild elephants and background scenes. Dataset preparation and annotation were carried out using the Roboflow platform. The YOLOv8 model was trained using Google Colab and later exported in TensorFlow Lite format for deployment on the Raspberry Pi 5. During operation, the Raspberry Pi 5 processed incoming images using the deployed model. When the target was detected, the Raspberry Pi 5 sent a command to the relay module. The relay then controlled the LED module and USB speaker. The system was designed so that the detection result, deterrence response, and operational information could be monitored through the ground control station. The connection and operational sequence of the real-time detection and deterrence subsystem are presented in Fig. 8.

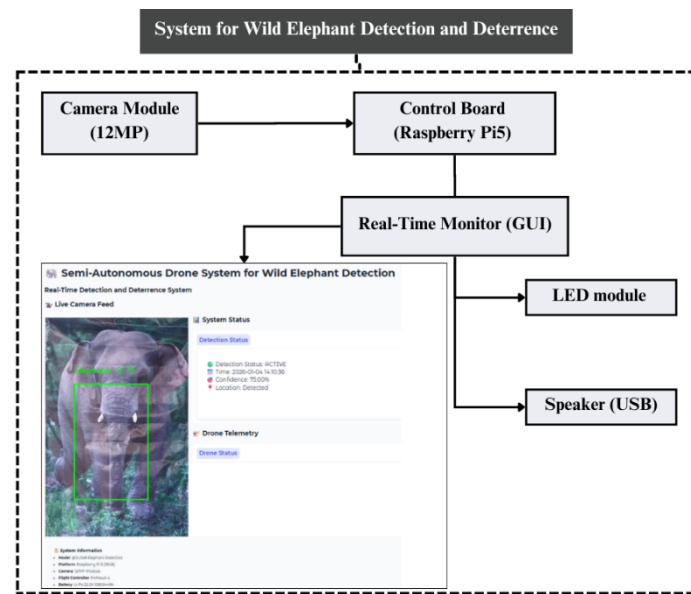


Figure 8 Connection and execution logic of the real-time detection and deterrence subsystem.

3. Testing

The prototype was evaluated through four functional tests: structural assembly, manual flight, semi-autonomous waypoint flight, and real-time target detection with deterrence activation. These tests were designed to assess the main functions described in Section III, including structural installation, flight control, waypoint navigation, target detection, deterrence response, and ground control station (GCS) reporting.

The results are reported as performance percentages based on the successful outcomes observed during each test. Since the experiments were conducted at the prototype level and under controlled conditions, the results represent preliminary functional performance rather than complete field validation.

3.1 Structural Assembly Test

The structural assembly test evaluated the installation of the upper structure, middle structure, lower structure, and deterrence-system mounting structure according to the CAD design. The upper structure achieved an assembly performance of 70%, while the middle and lower structures achieved 80%. The deterrence-system mounting structure recorded the highest performance at 90%, as shown in Fig. 9. The lower performance of the upper and middle structures was mainly associated with the installation of components and the load applied by the propulsion system and other equipment. The average structural assembly performance was 80%.

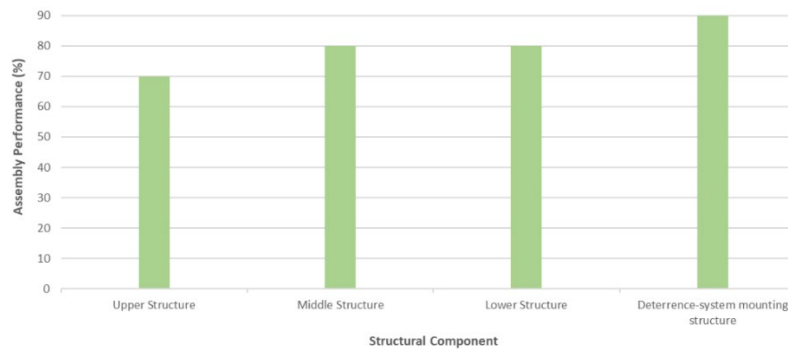


Figure 9 Structural assembly performance of the prototype hexacopter.

3.2 Manual Flight Test

Manual flight performance was evaluated in Stabilize and Loiter modes based on four flight-control functions: pitch, roll, throttle, and yaw, as shown in Fig. 10. In Stabilize mode, the recorded performance values were 70% for pitch, 90% for roll, 70% for throttle, and 90% for yaw. The average performance in Stabilize mode was 80%. In Loiter mode, all four flight-control functions achieved 100% performance, resulting in an average performance of 100%.

The results indicate that the prototype could be manually controlled in both flight modes. Stabilize mode required more continuous pilot correction during changes in flight position and attitude, whereas Loiter mode provided more stable position control. The overall manual flight performance was 90%.

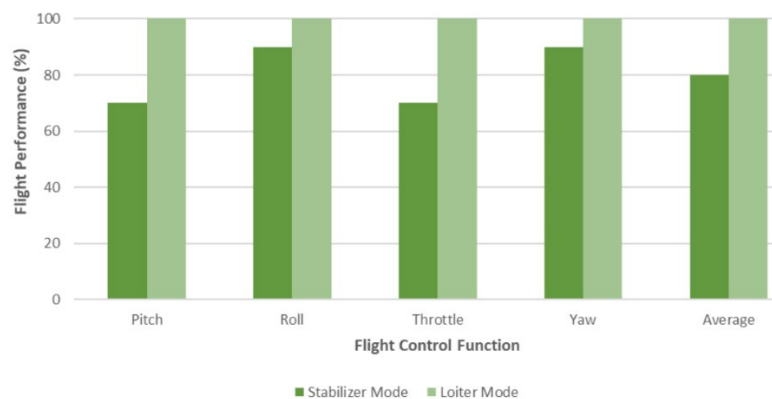


Figure 10 Manual flight performance in Stabilize and Loiter modes.

3.3 Semi-Autonomous Waypoint Flight Test

The semi-autonomous flight test evaluated the prototype along a planned route consisting of five waypoint functions: WP1 for takeoff, WP2 for hovering, WP3 for forward movement, WP4 for hovering, and WP5 for landing. The test results are presented in Fig. 11. WP1, WP2, and WP5 achieved a performance of 100%. WP3 and WP4 achieved 90%. The average performance across the five waypoint functions was 96%.

The lower performance observed at WP3 and WP4 was associated with the time required for the GPS module to acquire a stable signal, wind conditions, and the movement parameters configured in Mission Planner. These parameters may require further adjustment to improve the accuracy and smoothness of autonomous movement.

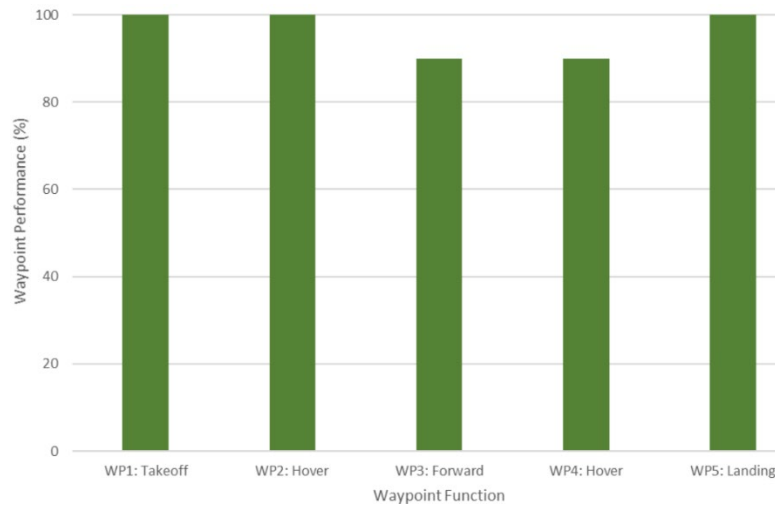


Figure 11 Semi-autonomous waypoint performance during the planned flight mission.

3.4 Real-Time Detection and Deterrence Test

The real-time detection and deterrence test evaluated three functions: target detection, deterrence activation, and GCS reporting. The test was conducted over 10 rounds using an elephant model in a controlled environment. This arrangement allowed the connection between the camera, Raspberry Pi 5, relay module, LED module, USB speaker, and GCS to be evaluated safely. The target detection function achieved a success rate of 80%, while deterrence activation also achieved 80%. The GCS reporting function achieved 70%, as shown in Fig. 12. The average performance of the three functions was 76.67%.

The results confirm that the prototype was able to perform the basic sequence of image capture, target detection, deterrence activation, and information reporting. Nevertheless, the GCS reporting result indicates that the communication and data-display process requires further improvement. In addition, because the test used an elephant model rather than live wild elephants, the results should be interpreted as preliminary functional results. They should not be considered representative of the system's final performance under real field conditions.

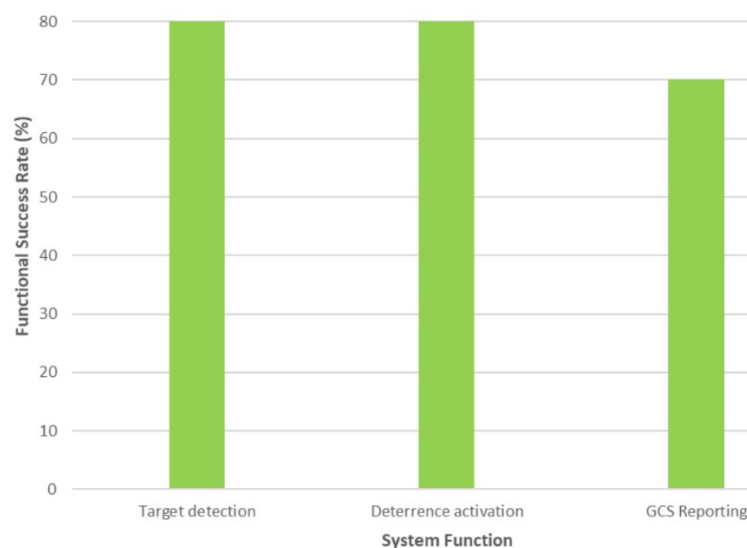


Figure 12 Functional success rates of target detection, deterrence activation, and GCS reporting.

4. Conclusion

This study presented the design and development of a prototype semi-autonomous hexacopter for real-time wild elephant detection and deterrence. The prototype integrated a hexacopter airframe, Pixhawk flight controller, ArduPilot firmware, Raspberry Pi 5, camera module, LED module, USB speaker, relay module, and ground control station into a single operational platform. The prototype was evaluated through structural assembly, manual flight, semi-autonomous waypoint flight, and real-time detection and deterrence tests. The structural assembly test achieved an average performance of 80%, while the manual flight test achieved an average performance of 90%. The semi-autonomous waypoint flight test produced the highest average performance of 96%. The real-time detection and deterrence test achieved an average functional success rate of 76.67%, including target detection, deterrence activation, and GCS reporting. The results indicate that the prototype was able to perform the basic sequence of flight operation, target detection, deterrence activation, and information reporting under controlled test conditions. However, the results should be considered preliminary because the detection test used an elephant model rather than live wild elephants, and the system has not yet been fully evaluated under diverse outdoor field conditions.

The prototype provides a foundation for further development of a semi-autonomous UAV platform for monitoring and deterring wild elephant intrusion. Future work should include field testing under different lighting, weather, distance, and background conditions. Additional evaluation should also report standard object-detection metrics, including precision, recall, F1-score, and mAP@0.5. Measurements of end-to-end system latency and battery endurance should be included to assess the suitability of the system for extended real-time operation.

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Comparative Study of Deep Learning Models for Glass Bottle Defect Detection using CiRA CORE ClassifTrain Platform

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Abstract

This study presents a comparative evaluation of five deep learning architectures for glass bottle defect detection: CiRAedNet (a Thai-developed model), MobileNet-V2, EfficientNet-B0, ResNet-18, and ResNet-50, implemented through the Thai-developed CiRA CORE ClassifTrain platform, a no-code tool that requires no programming expertise. All models were evaluated on the MVTec Anomaly Detection Dataset (Bottle category), an international benchmark. The objective is to identify the most suitable model for small and medium enterprises (SMEs) considering both accuracy and computational complexity. Experimental results revealed that CiRAedNet, with only 44,914 parameters, achieved the highest test accuracy of 91.38% and F1-score of 91.68%, outperforming ResNet-50 (25.6 million parameters, 84.48%) by 6.90 percentage points. Remarkably, CiRAedNet was the only model showing a positive generalization gap (+3.88%), while all other models exhibited significant overfitting. These findings demonstrate that domain-specific lightweight architectures can outperform large ImageNet-pretrained models on small industrial datasets (n=234), providing a practical solution for Thai SMEs adopting AI-based quality inspection.

Keywords: Defect Detection; CiRA CORE; Deep Learning; ClassifTrain; CiRAedNet

1. Introduction

Quality inspection in the glass bottle manufacturing industry is a critical process ensuring consumer safety and production efficiency. Currently, most inspection still relies on human inspectors, which has limitations regarding fatigue, consistency, and labor cost [1].

Deep Learning technology has been proven effective in solving this problem. The MVTec Anomaly Detection (AD) Dataset [2] has become the international benchmark for evaluating defect detection models. Recent work by Rezvani Boroujeni et al. (2025) [3] applied diffusion models to augment glass defect datasets and compared several CNN architectures for industrial glass inspection.

However, deploying Deep Learning in Thai small and medium enterprises (SMEs) still faces obstacles: programming complexity and lack of skilled personnel. The CiRA CORE platform [4], developed in Thailand, is a no-code tool that reduces this barrier, but it has not been systematically benchmarked on international standard datasets.

This research presents three contributions: (1) the first systematic benchmark of CiRA CORE ClassifTrain on the MVTec Bottle Dataset, (2) the first evaluation of CiRAedNet, a Thai-developed architecture, against international models, and (3) a trade-off analysis between accuracy and model complexity, beneficial for Thai SMEs.

2. Related Work

2.1 MVTec AD Dataset

Bergmann et al. [2] introduced MVTec AD as the first production-quality dataset for Industrial Anomaly Detection, covering 15 product categories including the glass bottle used in this research.

2.2 PatchCore and State-of-the-Art Models

Roth et al. [5] proposed PatchCore using a ResNet-50 backbone, achieving approximately 99% AUROC on MVTec Bottle. However, PatchCore requires complex Python programming, making it unsuitable for SME-level users.

2.3 Comparison by Boroujeni et al.

Rezvani Boroujeni et al. (2025) [3] addressed the class-imbalance problem in industrial glass manufacturing by using Denoising Diffusion Probabilistic Models (DDPMs) to generate synthetic defective glass images, comparing CNN architectures including ResNet50V2, EfficientNetB0, and MobileNetV2 implemented in Python and TensorFlow. While their diffusion-based augmentation improved recall for the minority defect class, the approach requires advanced programming skills, which is the gap this study addresses through a no-code platform.

2.4 CiRA CORE Platform

CiRA CORE [4] is a low-code/no-code platform developed in Thailand. It supports GPU acceleration via CUDA and offers 15 models in the ClassifTrain Node, including CiRAedNet, a lightweight architecture specifically designed for industrial inspection tasks.

3. Objectives

The objectives of this research are as follows:

(1) To establish the first systematic benchmark of the CiRA CORE ClassifTrain platform on the MVTec AD Bottle Dataset, an international standard dataset, in order to verify its applicability for industrial defect detection research.

(2) To evaluate and compare the performance of the Thai-developed CiRAedNet architecture against four internationally recognized deep learning models (MobileNet-V2, EfficientNet-B0, ResNet-18, and ResNet-50) in terms of accuracy, precision, recall, and F1-score.

(3) To analyze the trade-off between model accuracy and computational complexity, providing practical recommendations for small and medium enterprises (SMEs) in Thailand seeking to adopt AI-based quality inspection.

4. Methodology

The proposed framework consists of eight sequential steps, as illustrated in Figure 1. The process begins with (1) Data Collection, in which 292 images of glass bottles are obtained from the MVTec AD Bottle Dataset. Next, (2) Data Preprocessing and Restructuring organizes the images into a binary classification structure, splitting them into a training set of 234 images and a test set of 58 images. In step (3), the five deep learning models are selected and divided into two groups: lightweight models (CiRAedNet, MobileNet-V2, and EfficientNet-B0) and medium-sized models (ResNet-18 and ResNet-50). Step (4) performs Model Training through the CiRA CORE ClassifTrain Node using an input size of 224x224 pixels, a batch size of 64, and approximately 10,000 iterations. After training, step (5) conducts Model Evaluation using the EvalClassif Node with a threshold of 0.50. Step (6) computes the Performance Metrics, including accuracy, precision, recall, F1-score, and the confusion matrix. In step (7), a

Generalization Gap Analysis examines the trade-off between accuracy and model complexity by comparing test and training accuracy. Finally, step (8) draws a Comparative Conclusion to identify the most suitable model for SME deployment.

Proposed Framework Flow Chart

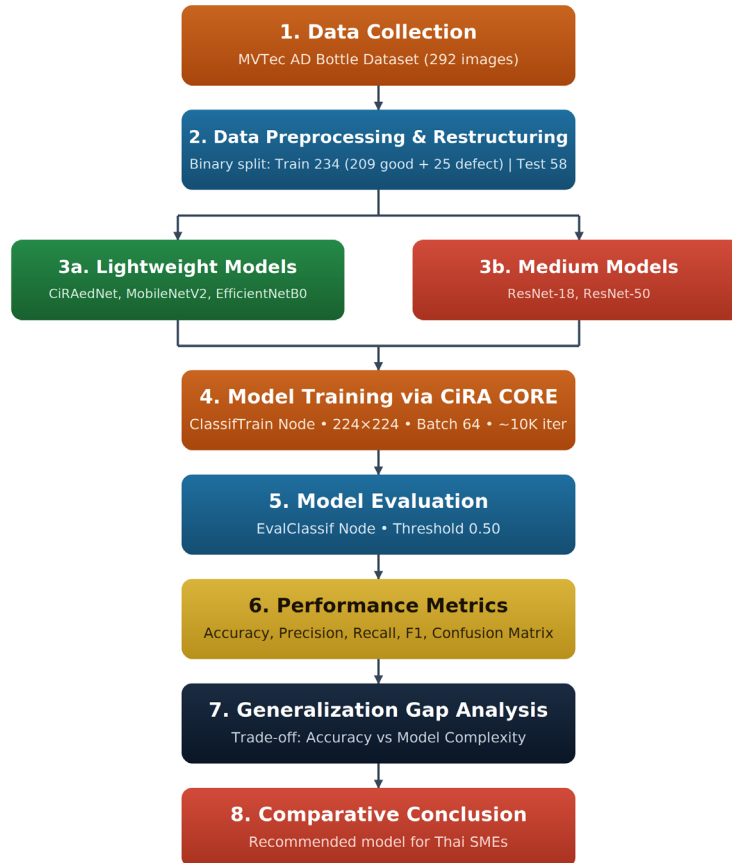


Figure 1 Methodology Flow Chart of the Proposed Framework

4.1 Dataset and Preparation

We used the MVTec AD Dataset [2], specifically the Bottle category, comprising 292 images at 900x900 pixels. It includes 229 normal (good) images and 63 defect images covering three types: broken_large (20), broken_small (22), and contamination (21). Defect images were randomly split at a 40:60 ratio into Train and Test sets, resulting in a Train set of 234 images (209 good + 25 defect) and a Test set of 58 images (20 good + 38 defect). Figure 2 shows examples of each defect type.

MVTec AD Bottle Dataset - Image Examples



Figure 2 Defect Types in Glass Bottles (MVTec Dataset)

4.2 Models Compared

We selected five models across two groups. Lightweight models: (1) CiRAedNet with 44,914 parameters (Thai-developed), (2) MobileNet-V2 with 3.4M [6], and (3) EfficientNet-B0 with 5.3M [7]. Medium models: (4) ResNet-18 with 11.7M and (5) ResNet-50 with 25.6M parameters [8].

4.3 Model Training

Training was performed through the CiRA CORE ClassifTrain Node. All models used an input size of 224x224 pixels, batch size of 64, sub-divisions of 8, and approximately 10,000 iterations, with data augmentation and class balancing enabled. Training ran on an NVIDIA RTX GPU via CUDA.

4.4 Model Evaluation

We used the EvalClassif Node of CiRA CORE to test the trained models on the Test set with a threshold of 0.50. Performance metrics include accuracy, precision, recall, F1-score, and the confusion matrix. We also computed the generalization gap between test and train accuracy to assess overfitting.

5. Experiments and Results

5.1 Training Results

Table 1 shows the training results for all five models. MobileNet-V2 achieved the highest training accuracy of 100.00% and the lowest loss of 0.010, followed by ResNet-50 (93.75%) and EfficientNet-B0 (92.92%). CiRAedNet and ResNet-18 both achieved 87.50%. Figure 3 shows the training screenshot of CiRAedNet from CiRA CORE ClassifTrain.

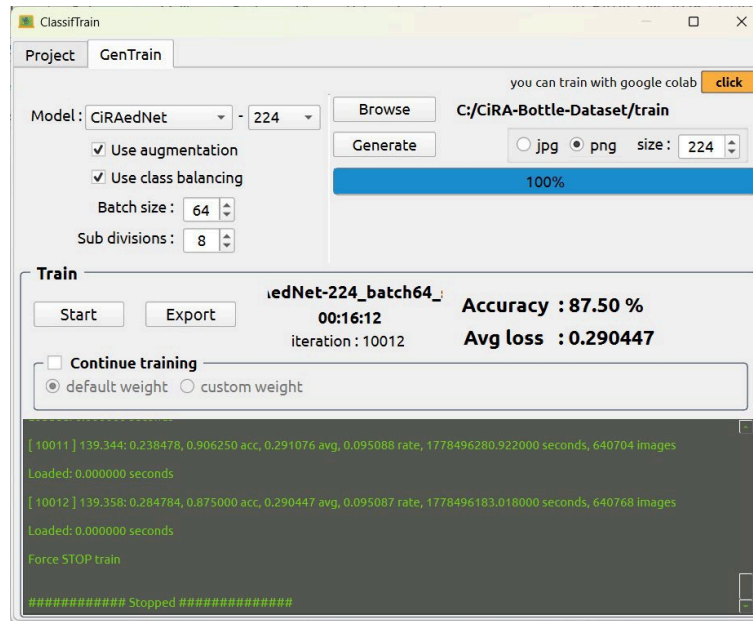


Figure 3 Training Screenshot of CiRAedNet from CiRA CORE ClassifTrain

Table 1 Training Results of Five Models

Model	Train Acc	Avg Loss	Time
CiRAedNet	87.50%	0.290	16:12
MobileNet-V2	100.00%	0.010	47:49
EfficientNet-B0	92.92%	0.700	83:31
ResNet-18	87.50%	0.143	32:57
ResNet-50	93.75%	0.182	82:00

5.2 Test Results

Test results on 58 images are shown in Table 2. The reported precision, recall, and F1-score are macro-averaged across the defect and good classes, as provided by the CiRA CORE EvalClassif Node, to give a balanced measure on the imbalanced test set. CiRAedNet achieved the highest test accuracy of 91.38% and macro F1-score of 91.68%, followed by ResNet-18 (89.66%), MobileNet-V2 (87.93%), ResNet-50 (84.48%), and EfficientNet-B0 (77.59%). Figure 4 shows the test confusion matrix of CiRAedNet, where the per-class view of the same result reports 100% precision and 86.84% recall for the defect class.

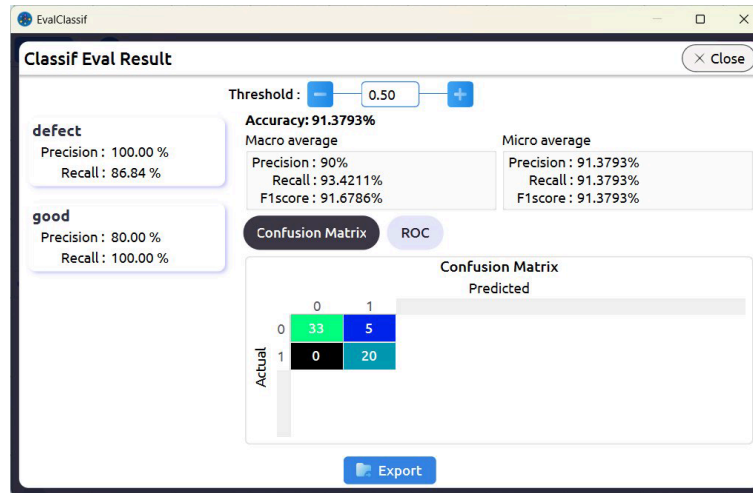


Figure 4 Test Confusion Matrix of CiRAedNet (Accuracy 91.38%)

Table 2 Test Results of Five Models (Precision, Recall, and F1-score are macro-averaged over both classes)

Model	Accuracy	Precision	Recall	F1-score
CiRAedNet	91.38%	90.00%	93.42%	91.68%
MobileNet-V2	87.93%	87.04%	90.79%	88.87%
EfficientNet-B0	77.59%	80.30%	82.89%	81.58%
ResNet-18	89.66%	88.46%	92.11%	90.25%
ResNet-50	84.48%	84.48%	88.16%	86.28%

5.3 Confusion Matrix Analysis

Table 3 shows the confusion matrix for all five models. All models achieved 100% precision for the defect class (no false positives), but differed in defect-class recall, indicating the number of missed defects. CiRAedNet missed only 5 of the 38 defect images (86.84% defect recall), while EfficientNet-B0 missed 13 (65.79%). This per-class view complements the macro-averaged metrics in Table 2 and confirms that CiRAedNet is the most reliable model at catching true defects.

Table 3 Confusion Matrix of Five Models

Model	TP	TN	FP	FN
CiRAedNet	33	20	0	5
MobileNet-V2	31	20	0	7
EfficientNet-B0	25	20	0	13
ResNet-18	32	20	0	6
ResNet-50	29	20	0	9

6. Discussion

6.1 CiRAedNet Outperforms Larger Models

The experiment revealed that CiRAedNet (44,914 parameters) achieved a test accuracy higher than ResNet-50 (25.6 million) by 6.90 percentage points, and also outperformed MobileNet-V2 and EfficientNet-B0. This supports the hypothesis that domain-specific models can outperform general-purpose models on specialized datasets.

6.2 Generalization Gap Analysis

Table 4 shows the generalization gap (test minus train accuracy) for all five models. CiRAedNet is the only model with a positive gap (+3.88%), indicating no overfitting, while EfficientNet-B0 has the largest negative gap (-15.33%), reflecting severe overfitting. This

phenomenon likely stems from EfficientNet's compound scaling design, which is optimized for large datasets such as ImageNet.

Table 4 Generalization Gap of Five Models

Model	Train Acc	Test Acc	Gap
CiRAedNet	87.50%	91.38%	+3.88
ResNet-18	87.50%	89.66%	+2.16
MobileNet-V2	100.00%	87.93%	-12.07
ResNet-50	93.75%	84.48%	-9.27
EfficientNet-B0	92.92%	77.59%	-15.33

6.3 Impact on Thai SMEs

Our findings have significant implications for Thai SMEs. Since CiRAedNet is Thai-developed and can be used through CiRA CORE without programming, requires minimal resources (44,914 parameters), is suitable for edge devices, and provides higher accuracy than more complex international models, this discovery reduces the barrier to AI adoption for SMEs and promotes the use of locally developed technology.

6.4 Limitations and Future Work

This study is limited by a small test set (58 images) and considers only the Bottle category. Future work should extend to other MVTec categories and test with real Thai industrial datasets, as well as consider edge device deployment in production lines.

7. Conclusion

This research compared five deep learning models on the MVTec Bottle Dataset using CiRA CORE ClassifTrain. We found that CiRAedNet, developed in Thailand, achieved the highest test accuracy at 91.38% and F1-score of 91.68%, exceeding ResNet-50 by 6.90 percentage points despite having 570 times fewer parameters. The research demonstrates that (1) CiRA CORE is a viable platform for industrial AI research, (2) CiRAedNet has sufficient performance to compete with international models, and (3) on small datasets, smaller domain-specific models tend to outperform ImageNet-pretrained models.

Acknowledgement

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Deep Learning-Based Classification of Pole-Top Equipment Configurations Using Transfer Learning: A Comparative Study of MobileNetV2, ResNet-18, and ResNet-152

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Abstract

Accurate identification of pole-top equipment configurations is important for supporting field inspection and asset registration of medium-voltage distribution poles. This paper presents a deep learning-based image classification approach for recognizing six standard pole-top configuration classes defined by utility engineering drawings: SP.1 (Single Pin Insulator 1 Phase), SP.3 (Single Pin Insulator 3 Phase), SP.AL.3 (Single Pin Alley 3 Phase), DP.1 (Double Pin Insulator 1 Phase), DP.3 (Double Pin Insulator 3 Phase), and CSC (Cable Spacer with X-Arm). A dataset of 300 images, balanced across the six classes (50 images per class), was collected from actual field operations and used to train and compare three convolutional neural network architectures under a transfer-learning setting: MobileNetV2, ResNet-18, and ResNet-152, trained on the Google Colab platform with a batch size of 64 and a subdivision of 8, for approximately 2,000 to 2,400 training iterations. Experimental results show that MobileNetV2 achieved the highest classification accuracy of 93.8% with an average loss of 0.1764, substantially outperforming ResNet-18 (70.3% accuracy, average loss 0.5973) and ResNet-152 (64.1% accuracy, average loss 0.9944), while also requiring the shortest training time and, at 2.27 million parameters and 8.65 MB, the smallest model size among the three architectures. On an independent test set of 90 field images, MobileNetV2 maintained the strongest generalization performance, with 88.89% accuracy and an 88.34% macro-averaged F1-score. The results suggest that, for a utility-specific dataset of this scale, a lightweight architecture generalizes considerably better than deeper networks, making MobileNetV2 a practical candidate for field-deployable pole-top configuration classification systems.

Keywords: image classification; deep learning; transfer learning; MobileNetV2; ResNet, pole-top equipment

1. Introduction

Reliable operation of the electrical distribution network depends heavily on the physical condition and correct configuration of pole-top equipment, such as cross-arms, insulators, cutout switches, and conductor arrangements. Distribution utilities typically define a set of standard pole-top configurations to guide construction and maintenance. Verifying that field poles conform to these standard configurations is currently performed manually by technicians during field inspection, a process that is time-consuming and dependent on individual experience.

Recent advances in deep learning, particularly convolutional neural networks (CNNs), have enabled automated visual inspection systems for power infrastructure with promising accuracy [1], [2]. However, most existing studies focus on detecting individual components,

such as insulators or arresters, within an image [3], [4], rather than classifying an entire pole-top image into a predefined configuration class. Configuration-level classification is a practical need for utilities during asset registration and standard-compliance auditing, yet it has received comparatively little attention in the literature, particularly for small, utility-specific datasets typical of field data collection.

This paper addresses this gap by proposing an image classification approach that categorizes pole-top images into six standard configuration classes. Three CNN architectures with different depth and computational cost—MobileNetV2, ResNet-18, and ResNet-152—are trained using transfer learning and compared under identical training conditions. The objective is to identify which architecture provides the best accuracy-efficiency trade-off for this small-dataset, utility-specific classification task.

2. Related Work

Several studies have applied deep learning to power infrastructure inspection. Yang et al. proposed SGI-YOLOv9, an improved YOLOv9-based detector for identifying crucial components in the power distribution network, incorporating a downsampling module and a global context fusion module to improve small-object detection accuracy under complex backgrounds [3]. Liu et al. proposed PD-YOLOv11 for power transmission tower component detection in UAV inspection imagery, combining backbone, neck, and detection-head improvements to handle multi-scale and small-target components [4]. These studies demonstrate the effectiveness of deep learning for object-level detection of individual power infrastructure components.

For the underlying classification backbones, He et al. introduced the residual learning framework (ResNet), which enables training of substantially deeper networks by mitigating the vanishing-gradient problem through identity shortcut connections [1]. Sandler et al. proposed MobileNetV2, a lightweight architecture built on inverted residual blocks with linear bottlenecks, designed to reduce computational cost while maintaining competitive accuracy, making it well suited for resource-constrained and mobile deployment scenarios [2].

The challenge of training deep CNNs on small datasets has also been studied extensively outside the power-infrastructure domain. Pasupa and Sunhem statistically compared shallow classifiers (support vector machine and single-hidden-layer artificial neural network) with a deep CNN on a small image dataset, finding that the shallow models achieved better average performance than an unregularized CNN, and that regularization techniques such as dropout and data augmentation were necessary for the deep model to remain competitive [5]. Similarly, the deep transfer learning survey by Plested and Gedeon observes that transferring fewer layers and adopting lighter architectures tends to yield better performance when the target dataset is small and only loosely related to the pretraining domain, whereas fine-tuning more layers of a deeper network is more beneficial when the target dataset is larger [6]. These findings are consistent with the accuracy trend observed among MobileNetV2, ResNet-18, and ResNet-152 in this study, as discussed further in Section 4.

While the works above focus on detecting individual components within an image, fewer studies address image-level classification of complete pole-top configurations against a utility-defined standard taxonomy using a small, field-collected dataset. This paper contributes an empirical comparison of transfer-learning performance across architectures of varying depth for this specific classification task, and relates the observed accuracy trend to the broader literature on deep learning with limited training data.

3. Methodology

3.1 Dataset Collection and Annotation

A total of 300 images of pole-top equipment were collected from actual field operations and manually labeled into six standard configuration classes according to utility engineering drawings: SP.1 (Single Pin Insulator 1 Phase), SP.3 (Single Pin Insulator 3 Phase), SP.AL.3 (Single Pin Alley 3 Phase), DP.1 (Double Pin Insulator 1 Phase), DP.3 (Double Pin Insulator 3 Phase), and CSC (Cable Spacer with X-Arm). Each of the six classes is represented by 50 images, forming a balanced dataset of 300 images used for model training. A separate, independently collected test set of 90 images (15 images per class) was reserved exclusively for evaluating generalization performance, as reported in Section 4.1, corresponding to a 70/0/30 train/validation/test split; no distinct validation subset was held out, and training progress was instead monitored via the training loss reported in Table 1. Images were captured under real field conditions, resulting in natural variation in lighting, viewing angle, and background complexity, as illustrated in Figure 1.

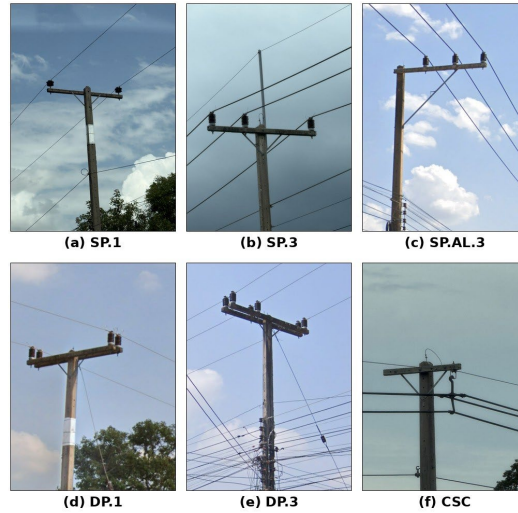


Figure 1 Example field images of the six pole-top equipment configuration classes: (a) SP.1, (b) SP.3, (c) SP.AL.3, (d) DP.1, (e) DP.3, (f) CSC

3.2 Model Architectures

Three CNN architectures were selected for comparison to evaluate the trade-off between model depth and performance on a small dataset: MobileNetV2, a lightweight architecture using inverted residual blocks with linear bottlenecks [2]; ResNet-18, a moderately deep residual network with 18 weighted layers [1]; and ResNet-152, a substantially deeper residual network with 152 weighted layers [1]. All three models were initialized with pretrained weights and fine-tuned on the collected pole-top image dataset using transfer learning.

3.3 Training Configuration

All models were initialized with pretrained weights and fine-tuned using the CiRA ClassifTrain Colab trainer (CiRA-AMI), a Darknet-based training framework, on a Google Colab instance with an NVIDIA T4 GPU backend. Prior to training, the CiRA ClassifTrain Colab DataGen stage was used to generate additional augmented training images via random rotation (-180° to 180° , in steps of 90°), contrast adjustment (0.2–1.2, in steps of 1.0), noise injection (up to a maximum level of 10, in steps of 10), and blur (up to a maximum level of 9, in steps of 9); these settings were identical across all three architectures. During training itself, the Darknet backend additionally applied on-the-fly jitter of rotation (up to $\pm 7^\circ$), hue (± 0.1),

saturation (up to ± 0.75), exposure (up to ± 0.75), and aspect ratio (up to ± 0.75).

Training used stochastic gradient descent with a momentum of 0.9 and L2 weight decay of 0.0005, a polynomial learning-rate decay policy (power = 4), and a batch size of 64 split into 8 subdivisions per iteration — that is, each batch of 64 images was processed as 8 sequential mini-batches of 8 images to stay within GPU memory limits. Architecture-specific settings differed as follows: MobileNetV2 was trained at an input resolution of 224×224 with an initial learning rate of 0.01, whereas ResNet-18 and ResNet-152 were trained at 256×256 with an initial learning rate of 0.1. Training was conducted for approximately 2,000 to 2,400 iterations per model — corresponding to 429, 518, and 452 epochs for MobileNetV2, ResNet-18, and ResNet-152, respectively, given the 300-image training set — with the exact iteration count, average training loss, and total training time recorded for each architecture, as summarized in Table 1.

4. Results and Discussion

Model performance was evaluated using classification accuracy and average training loss at the final recorded iteration. Total training time was also recorded for each architecture to assess practical feasibility for field deployment, where computational resources and training turnaround time are often constrained.

Table 1 Classification performance comparison

Model	Accuracy (%)	Avg. Loss	Iterations	Epochs	Training Time
MobileNetV2	93.8	0.1764	2,012	429	31:10
ResNet-18	70.3	0.5973	2,431	518	36:10
ResNet-152	64.1	0.9944	2,122	452	1:39:22

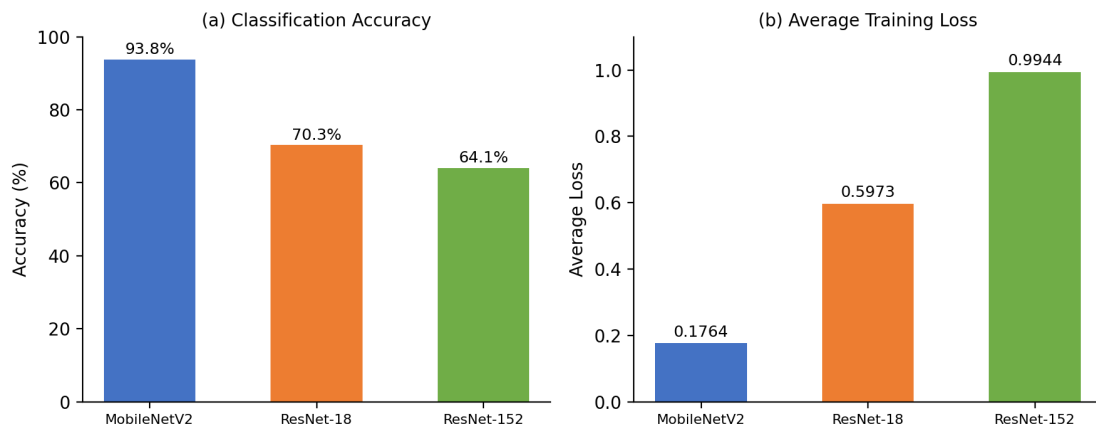


Figure 2 Comparison of (a) classification accuracy and (b) average training loss across the three architectures

Table 1 summarizes the classification performance of the three architectures, and Figure 2 visualizes the accuracy and average loss comparison. MobileNetV2 achieved the highest accuracy of 93.8%, with the lowest average loss of 0.1764, after 2,012 iterations and a training time of 31 minutes 10 seconds. ResNet-18 reached 70.3% accuracy with an average loss of 0.5973 after 2,431 iterations, requiring 36 minutes 10 seconds. ResNet-152 achieved the lowest

accuracy of 64.1%, with an average loss of 0.9944 after 2,122 iterations, and required the longest training time of 1 hour 39 minutes 22 seconds.

These results indicate an inverse relationship between network depth and classification performance on this dataset. Part of this gap is attributable to training configuration: MobileNetV2 was trained at 224×224 resolution with a learning rate of 0.01, whereas both ResNet variants were trained at 256×256 resolution with a learning rate of 0.1 — ten times higher (Section 3.3) — which may have led to less stable convergence for the ResNet variants within the available iteration budget. This is compounded by dataset size: with a training set of 300 images across six classes (50 images per class), the substantially larger parameter space of ResNet-152 is prone to overfitting or insufficient convergence, whereas the lightweight MobileNetV2 architecture generalizes more effectively from limited training data. This trend is consistent with the small-dataset findings of Pasupa and Sunhem [5] and the transfer-learning guidance of Plested and Gedeon [6], both of which suggest that lighter models or shallower fine-tuning are preferable when the target dataset is small. In addition to its superior accuracy, MobileNetV2 also required the shortest training time among the three architectures, making it the most practical choice for field-deployable classification systems where both accuracy and computational efficiency are important considerations.

To quantify this efficiency difference directly, Table 3 reports the number of trainable parameters, on-disk model size, and computational cost (in giga floating-point operations, GFLOPs, at each architecture's respective input resolution) for the three trained models, computed from their network definitions and cross-validated against the corresponding weight files. MobileNetV2 requires only 2.27 million parameters and 8.65 MB of storage, roughly 5 times smaller than ResNet-18 (11.01 million parameters, 42.01 MB) and 24 times smaller than ResNet-152 (55.52 million parameters, 211.80 MB).

Computationally, MobileNetV2 requires approximately 0.86 GFLOPs per inference at its 224×224 input resolution, compared with 4.69 GFLOPs for ResNet-18 and 29.13 GFLOPs for ResNet-152 at their 256×256 input resolution — roughly 5 times and 34 times more computation, respectively. All models were trained and evaluated on the same Google Colab T4 GPU instance described in Section 3.3; per-image inference latency was not separately benchmarked, so these GFLOPs figures do not directly measure wall-clock inference time, but they corroborate the training-time results in Table 1 and further support MobileNetV2 as the more practical choice for resource-constrained, field-deployable inspection systems.

Table 3 Model size and computational cost comparison

Model	Parameters (M)	Model Size (MB)	Input Resolution	GFLOPs
MobileNetV2	2.27	8.65	224×224	0.86
ResNet-18	11.01	42.01	256×256	4.69
ResNet-152	55.52	211.80	256×256	29.13

4.1 Confusion Matrix Analysis

To further assess the generalization ability of each architecture beyond the training accuracy reported in Table 1, each trained model was evaluated on an independent test set of 90 field images (15 images per class) covering all six pole-top configuration classes. Figure 3 presents the resulting confusion matrices for (a) MobileNetV2, (b) ResNet-18, and (c) ResNet-152, and Table 2 reports the corresponding per-class precision, recall, and F1-score.

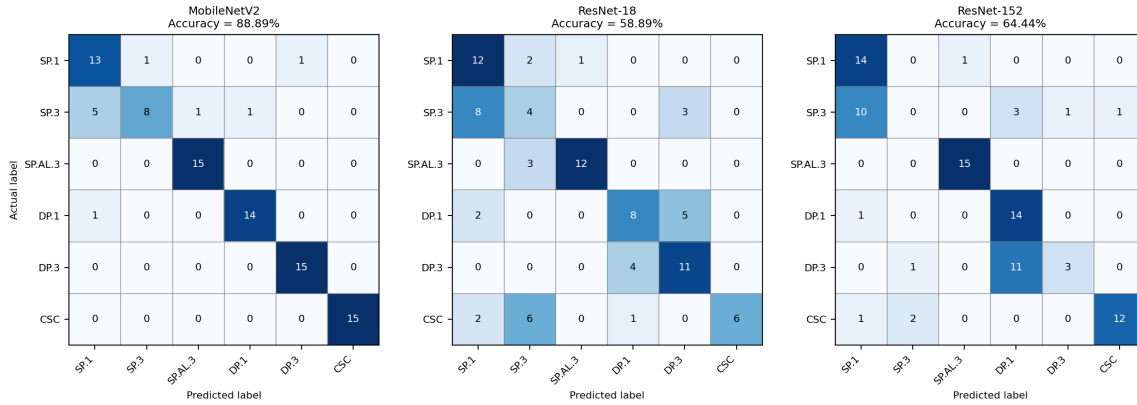


Figure 3 Confusion matrices of (a) MobileNetV2, (b) ResNet-18, and (c) ResNet-152 evaluated on the independent test set

MobileNetV2 achieved a test-set accuracy of 88.89% (80 of 90 images) and a macro-averaged F1-score of 88.34%. Its main source of error was confusion between SP.1 and SP.3, two visually similar single-pin configurations: 5 of 15 SP.3 images were misclassified as SP.1, giving SP.3 the lowest recall (53.33%) among the six classes, while SP.AL.3, DP.3, and CSC were classified without error.

ResNet-18 reached a test-set accuracy of 58.89% (53 of 90 images) and a macro-averaged F1-score of 58.82%. Errors were spread across several class pairs, most notably SP.1 versus SP.3 (8 of 15 SP.3 images misclassified as SP.1) and CSC versus SP.3 (6 of 15 CSC images misclassified as SP.3), which reduced CSC's recall to 40.00% despite 100.00% precision.

ResNet-152 achieved a test-set accuracy of 64.44% (58 of 90 images) — nominally higher than ResNet-18 — but a lower macro-averaged F1-score of 57.91%. This discrepancy arises because ResNet-152 failed to correctly classify any of the 15 SP.3 images (0.00% precision and recall for that class), with 10 of them misclassified as SP.1; its higher raw accuracy is instead driven by strong performance on SP.AL.3, DP.1, and CSC. This indicates that, despite a higher accuracy figure than ResNet-18, ResNet-152's per-class generalization remains the least balanced of the three architectures, consistent with the overfitting concern discussed in Section 4.2.

Across all three architectures, the classes most frequently confused with one another are SP.1 and SP.3, both single-pin insulator configurations that can appear visually similar depending on viewing angle. This suggests that further accuracy gains for these two classes are more likely to come from additional viewpoint diversity within the SP.1 and SP.3 classes specifically, rather than from overall dataset size alone. These results reinforce the conclusion that lightweight architectures such as MobileNetV2 are better suited to this small, utility-specific classification task, while also showing that raw accuracy alone can be a misleading indicator of generalization quality when errors are unevenly distributed across classes — a limitation that macro-averaged F1-score helps to reveal.

Table 2 Per-class precision, recall, and F1-score on the independent test set

Model	Class	Precision (%)	Recall (%)	F1-score (%)	Support
MobileNetV2	SP.1	68.42	86.67	76.47	15
	SP.3	88.89	53.33	66.67	15
	SP.AL.3	93.75	100.00	96.77	15
	DP.1	93.33	93.33	93.33	15

Model	Class	Precision (%)	Recall (%)	F1-score (%)	Support
	DP.3	93.75	100.00	96.77	15
	CSC	100.00	100.00	100.00	15
ResNet-18	SP.1	50.00	80.00	61.54	15
	SP.3	26.67	26.67	26.67	15
	SP.AL.3	92.31	80.00	85.71	15
	DP.1	61.54	53.33	57.14	15
	DP.3	57.89	73.33	64.71	15
	CSC	100.00	40.00	57.14	15
ResNet-152	SP.1	53.85	93.33	68.29	15
	SP.3	0.00	0.00	0.00	15
	SP.AL.3	93.75	100.00	96.77	15
	DP.1	50.00	93.33	65.12	15
	DP.3	75.00	20.00	31.58	15
	CSC	92.31	80.00	85.71	15

4.2 Limitations of the Dataset

The dataset used in this study consists of 300 images distributed evenly across six classes, with 50 images per class. While this balanced sample supports more reliable per-class performance estimates than a skewed distribution would, the overall sample size — and, in particular, the independent test set of 90 images (15 per class) used in Section 4.1 — remains small relative to typical image classification benchmarks, and several specific concerns follow from this. First, with only 15 test images per class, the reported test-set accuracy and F1-scores are subject to considerable variance and should be interpreted as indicative rather than precise; a different train-test split could plausibly yield noticeably different results, particularly for the lower-accuracy models. Second, configuration classes that are visually similar, such as SP.1 versus SP.3, are more prone to misclassification when represented by a limited number of examples; this was confirmed by the confusion matrix analysis in Section 4.1, which showed this pattern across all three architectures, and most severely for ResNet-152. Third, all images were collected from field operations within a limited geographic area and time period, so variation in pole material, hardware wear, camera equipment, and seasonal lighting conditions may not be fully represented, which could limit the models' generalization to poles from other regions or under different environmental conditions. Fourth, the substantial performance gap between MobileNetV2 and the two ResNet variants may partly reflect differences in training configuration: as detailed in Section 3.3, ResNet-18 and ResNet-152 were both trained with a learning rate of 0.1 — ten times higher than the 0.01 used for MobileNetV2 — and at a larger 256×256 input resolution, while batch size (64), subdivisions (8), and the augmentation policy were held constant across all three architectures. This higher learning rate may have contributed to less stable convergence for the ResNet variants, particularly the substantially deeper ResNet-152, and a systematic per-architecture learning-rate sweep would be needed to isolate this effect

from the architectural capacity/overfitting explanation discussed above. These limitations motivate the future work directions outlined in Section 5, particularly further dataset expansion — with emphasis on increasing viewpoint diversity within the visually similar SP.1 and SP.3 classes — and individually tuned learning rates and regularization strategies for the deeper architectures.

5. Conclusion

This paper presented a deep learning-based image classification approach for identifying six standard pole-top equipment configurations from field-captured images. Among the three architectures compared under transfer learning, MobileNetV2 achieved the best performance, with 93.8% training accuracy and 88.89% accuracy on an independent 90-image test set, considerably outperforming the deeper ResNet-18 and ResNet-152 architectures on this balanced, 300-image dataset, while requiring roughly 5 to 24 times fewer parameters and 5 to 34 times fewer computations (Table 3). These findings suggest that lightweight architectures are better suited to small, utility-specific classification tasks and are more practical for field-deployable inspection systems. Future work will focus on further expanding the dataset — particularly with additional viewpoint diversity for the visually similar SP.1 and SP.3 classes — evaluating additional lightweight architectures, individually tuning learning rates and other transfer-learning hyperparameters per architecture, and incorporating the classification model into a mobile or web-based tool to support field inspection by utility technicians.

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Multi-Objective Optimization for Engineer Workload Balancing and SLA Compliance

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Abstract

Task allocation in IT service engineering remains a persistent challenge. Conventional assignment methods, which rely heavily on subjective judgment rather than systematic competency assessment, frequently produce workload imbalances, employee burnout, and Service Level Agreement (SLA) violations. Therefore, this research proposes an integrated multi-objective optimization framework by combining the Non-dominated Sorting Genetic Algorithm II (NSGA-II) with the Dreyfus Model of Skill Acquisition to establish a systematic Skill-to-Task Matching mechanism. The proposed framework simultaneously optimizes three conflicting objectives: maximizing technical alignment, minimizing workload imbalance, and minimizing SLA risk by applying a Quadratic Penalty Function. By treating personnel proficiency as dynamic constraints rather than static variables, the model bridges mathematical optimization with the psychological realities of technical expertise, yielding a data-driven approach that improves operational efficiency, reduces human error, and strengthens service reliability.

Keywords: Task Allocation; Multi-objective Optimization; NSGA-II; Dreyfus Model; SLA; Human Error; Skill Matrix

1. Introduction

In the contemporary digital era, the management of Information and Communication Technology (ICT) infrastructure has emerged as a fundamental mechanism driving organizational success. Responsible departments are increasingly confronted with multifaceted and highly complex workloads that span various technical dimensions. These responsibilities typically include, but are not limited to, the oversight of network security, wireless infrastructure, Voice over IP (VoIP) systems, server administration, and the maintenance of core network hardware such as routers and switches. Despite the critical nature of these tasks, a recurring challenge in practical settings is the reliance on traditional task allocation processes. These conventional methods often depend heavily on individual discretion or subjective intuition, which frequently results in a severe imbalance of labor across the technical team. The practical implications of such imbalances are significant. In practice, highly proficient engineers routinely absorb workloads beyond their sustainable capacity, risking chronic fatigue and burnout, while less experienced colleagues remain underutilized. This 'expert's burden' not only erodes team morale but entrenches systemic inequality across the workforce. Furthermore, it arguably poses a direct threat to the stability of the organization's IT ecosystem. When task assignments fail to align with the actual expertise levels of the staff, the probability of human error increases, leading to higher rework rates and, most critically, the potential for Service Level Agreement (SLA) violations regarding both system continuity and information security.

This research addresses these challenges by mathematically balancing three competing priorities: operational efficiency, equitable workload distribution, and rigorous security compliance. The study

aims to develop a sophisticated skill-to-task matching mechanism centered on a sample group of ten engineers. These participants represent core technical competencies, including Security, Wireless networking, VoIP, Server administration, Datacenter Facilities, and Router/Switch management. By optimizing this matching process, the study ensures that each specific workload is governed by the individual with the most appropriate capability. The broader objectives of this study involve reducing workload disparity to foster a more equitable environment and enhancing personnel development. Simultaneously, the research seeks to mitigate the risks of SLA breaches by controlling the likelihood of operational errors. To achieve this, the scope of the investigation centers on the application of the Non-dominated Sorting Genetic Algorithm II (NSGA-II). As a metaheuristic technique designed for multi-objective combinatorial optimization, NSGA-II provides a robust framework for identifying optimal solutions. Ultimately, this approach facilitates a transition from manual, ad-hoc decision-making toward a sustainable, data-driven management system characterized by mathematical precision.

2. Literature Review

Optimization is fundamental to engineering decision-making, particularly when managing complex resources under strict operational constraints. These techniques are generally categorized based on variable characteristics and search methodologies. According to Hillier and Lieberman (2021) [1], exact methods are designed to identify the global optimum through structured mathematical models. These include Linear Programming (LP), where objective functions and constraints maintain strictly linear relationships with continuous decision variables $x_j \geq 0$. The Simplex Method is typically employed here to explore the vertices of the feasible region. Conversely, Integer Programming (IP) addresses discrete decision variables, such as binary choices $X \in \{0,1\}$ common in personnel allocation. IP models are significantly more complex due to the non-continuous solution space, requiring algorithms like Branch-and-Bound to systematically partition the space and apply "pruning" to discard sub-optimal regions [1].

However, many contemporary engineering tasks are classified as NP-Hard, rendering exact solutions computationally prohibitive. Consequently, researchers frequently employ approximate methods to identify near-optimal solutions within viable timeframes. NSGA-II is a prominent metaheuristic for multi-objective optimization, effective when objectives such as maximizing SLA quality and minimizing costs conflict (Katoch et al., 2020) [2]. Its efficacy derives from three core mechanisms: Fast Non-dominated Sorting, Crowding Distance to maintain solution diversity, and an Elitism Strategy to preserve high-quality traits across generations.

The practical application of these techniques is most critical within the context of SLAs. In modern engineering, an SLA encompasses system uptime, quality, and operational security. Based on intelligent network management frameworks [3], SLA violations often stem from resource allocation failures that ignore task complexity, particularly in specialized domains involving Security, Wireless networking (including Multipath signal fading analysis), VoIP, and Datacenter Facilities. Current trends suggest a shift toward proactive SLA management, utilizing Machine Learning (ML) to forecast potential breaches [4]. Research into system breach explanations [5] indicates that violations are frequently linked to inconsistencies between system status and operator skill levels, suggesting that human factors are as critical as technical infrastructure [3], [5].

Effective management in these high-stakes environments requires an objective competency assessment. The Dreyfus Model of Skill Acquisition [6] provides a structured framework for this, outlining a five-stage transition

Novice : Adheres strictly to rules without contextual awareness.

Advanced Beginner : Recognizes recurring patterns with guided execution.

Competent : Capable of independent planning and prioritization.

Proficient: Possesses a holistic view of system anomalies.

Expert: Achieves intuitive resolution of critical issues, such as security breaches or VoIP outages, through deep experience. Integrating the Dreyfus Model [6] into a mathematical skill matrix is vital, as misaligned assignments directly influence the Human Error Probability (HEP). According to James Reason's "Swiss Cheese Model" [7], errors occur when systemic failures and active human mistakes align. In IT contexts, these are often skill-based errors stemming from a lack of pattern recognition under pressure. Such mistakes lead to an increased Rework Rate the volume of work redone due to quality failures which serves as a primary driver of SLA breaches and inflated costs [7].

Despite the robustness of multi-objective optimization and the depth of Human Error Theory, a significant research gap exists in the dynamic integration of human proficiency levels into automated allocation models. While exact and approximate methods provide a mathematical foundation, they often treat human resources as static variables, failing to account for the non-linear relationship between the Dreyfus skill stages and the resulting Rework Rate.

The foregoing review reveals a consistent gap: existing optimization models treat human proficiency as a fixed parameter, overlooking the non-linear relationship between skill acquisition and error probability. To address this, the present study proposes an integrated framework combining NSGA-II with the Dreyfus Model, embedding proficiency levels as dynamic constraints within a multi-objective formulation. The following section details the methodological design of this framework. By incorporating the Dreyfus Model and Human Error Theory [7] as weighted constraints, the proposed solution aims to minimize SLA violations and Rework Rates simultaneously. This contribution provides a novel approach to engineering management by bridging the gap between mathematical metaheuristics and the psychological realities of technical proficiency, ensuring more resilient service delivery.

3. Methodology

This research proposes a methodological framework for developing an engineering task allocation model using Multi-objective Optimization (MOO). The primary goal is to establish a sustainable equilibrium between operational efficiency and the stability of Service Level Agreements (SLA). The methodology is structured into several distinct phases, ranging from data preparation to the implementation of evolutionary algorithms.

3.1 Data Acquisition and Preparation

3.1.1 Skill Matrix Structure

The foundational data for this study involves the competency profiles of ten engineers across six core technical domains. To ensure objectivity, a Skill Matrix was developed using a proficiency scale of 1 to 5, as established in the framework discussed in Section 2.3. This matrix serves as the primary input for assessing the suitability of each engineer for specific technical challenges.

Table 1: Engineer Skill Matrix

Tech-Skill level from 1 (lowest) to 5 (Highest)						
	Security	Wireless	VoIP	Server	Datacenter Facilities	Router
A	3	2	1	5	4	3
B	3	3	1	4	2	4
C	5	4	2	2	2	4
D	3	4	5	2	2	3
E	5	4	1	2	2	4
F	5	3	2	3	2	3
G	4	4	3	3	5	5
H	2	3	4	5	5	4
I	3	4	2	3	3	5
J	2	4	5	2	2	4

3.1.2 Required Skill Levels (R_j)

To mitigate SLA risks and ensure quality control, the model incorporates minimum skill level thresholds as baseline competencies for each task category. Tasks are tiered into three levels based on their criticality

- Critical Tasks ($R_j = 5$): Encompassing Security and VoIP systems, where errors could lead to major organizational disruptions.
- Standard Tasks ($R_j = 3$): Including Server administration and Datacenter Facilities management.
- Support Tasks ($R_j=2$): Covering Wireless infrastructure and Router/Switch maintenance.

3.2 Definition of Variables and Mathematical Notations

To formalize the optimization problem, the following indices, parameters, and decision variables are defined

3.2.1 Indices

- i : Index for the engineer performing the task, $i \in \{1, 2, \dots, n\}$
- j : Index for the specific task to be allocated, $j \in \{1, 2, \dots, m\}$

3.2.2 Parameters

- S_{ij} : The skill level of engineer i in task category j , ranging from 1 to 5.
- R_j : The minimum skill level required for task j to prevent SLA violations.
- C_i : The maximum capacity limit for engineer i (the maximum number of concurrent tasks).
- L_i : The actual workload assigned to engineer i
- $\bar{L}$: The average workload across the entire engineering team.

3.2.3 Decision Variables

X_{ij} : A binary variable representing the assignment status:

$X_{ij} = 1$ if task j is assigned to engineer i .

$X_{ij} = 0$ otherwise.

3.3 Mathematical Modeling

3.3.1 Objective Functions

The model seeks to optimize three conflicting objectives simultaneously

1. Maximize Technical Alignment (f_1): This function ensures that tasks are assigned to engineers with the highest relevant expertise. By maximizing the cumulative skill scores of all assigned tasks, the system effectively optimizes technical performance.

$$\text{Maximize } f_1 = \sum_{i=1}^n \sum_{j=1}^m (s_{ij} \cdot x_{ij})$$

2. Minimize Workload Imbalance (f_2): This objective promotes distributive justice within the team. By minimizing the standard deviation of individual workloads (L_i) relative to the team average ($\bar{L}$), the model prevents the "expert's burden" phenomenon.

$$\text{Minimize } f_2 = \sqrt{\left(\sum_{i=1}^n (\bar{L} - L_i)^2 \right) \cdot \frac{1}{N}}$$

3. Minimize SLA Risk Score (f_3): This function acts as a safeguard against human error. A penalty function is applied if an engineer's skill level (S_{ij}) is lower than the required threshold

(R_j). A quadratic penalty is utilized to aggressively discourage high-risk assignments.

$$\text{Minimize } f_3 = \sum_{i=1}^n \sum_{j=1}^m (P_{ij} \cdot X_{ij})$$

Where $P = (R_j - S_{ij})^2$

3.3.2 Constraints

To ensure the feasibility of the solutions, the following constraints are enforced:

- Assignment Constraint: Every task j must be assigned to exactly one engineer i to avoid redundancy or omission.
- Capacity Constraint: The total workload for any individual engineer (L_i) must not exceed their predefined capacity (C_i).

3.4 Algorithmic Processing

This study utilizes NSGA-II, a robust evolutionary algorithm for multi-objective optimization, through the following stages

1. Problem Encoding: Uses integer encoding where chromosome length equals the total tasks, and gene values represent the assigned engineer index.
2. Fitness Evaluation: Candidates are evaluated against three objective functions. Solutions violating constraints are penalized to ensure their exclusion from subsequent generations.
3. Genetic Operations: This stage employs Binary Tournament Selection to identify high-quality parents and integer-based crossover for offspring production. Mutation is then introduced to maintain genetic diversity, ensuring the algorithm avoids local optima and effectively explores the solution space.

3.5 Evaluation and Performance Testing

To validate the model, a retrospective comparison is conducted between the model's outputs and historical manual assignment data. Performance is measured using three primary indicators:

- Resource Utilization Efficiency: Calculated via the average skill level per task to verify the "best-fit" principle.
- Workload Balance Index: Measured by the reduction in the standard deviation (SD) of workloads.
- Risk Mitigation Efficacy: Assessed by the percentage reduction in cumulative penalty points within the system.

3.6 Research Environment and Tools

The computational framework for this research is built using the following tools:

- Python 3.10: The primary programming language for model development.
- PyMoo Library: A specialized framework for implementing the NSGA-II algorithm.
- Pandas & NumPy: Utilized for data manipulation and statistical analysis.
- Google Colab: Employed for processing and simulation.

4. Results and Discussion

4.1 Experimental Environment and NSGA-II Parameters

The experimental phase of this study was conducted within a Google Colab cloud computing environment, utilizing Python 3.10. The core optimization was processed via the PyMoo Library, which is specialized for multi-objective evolutionary algorithms. For data manipulation and statistical rigor, Pandas and NumPy were employed. The input dataset consisted of a Skill Matrix for ten engineers (labeled A through J) across six critical technical domains: Security, Wireless, VoIP, Server, Datacenter Facilities, and Router/Switch. Proficiency was measured on a 1–5 scale based on the Dreyfus Model of Skill Acquisition [6].

To ensure the algorithm reached convergence while maintaining diversity, the following NSGA-II parameters were configured:

- Population Size: 200
- Generations: 300
- Crossover Rate: 0.90 (Two-Point Integer Crossover)

$$\frac{1}{n} \text{ (Polynomial Mutation)}$$

- Mutation Rate:
- Random Seed: 42 (for reproducibility)

4.2 Overall Results: Skill and Penalty Matrices

The assignments selected by the NSGA-II model (indicated by blue frames in the Figure 4.1) consistently align with cells where the Penalty = 0. This suggests that the model succeeded in identifying assignment configurations that completely avoid SLA risks by ensuring every engineer's skill level meets or exceeds the required (R_j).

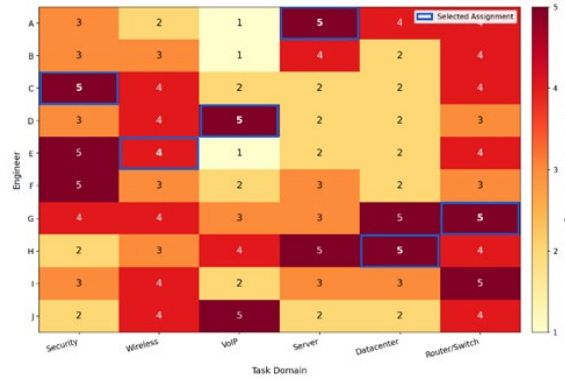


Figure 4.1: Engineer Skill Map and Task Assignment Results.

4.3 Objective 1: Technical Alignment (f_1)

The first objective function (f_1) aims to maximize the total technical competency of the team. The NSGA-II model achieved an f_1 score of 1719.0, representing a 16.2% improvement over the Current Practice (1479.0). The results confirm that every task was assigned to an engineer whose skills were at least equal to the required level. Furthermore, This alignment is consistent with the Dreyfus Model [6], which posits that higher-tier skills are essential for the safe and efficient execution of complex technical tasks.

4.4 Objective 2: Workload Imbalance (f_2)

To address the issue of distributive fairness, f_2 calculates the standard deviation of workloads. The NSGA-II model produced an f_2 score of 1.96, which is 81.8% lower than the Current Practice.

4.5 Objective 3: SLA Risk Score (f_3)

Maintaining service stability is the most critical objective of the three. In this study, the NSGA-II model achieved an f_3 score of 92.0, effectively a 76.2 % reduction in risk compared to the Current Practice (386.0). This outcome validates the use of a Quadratic Penalty Function. By squaring the skill gap, the algorithm is forced to prioritize the avoidance of high-risk assignments over marginal gains in other objectives. This approach aligns with Reason's Human Error Theory[7], which emphasizes that placing under-qualified personnel in critical roles is a primary latent failure in system stability.

4.6 Summary of Performance Evaluation

The table 4.1 and Figure 4.2 below summarizes the efficiency gains across all three criteria established in the methodology

Table 4.1: Performance Summary as
NSGA-II vs Current Practice

Objective	Current Practice	NSGA-II	Improvement
f_1	1479.00	1719.00	+16.2%
f_2	10.74	1.96	-81.8%
f_3	386.00	92.0	-76.2%

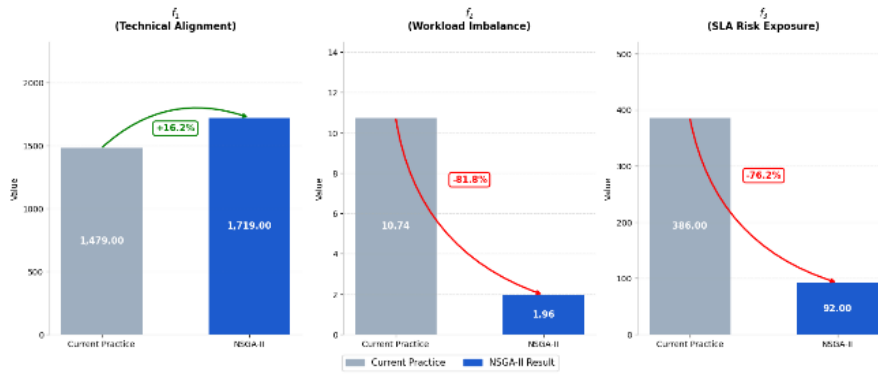


Figure 4.2: Benchmarking NSGA-II
Results Against Current Practice

4.7 Discussion

The experimental results confirm all three research hypotheses.

1. Skill Matching: The model correctly prioritized Expert levels for critical tasks, improving the total alignment score from 1479 to 1719.0. For instance, the Security task was assigned to Engineer F ($S_{ij}=5$) and VoIP to Engineer D ($S_{ij}=5$), matching the $R_j=5$ requirement. This follows the Dreyfus Model [6] logic that critical infrastructure requires intuitive expertise to minimize Human Error [7].
2. Workload Equilibrium: A substantial reduction in the workload standard deviation from 10.7443 to 1.9596 confirms that the model effectively maintains fairness. This balancing effect is expected to be even more significant as the system scales with higher task volumes.
3. Risk Mitigation: SLA Risk Score (f_3) of 92.0 a significant decrease from the Current Practice baseline of 386.0 suggests that the Quadratic Penalty function is significantly more effective than a linear approach. By disproportionately penalizing skill gaps, this function acts a strong mathematical constraint that limits the algorithm from compromising security integrity for marginal gains in workload distribution. This outcome is highly consistent with modern SLA Management frameworks [3-5].

5. Conclusions

This study successfully developed a multi-objective optimization framework for IT engineering task allocation using the Non-dominated Sorting Genetic Algorithm II (NSGA-II) in conjunction with the Dreyfus Model of Skill Acquisition. Experimental results demonstrate that the proposed model simultaneously achieved all three objectives: maximizing Technical Alignment (+16.2%), minimizing Workload Imbalance (-81.8%), and significantly reducing the SLA Risk Score (-76.2%). Statistical

validation against 1,000 random baseline runs confirmed that these results were statistically significant and not attributable to chance. This study demonstrates that metaheuristic optimization offers a viable, systematic alternative to ad hoc task allocation in IT workforce management one that simultaneously upholds service quality and promotes equitable workload distribution.

6. Future Directions

Future work aims to scale this framework for larger organizations and real-time scheduling. Integrating hybrid metaheuristics or DRL could further optimize resource allocation and workforce development in volatile IT landscapes.

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Developing a Remote Learning System for Robotic Arm Applications

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Abstract

The objective of this research is to develop a remote robotic arm learning system; to enhance the teaching and learning of robotic arm kinematics through remote operation and programming techniques. The developed system consists of a lightweight, autonomous 6-degree-of-freedom (6-DOF) articulated robotic arm designed to emulate the functionality of industrial robotic manipulators, together with a user-side platform that enables remote robot control and programming. The system architecture is organized into three functional layers: (1) the High-Level Layer, which provides a Graphical User Interface (GUI) developed using Python and ttkbootstrap; (2) the Middleware Layer, which performs kinematic computation using the PyBullet Physics Engine and ROS 2 Services; and (3) the Low-Level Layer, which controls the Dynamixel servo motors. Communication between system components is implemented using the MQTT protocol, while PeerJS is employed to provide real-time video streaming for remote monitoring of robot operations. To facilitate practical learning, the GUI supports three operating modes: Jog Mode for manual joint control, Velocity Mode for joint position control, and Cartesian Mode for end-effector control based on Cartesian coordinates (X, Y, Z) and orientation (Roll, Pitch, and Yaw). The proposed system was evaluated through two experimental sessions involving participant-based data collection to assess its performance and educational effectiveness. The findings are expected to provide a foundational framework for the advancement of remote robotics education and contribute to the development of science, technology, and innovation, thereby supporting the preparation of future human resources for the Industry 5.0 era.

Keywords: Robotic Arm; Remote Learning; Remote Control; Industry 5.0

1. Introduction

In accordance with the Thai government's policy on workforce development, enhancing citizens' engineering competencies is recognized as a key strategy for strengthening national human capital and preparing the workforce across all age groups. Developing skills that align with the rapidly evolving demands of technology-driven labor markets is essential for improving employability and supporting lifelong learning. Particular emphasis has been placed on cultivating competencies in robotics and automation from the secondary and vocational education levels, enabling students to develop familiarity with emerging technologies, acquire practical experience, and progressively build expertise toward advanced applications. Such initiatives are expected to establish a strong foundation of knowledge and technical capabilities for future researchers and engineers, thereby contributing to the country's scientific, technological, and innovation capacity. Recognizing this opportunity, this research proposes the development of a robotic learning platform that integrates remote robot control technologies to enhance learning in robotics and automation. By enabling remote access to high-cost robotic systems, the proposed approach aims to broaden educational opportunities for upper secondary and vocational students while fostering the next generation of professionals in science,

engineering, and advanced innovation in Thailand.

Thailand's educational institutions operate under diverse contextual conditions, including differences in geographical location, infrastructure, and institutional resources. Schools are distributed across urban areas, industrial regions, and remote locations, resulting in substantial variation in campus size, classroom capacity, and laboratory facilities. While some institutions possess sufficient space to accommodate large-scale educational equipment, others face significant limitations in installation space, restricting students' access to specialized learning resources. According to interviews conducted with schools participating in the Robotics Curriculum Development Project organized by the Field Robotics Institute during 2020–2022, limited physical infrastructure remains a major barrier to the implementation of robotics laboratories. Furthermore, institutional policies and budget allocation practices vary considerably among schools, influencing their ability to procure educational equipment and support robotics-related learning activities. Consequently, students' opportunities to access robotics and automation technologies are not equally distributed across educational institutions.

To prepare future human resources for Industry 5.0 era, characterized by close collaboration between humans and intelligent robotic systems, it is essential to expand access to robotics and automation education through advanced remote technologies. This requires the development of innovative learning mechanisms that support robotic arm applications in a wide range of educational scenarios while accommodating the physical constraints of limited laboratory space. In addition, adaptive learning environments should be designed to optimize the utilization of available installation areas and support diverse instructional activities. By integrating essential robotics concepts and practical applications into multiple simulated and real-world operating environments, the proposed learning system aims to maximize the educational value of robotic arm laboratories while providing flexible, accessible, and scalable learning experiences for students regardless of institutional limitations [1, 2].

2. Research Methodology

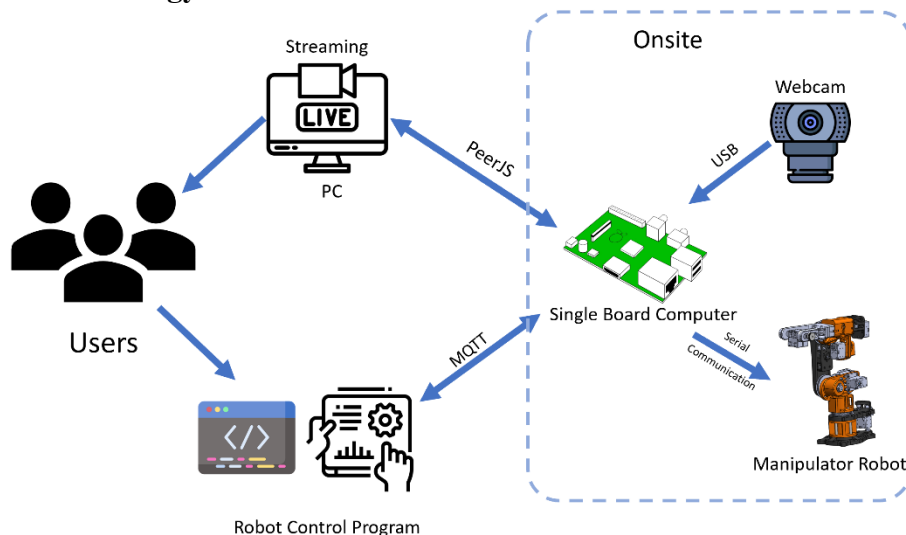


Figure 1 System Overview.

To enable users to remotely control and program the robotic arm, the proposed system is designed with two primary components. The first component is the robotic arm subsystem, which is required to operate autonomously while supporting real-time video streaming for remote monitoring. The second component is the user-side subsystem, which provides an

interface that enables users to observe the live video stream of the robotic arm and remotely control its operation and programming. The overall architecture of the proposed remote robotic arm learning system is illustrated in Figure 1.

2.1 Robot Arm Design

For the robotic arm developed in this study, the design objective was to emulate the functionality of the industrial robotic manipulators that are most widely adopted in manufacturing and automation applications. Accordingly, a six-degree-of-freedom (6-DOF) articulated robotic arm was designed to provide kinematic characteristics comparable to those of conventional industrial robots [3, 4]. The design requirements of the proposed robotic arm are summarized as follows:

1. The robotic arm must be capable of autonomous operation without requiring an external computer for execution.
2. The robotic arm must be lightweight to facilitate portability, transportation, and deployment in educational environments.
3. The robotic arm must exhibit operational characteristics comparable to those of industrial robotic manipulators, enabling realistic learning and practical training experiences.

2.2 System Architecture Overview

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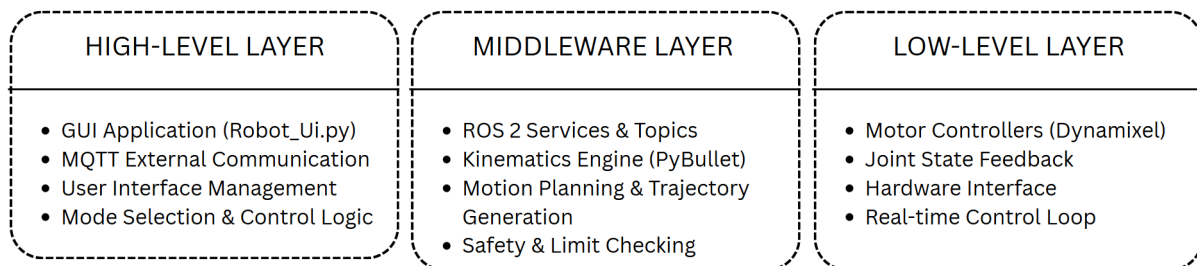


Figure 2 System Layer.

High-Level Layer (Application Layer) serves as the primary interface through which users interact with the system. It consists of a Graphical User Interface (GUI) developed using Python and the ttkbootstrap framework. The application layer is responsible for receiving user commands, displaying the real-time status of the robotic arm, and managing communication with external system components via the MQTT protocol. In addition, this layer performs data conversion between user-friendly representations (e.g., millimeters and degrees) and the internal representations required by the system (e.g., meters and radians), ensuring compatibility with the kinematic computation and robot control modules.

Middleware Layer (Processing Layer) functions as the core processing unit of the proposed system, responsible for computation, decision-making, and coordination between the application and hardware layers. It integrates the PyBullet Physics Engine for robotic kinematic computation, ROS 2 Services for inter-process communication, and a motion planning module for trajectory generation. The middleware layer performs forward and inverse kinematics calculations, validates motion commands to ensure safe operation, and translates high-level user commands into low-level control instructions that can be executed by robotic hardware.

Low-Level Layer (Hardware Control Layer) directly interfaces with robotic hardware and

is responsible for controlling the Dynamixel servo motors, acquiring sensor data, and transmitting position or velocity commands to the actuators. In addition, the hardware control layer incorporates safety monitoring and error-handling mechanisms to detect abnormal operating conditions, prevent unsafe robot behavior, and ensure reliable system operation during remote execution.

The proposed system is implemented based on an event-driven architecture, in which system operations are triggered by various events, such as user interactions through the GUI, incoming MQTT messages, and changes in the robotic arm status. This architecture enables real-time system operation and allows the system to rapidly respond to dynamic changes during robot execution. The data flow diagram is shown in Figure 3.

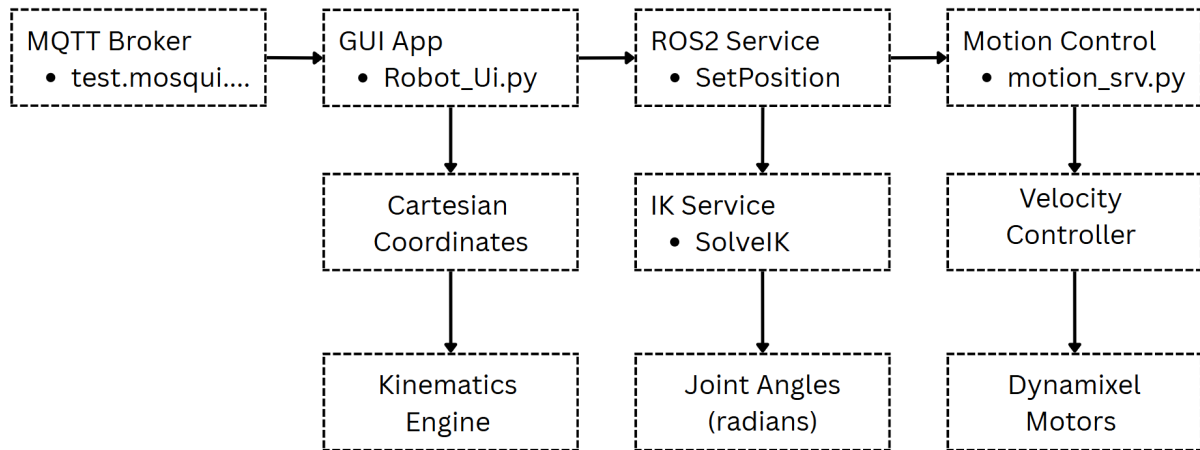


Figure 3 Detailed Flow.

2.3 Robot Structural Design

The robotic arm is designed as an articulated robot (jointed arm) in which all motion axes are configured as revolute joints, providing a total of six degrees of freedom (6-DOF). The robot consists of six Dynamixel motors, with each motor responsible for driving an individual joint through a transmission system comprising synchronous belts and gear reduction mechanisms. The transmission ratio of each joint is optimized according to its position and required torque characteristics.

The transmission system enables efficient and precise motion control for each axis. Each motor directly drives the corresponding joint through a pulley and belt mechanism, which is designed to provide sufficient torque capacity according to the mechanical requirements of each axis. The six-axis robotic arm provides the following range of motions:

- S-axis (Shoulder rotation): Base rotation around the vertical axis.
- L-axis (Lower arm): Elevation and lowering motion of the lower arm.
- U-axis (Upper arm): Flexion and extension motion of the upper arm.
- R-axis (Wrist roll): Rotation of the wrist around the arm axis.
- B-axis (Wrist pitch): Upward and downward tilting motion of the wrist.
- T-axis (Wrist yaw): Left and right rotational motion of the wrist.

The end-effector is controlled to achieve the desired position and orientation through the coordinated synthesis of all six joints (joint-space synthesis). This coordinated motion enables the robotic arm to perform accurate manipulation tasks within a three-dimensional workspace.



Figure 4 Side and Isometric Views of Robotic Arm.

Revolute joints enable independent rotational motion along each axis, allowing the robotic arm to achieve flexible movement and precise control of joint angles and orientations. This joint configuration is well suited for articulated robotic manipulators, where accurate control of position and direction is required. To evaluate the accessibility and operational capability of the robotic arm within its reachable area, the workspace characteristics and dimensions were analyzed using the robot's CAD model. The workspace analysis was conducted from different viewing perspectives. The top view illustrates the rotational workspace of the robot base (S-axis), which provides a maximum rotation range of 270 degrees. The maximum reachable radius is approximately 385.1 mm. The side view represents the vertical and horizontal motion ranges of the robotic arm. The maximum horizontal reach is approximately 391.5 mm, while the maximum vertical reach is approximately 524 mm. The minimum vertical distance from the base is approximately 70.05 mm. The workspace analysis provides essential information for evaluating the robot's reachable area and verifying the suitability of the proposed robotic arm design for various manipulation tasks. Figure 5 is the workspace of robot.

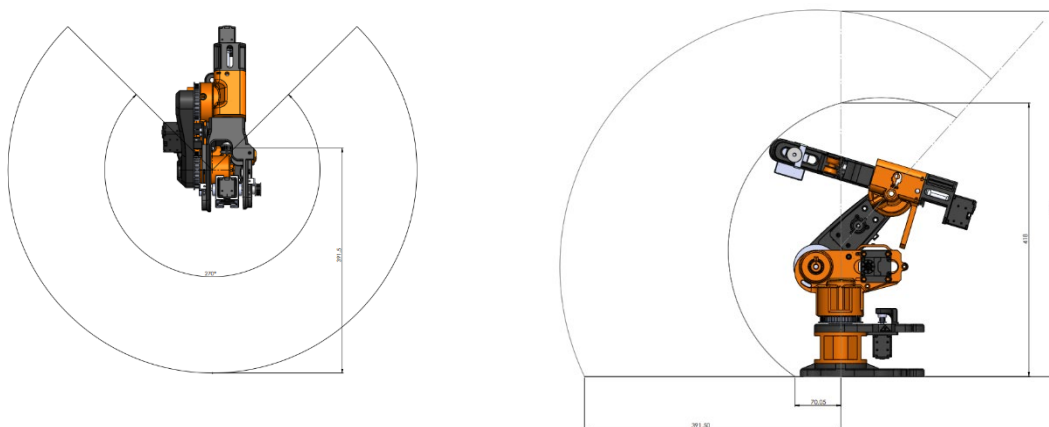


Figure 5 Robot Workspace.

2.4 Electrical System

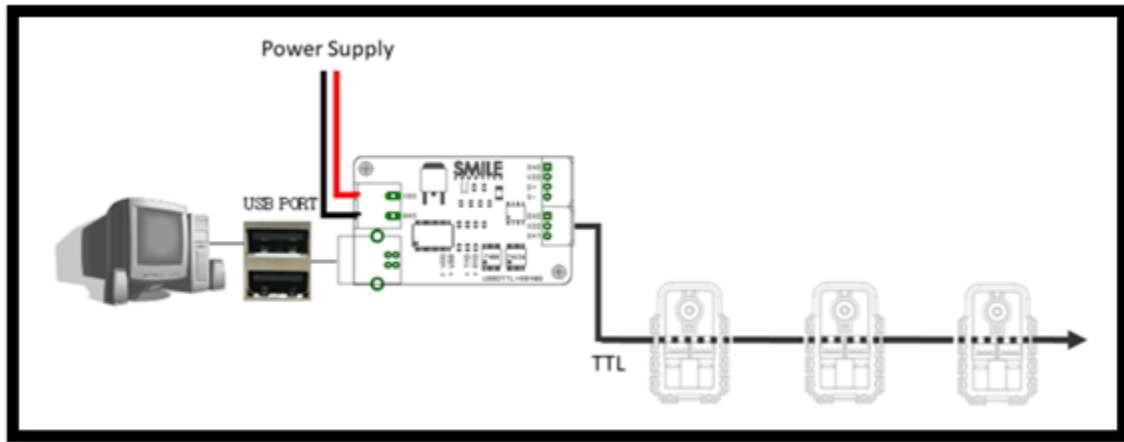


Figure 6 Operation of SMILE Board [5].

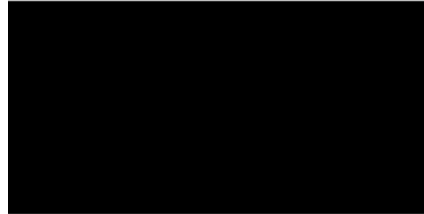
A 12 V DC power supply is used to provide electrical power to the Dynamixel motors and all other system components. A 5 A fuse is implemented to protect the electrical circuit from short circuits and excessive current conditions (overcurrent protection). For power distribution circuit, The circuit receives a 12 V DC input from an external power supply and converts it to 5 V DC to supply power to the Raspberry Pi 5 and other electronic components. A step-down voltage regulator is used to convert the input voltage from 12 V DC to 5 V DC, which is required for the operation of the Raspberry Pi 5 and associated electronic devices. The SMILE board is used as an interface between the Raspberry Pi 5 and the Dynamixel motors, enabling communication and control between the computing unit and the robotic actuators.

2.5 Remote Robotic Arm Video Streaming Using PeerJS

The researchers developed a video streaming application and deployed it through the following URL: <https://test-p2p-six.vercel.app/robot>. The application was designed to enable remote monitoring of the robotic arm by providing real-time video transmission between the robotic system and the user interface.

Current ID: 4ff8f6af-963f-4091-81ea-75c1cf22f161

Remote Video



Your Video

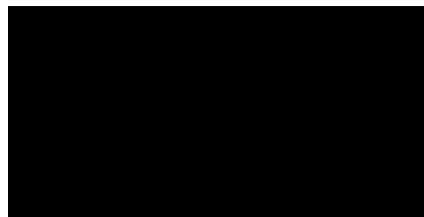


Figure 7 Streaming Web Interface.

2.6 Application of EMG Sensors with the Robotic Arm

In this study, an Electromyography (EMG) sensor is integrated with the robotic arm system as illustrated in Figure .

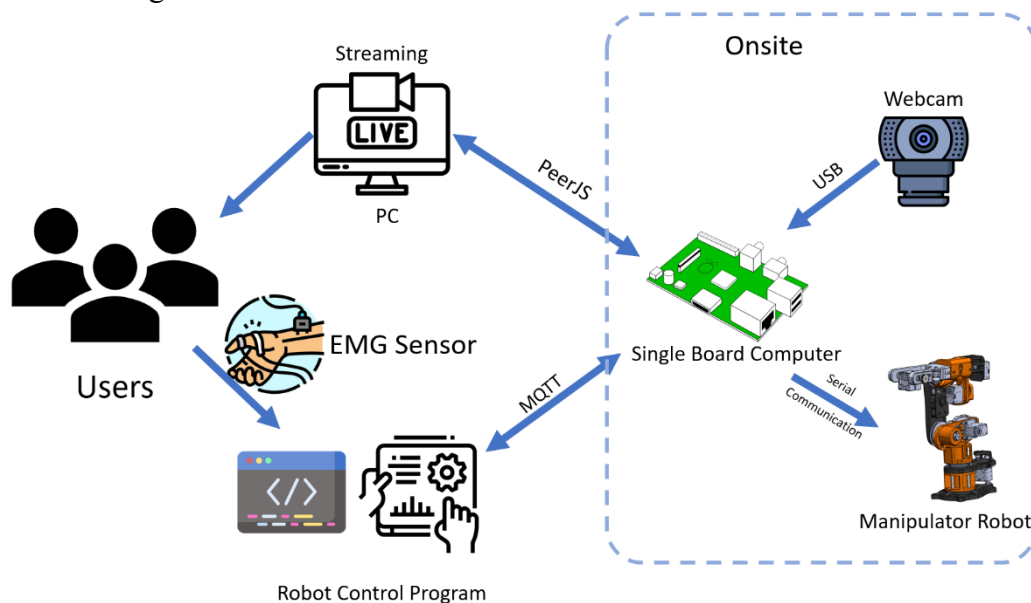


Figure 8 Integration of EMG Sensors with a Robotic Arm System.

3. Data Collection from Test Participants

For the participant evaluation, the researchers conducted a training program consisting of the following topics: (1) Introduction to Robotic Arm, (2) Mathematics for Robotic Arm Applications. (3) Internet of Things (IoT) with Robotics, and (4) Teleoperation Robotic Arm Workshop. The data collection process was conducted in two sessions, with 30 participants

participating in each session. The first session was conducted on August 30, 2025, and the second session was conducted on August 31, 2025.

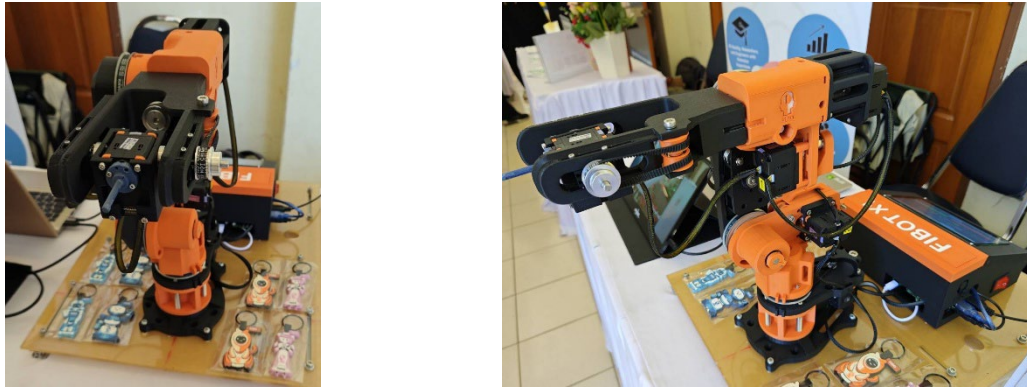


Figure 9 Developed Robot Arm.

average 5.02 / 8 points	median 6 out of 8 points	period 1 - 8 points
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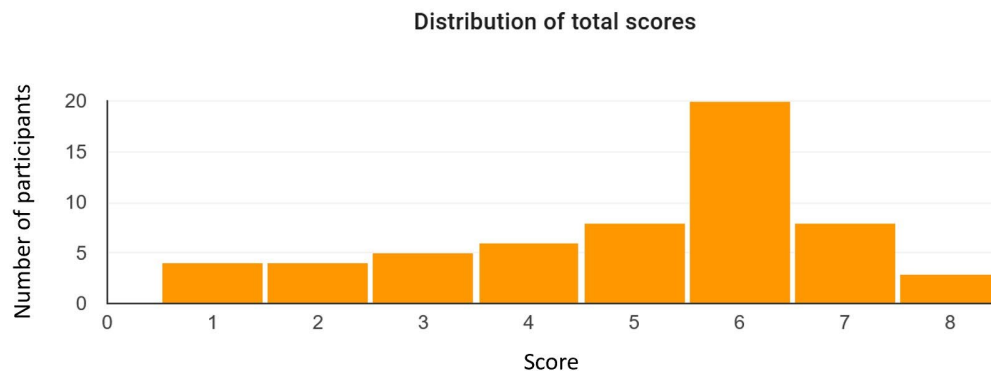


Figure 10 Graph showing scores of 52 training participants.

After completion of the training sessions, an evaluation questionnaire was distributed to the participants. A total of 52 participants responded to the assessment, achieving an average score of 5.1 out of 8 points. The collected results were used to evaluate the effectiveness of the developed robotic learning system and the participants' understanding of robotic arm technologies.

4. Conclusion

This research aims to address the challenges associated with limited access to high-cost robotic technologies and restricted installation space in educational institutions, particularly at the upper secondary and vocational education levels. These limitations reduce students' opportunities to gain practical knowledge and experience in robotics and automation, which are essential competencies for preparing future human resources for Industry 5.0, an era emphasizing collaborative interaction between humans and robotic systems.

The developed system consists of two main components. The first one is A 6-degree-of-freedom (6-DOF) articulated robotic arm. The robotic arm is designed to operate autonomously

without requiring an external computer, while maintaining lightweight characteristics for convenient transportation and deployment in educational environments. The proposed robotic arm provides operational capabilities comparable to industrial robotic manipulators, with a maximum payload capacity of 2 kg at the end-effector. All joints are configured as revolute joints to achieve articulated motion similar to conventional industrial robots. The second one is A user-side system. The user system enables remote access to the robotic arm through real-time video streaming and provides remote operation and programming capabilities.

The proposed system is developed based on a three-layer architecture consisting of the High-Level Layer, Middleware Layer, and Low-Level Layer. The MQTT protocol is employed as an event-driven communication mechanism between system components. A graphical user interface (GUI) is developed using Python and the ttkbootstrap framework to provide an intuitive control environment for users. The GUI supports three primary operating modes to enhance control flexibility: (1) Jog Mode, which enables precise manual joint manipulation; (2) Velocity Mode, which provides direct joint position control; and (3) Cartesian Mode, which enables automatic end-effector position and orientation control in Cartesian space through inverse kinematics computation. In addition, predefined motion sequences, referred to as Special Actions, are implemented for system demonstrations, capability validation, and operational testing. The robotic platform is powered by a 12 V DC 8 A power supply and integrates a Raspberry Pi 5 with the SMILE control board for interfacing with Dynamixel motors. Furthermore, PeerJS is utilized to support remote robotic video streaming.

The research evaluation was conducted through experimental data collection involving 52 participants to assess the usability and learning effectiveness of the developed system.

Acknowledgement

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(Full paper)



Startup Perspectives of Selected Filipino Technopreneurship Students

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Abstract

The Philippines has been gradually shifting attention from the traditional entrepreneurial undertakings to establishing startups as a means to spur more innovative ventures and encourage more competition. During the past few years, startups have been increasingly attractive to younger generations as an alternative for either employment or for their first business venture. However, many structural issues within the Philippine environment stem from the lack of a widely accepted concept of what startups are and what are they supposed to do. This research explores the ideas of a select group of students taking Technopreneurship classes regarding what a startup is, the work of a startup founder, and the challenges hinder their them in launching their own startups. Qualitative responses from 286 students were subjected to content analysis, observing recurring themes that were then systematically tracked to gain deeper insights into the respondents' perspectives. The results showed that only a few potential founders appreciate the importance of innovation in setting up a startup, but many also believe that startup founders should primarily work on product delivery, marketing, and networking. Furthermore, many also point to funding as a major challenge in launching a startup. These qualitative insights provide initial insights on what startups are in this particular country context that has a budding ecosystem.

Keywords: Startup, Technopreneurship, Innovation, Innovative Entrepreneurship, Innovative Entrepreneur

1. Introduction

1.1 Philippine Startup Ecosystem

During the past few years, there have much focus and push towards innovation and entrepreneurship in the Philippines, especially in the context of startups [1], [2], [3]. The Philippine start-up landscape is growing rapidly, numbering between 700 and 1,200 [4], [5]. The country's start-up ecosystem value is US\$ 6.3 billion as of 2024 [4]. Startups contributed an estimated 3% to the country's nominal GDP *in 2024* and generated approximately 200,000 jobs *as of 2024*. Majority of the startups target operational efficiency and digitalization within the fintech, e-commerce, health, human resources, and education sectors, utilizing business-to-business, and business-to-consumer business models. E-commerce is by far the leading sector, generating an impressive average of over \$45 million [6]. Startup Genome, an international research platform that has extensively documented the Philippine startup ecosystem, observed several key advantages driving the growth of Manila's ecosystem: (a) a young, tech-savvy, and talented workforce with pool, who are continuously upskilled in engineering and technology by industry experts; (b) a robust government support guided by regulatory frameworks that actively encourages entrepreneurship, such as the Philippine Innovation Act, the Innovative Startup Act, and the Tatak Pinoy Act, wherein the Philippine government's Department of

Trade and Industry (DTI), the Department of Science and Technology (DOST), and the Department of Information and Communications Technology (DICT) collaborate to establish new Technology Business Incubators (TBIs) and guide them to financial self-sustainability, secure funding and investments, and raise more Filipino unicorns; and (c) a booming digital economy driven by surging domestic demand for digital products and services, which is projected to hit \$80–\$150 billion by 2030 [4]. However, this has led to several issues within the Philippine environment: (1) The lack of policy directions from the top; (2) The lack of a clear strategic direction on how different stakeholders can come together to enhance the startup environment; and (3) The lack of measurable impact assessments. In turn, one of the major culprits causing these is the lack of a common and widely accepted understanding of what startups actually are and what they are supposed to do to contribute to the economy and to society [2], [3], [6].

1.2 Startup and Filipino Youth

Data from the Philippine Statistics Agency (PSA) show a relatively young population, having a median age of 25.3 years [7]. Youth (15 – 29 years) have a great potential in the economic development of the Philippines. As of 2020, they comprise approximately 30% of the entire population [8]. Startups have been increasingly attractive to younger generations as an alternative for either employment or for their first business venture. Hence, intentions to create a startup becomes an interesting phenomenon to observe. According to Gobi Core, one of the major partners of the Philippine government's Startup Venture Fund (SVF), there are startup founders who are as young as 21 years old [9], and many young entrepreneurs have indicated that their planned businesses would be offering novel products and services [10].

Starting a business hinge on spotting opportunities and converting these opportunities to profitable business propositions [11]. An individual's decision to start a business may be influenced by perceptions about business [12]. This is important considering that founders face a lot of challenges in running their startups [13], [14]. As more young people exhibit startup skills and tendencies, there is a need to know and understand their perceptions about startups as preparation in launching one in the future. Hence, this research aims to frame these fragmented experiential and insight-driven sentiments into a more cohesive understanding of what startups actually are in the Philippine setting.

1.3 Research Questions and Significance of the Research

Specifically for the context of a select group of Filipino university students taking up a Technopreneurship subject, the following research questions are as follows:

RQ1: How do these selected young Filipinos perceive startups?

RQ2: What are these selected young Filipinos perceptions of a startup founder's job?

RQ3: What are the key factors that deter these selected young Filipinos from launching their own startup?

Especially in light of calls for reform, such as introducing institutional accountability and strategic upskilling [6], the main beneficiaries of this proposed research are the policy makers of startup, Technopreneurship, and other innovation-related courses and programs. The results of this research will help determine the important internal and external factors that can shape a college student's startup perceptions. This in turn will provide directions on how to create that environment that is conducive for people to favorably perceive startups as a career option.

2. Review of related literature

2.1 Startup Definition and Comparison with a Typical SME

According to the Asian Development Bank (ADB), the Philippines has more than 1.2 million enterprises in operation as of 2024, more than 99% of which are categorized as micro, small, and medium enterprises (MSMEs). Also as of 2024, MSMEs account for almost 65% of the country's total employment [15]. There is no consensus as to the exact definition of a startup. Looking at several studies that explore the different definitions of startup, several themes emerge. These themes include structural independence (set up as a business), operational age (at most between five and 10), firm size (small to medium), innovation potential/technologically-driven, growth-orientation/scalability, operating under uncertainty/resource limitations, including financial limitations, presence/absence of a product or service, and the importance of business model in its success [16], [17], [18], [19], [20], [21], [22], [23]. Although startups and MSMEs may seem similar, especially in size in terms of number of people in the organization, they have several distinct features, two of which are scalability and innovation orientation [16], [24], [25], [26]. However, despite these efforts, there seems to still be a lack of understanding what startups are [18], [19], [21]. In this sense, given the fact that multiple events and efforts are constantly being made to "bring together stakeholders" in order to "discuss policy directions" and "come up with strategic recommendations" imply that the Philippine startup environment lacks a unified understanding on what startups ought to be all about.

2.2 Startups and Innovation

In general, startups have a very high failure rate, with 90% being the often-quoted value [20], [23], [27]. Looking at local enterprises, it was reported in 2017 that although the Philippines achieved the highest new business rate among Asian countries, it also had the highest business discontinuance rate in the region [28]. The Philippines' discontinuance rate of 12.2% is almost three times that of the average of Asia, which stood at 4.6% [29]. The high discontinuance rate is attributed to weak business performance and profitability in saturated markets [28], [30].

One of the factors that determine the success of a startup is its market offering [20]. The success of its innovative market offering contributes to its success in the marketplace [20], [31], [32], [33]. There have been reports and criticisms, both present and past, that the products of the country's startups lack innovation [34], [35], that most Filipino entrepreneurs sell products that are not novel [10], and that our local enterprises rarely engage in innovation [36], [37], [38].

The potentially innovative products of startups can overcome such challenges. Based on World Intellectual Property Organization's (WIPO) 2025 Global Innovation Index (GII), the Philippines ranked 50th overall among 139 economies, showing steady improvement over the last four years: from 59th in 2022, 56th in 2023, and 53rd in 2024 [39]. The GII is an annual ranking of countries by means of their capacity for and success in innovation. However, the faltering performance of startups in recent years to sustain this perceived momentum reflects the more structural issues that are facing those who want to engage in this sector [6].

3. Methodology

The respondents were business and engineering students from a national university taking up Technopreneurship classes. These students were at least of junior standing in their respective courses at the time of the survey. Data was collected through an online survey using Google Forms. The survey was conducted between September 2024 and January 2025. Participants were informed that their involvement was entirely voluntary and that their responses would

remain strictly confidential. Also, respondents can choose multiple answers. They were assured that data would be securely stored, used exclusively for academic research, and free of any personally identifiable information.

Before the actual data collection, expert validation and pre-testing were employed to ensure the quality of the survey instrument. The questions were reviewed and evaluated by a senior business and management faculty member prior to a trial run with selected students. Appendix A shows the survey questions used for this research (*See Appendix A: Survey Questions and Sample Responses*).

The use of students as target respondents is supported by several studies. A well-educated individual is more likely to set up a business compared to non-educated counterparts [40]. It has become common practice in entrepreneurial research to employ these groups as respondents [41], [42], [43] because they are of similar age and qualifications, making them more homogeneous [44]. Setting up a business is a realistic option for students who are making career choices [42], [45], [46], and it is advantageous for the economy if students engage in entrepreneurship and take advantage of the existing entrepreneurial opportunities [47]. All these characteristics are in line with the profile of Filipino founders [6].

Utilizing content analysis, recurring themes were systematically tracked to gain insight into the respondents' perspectives. The responses were interpreted following the themes identified in the review of related literature [16], [17], [18], [19], [20], [21], [22], [23], and were done so solely by the researcher. This approach enabled the researcher to pinpoint critical gaps and assess the fit of the startup concept within the viewpoints of aspiring Filipino founders, allowing for a grounded evaluation of the concept.

4. Results

The study had 286 respondents. The response of each respondent may contain several themes, or coded responses. Of these respondents, around 60.00% were male. Majority respondents were aged 20 to 24 years old (almost 86.00%). These students are mostly in senior/4th year standing based on their respective curricula (almost 60.00%). This age group is like the ones used in other student entrepreneurship-related studies, e.g., [41], [42], [43], [45], [46], [47].

The responses for RQ1 (*How do these selected young Filipinos perceive startups?*) are illustrated in Figure 1, based on 557 coded responses (*See Figure 1 Major themes (n=286)*). The prevalent views about startups are the following: (a) it involves setting up a new business (268, or 48.11%); (b) it involves coming up with a new or novel product that addresses certain markets or societal issues (194, or 34.83%); and (b) Others (95, or 17.06%). Of the 268 responses on setting up a new business, 111 (41.42%) indicated the importance of technology or innovation as part of establishing the new business. Also, of the 95 responses categorized as "Others", 36 (37.89%) involved scaling, 32 (33.68%) highlighted the need for investors, and 12 (12.63%) viewed startups as companies that operate in an uncertain environment. Appendix A shows sample answers (*See Appendix A: Survey Questions and Sample Responses*).

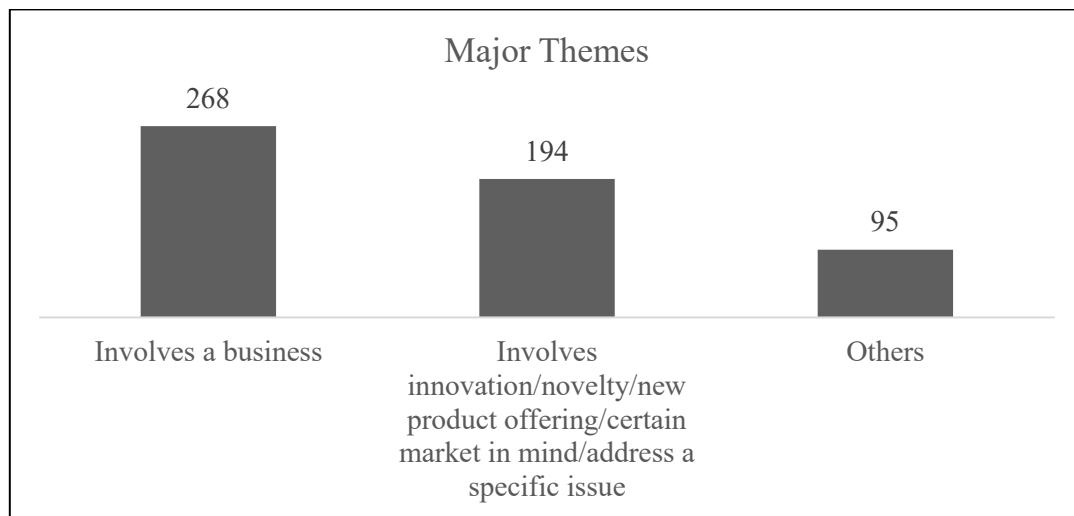


Figure 1 Major themes (n=286)

The responses for RQ2 (*What are these selected young Filipinos perceptions of a startup founder's job?*) are illustrated in Figure 2, based on 603 coded responses (*See Figure 2 Perceptions about a Founder's work (n=286)*). The results show that founders are supposed to be heavily involved in R&D and product development (160 responses, or 26.53%), marketing efforts (114 responses, or 18.91%), establishing the vision, the mission and long-term aspects of the business (83 responses, or 13.76%), and networking and funding-related activities (78, or 12.94%). Appendix A shows sample answers (*See Appendix A: Survey Questions and Sample Responses*).

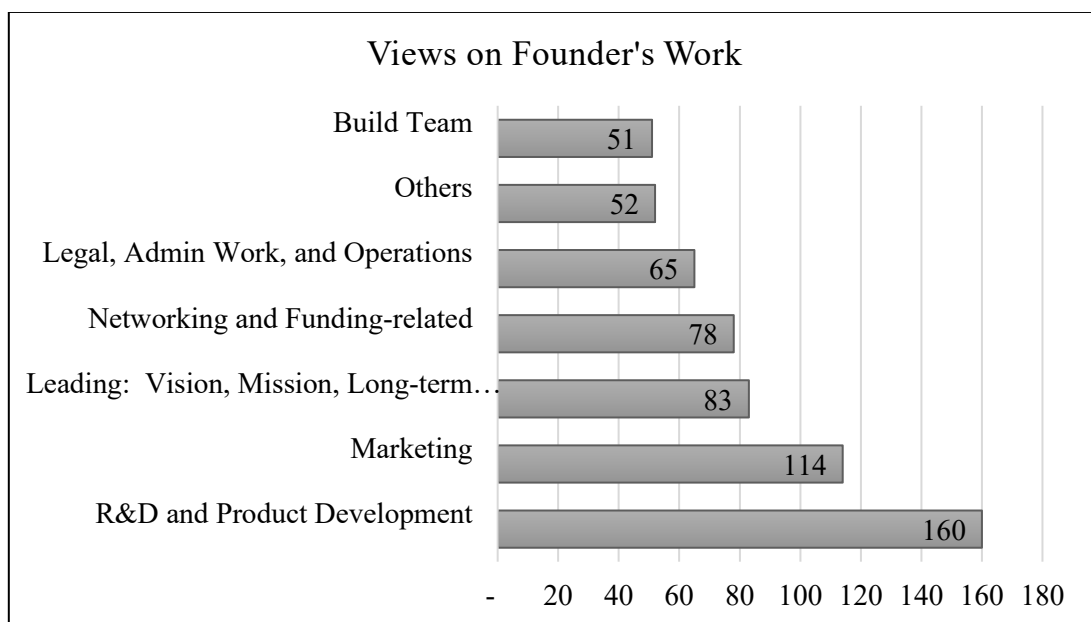


Figure 2 Perceptions about a Founder's work (n=286)

Lastly, the responses for RQ3 (*What are the key factors that deter these selected young Filipinos from launching their own startup?*) are illustrated in Figure 3, based on 1,093 coded responses on a predetermined list of choices (*See Figure 3 Perceived Challenges (n=286)*). The top five challenges are capital requirements and funding as the primary challenge in

setting up a startup (229 responses, or 20.95%), followed by lack of network (179 responses, or 16.38%), lack of a viable idea or product (169 responses, or 15.46%), lack of necessary skills and knowledge (158 responses, or 14.46%), and preference for employment (143 responses, or 13.08%). Appendix A shows sample answers (*See Appendix A: Survey Questions and Sample Responses*).

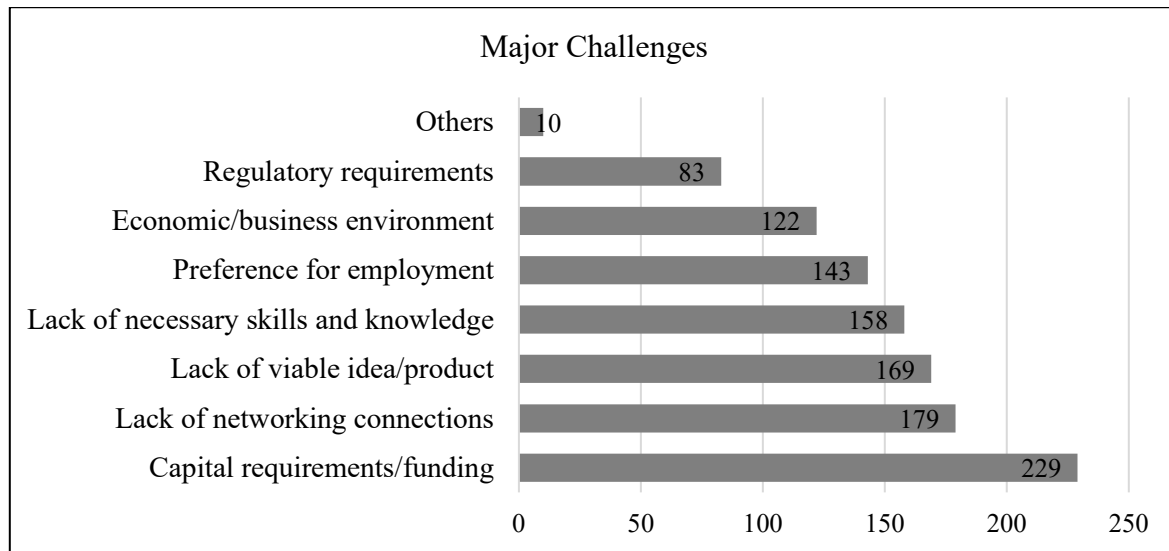


Figure 3 Perceived Challenges (n=286)

5. Discussion

RQ1: How do these selected young Filipinos perceive startups?

The respondents' understanding of what a startup is important because of the following points. First and foremost, they should be aware that they are launching a business. This awareness is crucial because starting and managing a venture requires new skills and heavy responsibilities [16]. Second, because only 35% of the respondents indicated that their startups feature novel products or services, and only 20% of those who relate startups with 'business' value technological innovation, this raises a critical concern. New, small firms inherently face a market disadvantage against established competitors who leverage economies of scale, cost efficiencies, and dominant market shares [16], [18]. To compete effectively with these industry giants, startups must innovate and differentiate their offerings, a reality that prospective founders must fully understand. Finally, it is concerning that very few respondents recognize the importance of scaling within an uncertain environment. A lack of awareness of, and preparation for, scaling up may leave founders vulnerable. Consequently, this misunderstanding should be investigated as a factor that may potentially cause the high failure rate among startups.

RQ2: What are these selected young Filipinos perceptions of a startup founder's job?

Regarding the perception of a founder's role, the prevailing view is that they must balance product delivery with marketing demands. Additionally, they are expected to actively network within the startup ecosystem, particularly to secure funding. While these responsibilities are undeniably important, a startup remains a business at its core, and businesses require a concrete vision to survive. Consequently, a founder must possess a long-term orientation to ensure they stay true to that vision. The insights into the startup characteristics and the role of a founder

should be aligned with the core strengths of Filipino founders, a synergy that becomes vital as the majority look to scale globally [6].

RQ3: What are the key factors that deter these selected young Filipinos from launching their own startup?

Regarding the challenges potential founders anticipate, those listed above align closely with the concerns raised by most established founders [13]. Addressing a simple lack of capital is insufficient; awareness of and access to existing funding must also be enhanced, particularly regarding application processes. Furthermore, startup ecosystem enablers, such as incubators and accelerators, can mitigate hurdles related to limited networks, unviable product ideas, and skill gaps [9]. Conversely, a preference for traditional employment presents a more complex challenge, as it reflects an individual's desire for stability, reliable income, and lifestyle predictability. Consequently, developing a robust incentive system is vital to encouraging young people to pursue technopreneurship. And while government entities are recognized for mentorship, exposure, and regional scaling support within the ecosystem, there is a significant need to improve the bureaucratic processes of government entities because such inefficiencies reduce their otherwise very positive impact [6], [9].

6. Implications

On the theoretical aspect, this study provides much empirical evidence, and therefore theoretical implications, regarding how potential founders view startups vis-à-vis what a startup should be, especially in the context of innovation. Entrepreneurship in general has been defined in various ways [45], which has caused some issues on how it can be fully explained. By extension, the same thing is observable with startups [2], [3], [6], [18], [19], [21]. This research sheds some light by providing some initial qualitative directions on framing what startups are: Startups involves a business that has some form of innovation or novelty that addresses certain markets with specific needs; whose founders focus on R&D and product development and on marketing; but face capital funding and networking challenges. This initial conceptual definition provides an opportunity for further theorizing and discussion. Furthermore, by introducing a country-specific setting, this research heeds the call for research on entrepreneurship to be more cognizant on the effects of demographic and cultural context [42], [44], and moreso for startups.

Regarding practical implications and recommendations, educational and training programs on Technopreneurship, and maybe later on developing startups, targeted towards younger audiences such as college students, can consider making innovation, R&D, product development, and marketing core topics to address the challenges of lack of a viable idea or product and product-market fit. This reflects what past studies have advocated regarding targeted educational and training programs in this context [42]. Furthermore, increasing awareness of how and where to access capital funding sources should also be part of this education and training, consistent with what past studies also recommend [40]. And lastly, validating these proposed themes and topics through constant delivery and review of these educational and training programs will also have to be made along the way.

7. Conclusions, Limitations, and Future Research Directions

Past works have repeatedly emphasized that in order to provide proper and systematic support for startups, clearly defining what startups are in the first place is crucial [18], [19], [21]. This research explored the ideas of selected Technopreneurship students regarding what a startup is, the work of a startup founder, and the challenges that hinder them in launching their

own startup. This is to address the conceptual gap between what the literature advocates and what the present Philippine reality perceives as to what startups are. The results showed that only a few potential founders appreciate the importance of innovation in setting up a startup, and majority of the potential founders believe that they should primarily work on product delivery, marketing, and networking. Majority of the potential founders also identify funding as a major challenge in launching a startup, among others.

The overarching objective of this research is to gain a comprehensive understanding of the Philippine startup ecosystem at an individual level. By analyzing the mindset of potential Filipino founders, tailored educational programs and supportive policies can be designed to incentivize their entrepreneurial endeavors. However, similar to past researches' respective sample profiles [40], [44], [46], this present research covers only a small portion of the potential population of future Filipino founders. The responses to this research came from a restricted student sample coming from a single institution relying on self-reported perceptions. Furthermore, the interpretation of the qualitative response relied on a single channel. These significantly restrict overall generalizability of the results.

To fully realize this objective, future research should significantly expand the respondent pool to include students from diverse disciplines, working professionals, and established founders. This is to reflect the bigger reality that startups work in an ecosystem where multiple diverse stakeholders should work together. For instance, a broader student demographic would allow for a comparative analysis across engineering, business, and non-technical fields, reinforcing the principle that successful innovation requires interdisciplinary collaboration. Incorporating professionals would reveal whether corporate work experience significantly changes startup perceptions, while studying actual founders would offer a valuable comparison against potential founders. Additionally, gathering insights from other ecosystem players, such as mentors, would provide a more balanced ecosystem view. Lastly, probing further on the perceived roles of founder and the highlighted challenges hounding startups provide for ample opportunity to explore and produce more interesting insights that are useful to enhance startup environments.

Declaration of AI use

This present manuscript has been subjected to Google Gemini (<https://gemini.google.com/app>) to improve linguistic clarity and grammatical accuracy.

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Appendix A: Survey Questions and Sample Responses

Question 1: What is your understanding of a startup?	Question 2: What is your understanding of a startup founder's work?	Question 3: What are the possible factors that are stopping you from establishing a startup? Please check all that apply to you.
<i>"Startups are newly founded ventures built from a perceived problem and the assessed market demand of an innovative product or service. These businesses are still trying to break into the market, so startups mostly focus on researching ways and gathering information on how to make their products or services functional and relevant to the target market."</i>	<i>"A founder is often part of a team where members have specific roles. The founders of a startup are in charge of developing the technology, hiring team members, finding customers, and scaling up the business."</i>	Choices include the following: • Capital requirements/funding • Regulatory requirements • Economic/business environment • Lack of necessary skills and knowledge • Lack of viable idea/product • Preference for employment • Lack of networking connections • Others (which the respondent can specify)
<i>"For me, based on what I have learned, a startup is a newly established business designed for rapid growth and scalability, driven by an innovative business model. Startups have the potential to make a significant impact on the market as they expand dramatically, often by addressing unmet needs or introducing disruptive solutions."</i>	<i>"A startup founder brainstorms ideas and pioneer new technologies, whether product or service, that provide solutions to current issues and create a positive change to society."</i>	
<i>"It's like a newly created business related to tech"</i>	<i>"A startup founder is the person who starts the business. They do a bit of everything, coming up with ideas, getting money, building the team, talking to customers, fixing problems, and just trying to make sure the business survives and grows. It's a lot of hard work and long hours."</i>	

Note: The responses shown for each row do not correspond to the same respondent.

Knowledge Transfer in Domain-Specific AI Development: A Social Network Perspective on Cross-Professional Collaboration

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Abstract

This study examines cross-functional knowledge transfer (KT) in the development of a domain-specific artificial intelligence (AI) product, focusing on the conversion of expert tacit knowledge into usable forms. Adopting a diagnostic case study approach, it integrates the Socialization, Externalization, Combination, and Internalization (SECI) model to assess knowledge conversion processes with Social Network Analysis (SNA) to map knowledge flows and identify key experts. The SECI analysis reveals a significant bottleneck at the externalization phase, reflecting business teams' limited capacity to codify experiential knowledge into explicit, transferable formats. SNA findings show the knowledge transfer network is fragmented, highly centralised, and asymmetric. This reliance on a small number of critical knowledge brokers creates a single point of failure and underscores the need for targeted organisational intervention.

Keywords: Cross-functional knowledge transfer; domain-specific AI; tacit knowledge; SECI model; Social Network Analysis (SNA)

1. Introduction

The rapid advancement of artificial intelligence (AI) in specialised business domains such as tendering and bidding has introduced new challenges for organizational knowledge management. Such knowledge-intensive AI initiatives require sustained collaboration between business domain experts, who hold contextual understanding of work processes and decision logic, and AI developers, who translate that expertise into technical models. Because domain-specific AI products depend on the integration of heterogeneous knowledge bases, their quality hinges on technical sophistication and the effectiveness of cross-functional knowledge transfer (KT); failures in this exchange can directly constrain the relevance and performance of AI solutions.

A central difficulty lies in the transfer of tacit knowledge. Polanyi [1] argued that individuals often know more than they can tell, highlighting the challenge of articulating experiential judgment and situated know-how in explicit terms. This is especially salient in domain-specific AI projects, where business experts rely on practical insight and contextual interpretation rarely captured in formal documentation; AI teams must access this knowledge and operationalise it into rules, workflows, or model design [2]. Developing specialised AI systems is thus as much a knowledge-conversion challenge as a technical one.

Current literature offers limited empirical insight into how tacit domain knowledge is

transferred across professional boundaries during domain-specific AI development. Existing studies rarely connect knowledge conversion processes with the underlying relational structures. This leaves a limited understanding of where knowledge conversion breaks down in cross-professional AI teams, and how dependency on central actors may create structural vulnerabilities.

To address this gap, this study presents a Stage 1 diagnostic case study of a Chinese bidding and tendering company developing an AI agent. By integrating the SECI model [3] to assess knowledge-conversion bottlenecks, with Social Network Analysis (SNA) [4] to identify critical knowledge brokers, this research establishes an empirical foundation for future intervention design.

This study contributes to knowledge management theory by demonstrating that the core challenge in domain-specific AI development is the systematic externalisation of tacit expertise across professional boundaries. Furthermore, coupling SECI with SNA provides a structurally grounded explanation for KT, clarifying why certain projects remain dependent on a few knowledge brokers and face potential single points of failure.

2. Literature Review

This section reviews theoretical perspectives on KT and conversion across professional teams, and the mechanisms for improving KT performance in domain-specific AI projects.

The SECI model, Socialization, Externalization, Combination, and Internalization, provides a foundational framework for understanding organizational knowledge creation through the interaction between tacit and explicit knowledge [3], [5]. This framework is especially relevant to domain-specific AI development, where AI systems depend on transforming business experts' experience-based insights into forms that technical teams can interpret and operationalise. Among the four modes, externalization, translating tacit knowledge such as professional judgment and heuristics into explicit, codifiable form, is particularly critical [3], [5]; failure at this stage can result in AI systems that capture only superficial procedural knowledge while missing the deeper reasoning underlying expert decision-making. The SECI model further characterizes knowledge creation as an iterative "knowledge spiral" [5], reflecting the repeated business-technical interaction needed to refine domain logic in AI projects.

While SECI explains how knowledge is converted, it does not account for how knowledge moves through relationships among actors. SNA addresses this gap by mapping the structure of ties among individuals to measure communication, collaboration, and knowledge-flow patterns, revealing informal structures of influence not visible in formal organizational charts [4], [6]. SNA is particularly valuable for identifying high-leverage actors: individuals with high betweenness centrality often function as knowledge brokers, connecting otherwise disconnected groups and mediating information flow across professional boundaries [4], [7]. This study operationalises these structural properties using established directed-network measures: centrality and centralisation [8], connectivity under weak and strong tie definitions [9], a relational approach to network boundary specification [10], and an account of asymmetry in self-reported relational data [11].

Beyond identifying key actors, network structure also shapes the ease of KT itself: cohesion and range within a network influence how readily knowledge moves across it [12]. Where KT crosses distinct professional practices, as between business and technical teams, differences in assumptions, vocabulary, and standards can constitute a pragmatic boundary requiring active translation rather than simple transfer [13]. These perspectives inform the present study's interpretation of where and why, cross-functional knowledge conversion is

structurally constrained.

3. Methodology

This study follows an Input-Process-Output-Outcome design. This study is a diagnostic case study combining a SECI questionnaire and SNA to examine knowledge conversion and transfer within a cross-professional team delivering a domain-specific AI project. The SECI instrument assesses how tacit and explicit knowledge are created, shared, and applied among team members. SNA maps two relational networks to identify structurally important actors and patterns of connection.

Network construction, data validation, and structural calculations were carried out in Python (NetworkX), with centrality and centralisation indices cross-validated in UCINET 6.

3.1 Data Source

Data was collected from participants in a project developing a domain-specific AI product for a bidding and tendering business unit. Thirteen formally assigned project team members completed both the SECI questionnaire and the SNA nomination items, giving a full response rate for the core team. Team members were classified into four functional groups: Business (BU), Technical (TE), Management (PM), and Organizational Support (SU). The sample comprised a total of 13 participants, including five TEs, four BUs, two PMs, and two SUs.

The SNA instrument used a relational boundary specification [10]: any actor named as a genuine contact by a core member was eligible for inclusion, regardless of formal project membership. This yielded five further actors, bringing the SNA sample to 18. These five actors sat outside the formally assigned team, so the SECI questionnaire was not administered to them; this is a deliberate boundary decision, and their ties were reported directly by the core members who named them. Ties reported by core members toward a boundary actor were retained. A boundary actor's own self-reported ties were retained only where independently corroborated by another respondent. One boundary actor was excluded from the final sample on this basis.

SECI and SNA data are analysed at different levels of aggregation. SECI is analysed at the level of the whole team ($n = 13$), consistent with the model's focus on the conversion process itself and with the small size of some functional groups. SNA is analysed with the full four-group classification ($n = 18$), since group-level structural comparison is itself part of the analytic aim.

3.2 Measurement of SECI

The questionnaire assessed perceptions of the four SECI processes using twelve items, three per dimension, developed from Nonaka's [3] account of each process and reviewed for content fit prior to distribution. All items used a four-point scale. Response wording was written separately for each item to match its specific content (see the response-category key, Table 1).

Table 1. Wording of Response Categories by SECI Item

Dimension	Item	Cat. 1	Cat. 4
Socialization	Informal exchange frequency	None, formal meetings only	Fairly frequent
Externalization	BU tacit-to-explicit conversion	Difficult, inarticulable	Structured, high-quality output
Combination	Explicit-knowledge quality	Scattered, poor quality	Unified, high-quality
Internalization	Trust in adoption	Low trust, resistant	High trust, daily use

Note. One representative item is shown per dimension; the remaining eight items follow the same category-anchoring logic.

The three items within each dimension were designed to capture distinct facets of that process. For Socialization, for instance, the three items address behavioural frequency, perceived understanding, and institutionalization. This item structure is consistent with formative measurement [14]: each item defines a separate part of the construct, and the three items together compose it. Response categories are ordinal, without equal spacing between points. Composite mean scores were therefore not used as the primary unit of analysis; item-level frequency distributions are reported instead.

3.3 Measurement of SNA

Two directed networks were constructed from nomination data (Table 2). The Knowledge-Transfer (KT) network represents advice-seeking (A to B: A seeks help or advice from B), built from two complementary items, one naming those who approach the respondent for help, one naming those the respondent approaches. The Collaboration network represents close working relationships (A to B: A named B as a close collaborator), built from a single nomination item.

Table 2. The SNA Questionnaire Design

Network	Question (Condensed)	Objective
Collaboration	Who did you collaborate closely with on the project (e.g., joint documents, meetings, data exchange)? How often?	To identify collaboration patterns among team members.
Knowledge Transfer	Two complementary items: who do you turn to for help or advice, and who turns to you? How often?	To identify KT structure and key actors.

Both networks are directed and were not symmetrized at construction: a nomination in one direction carries no assumption of a matching nomination in the other. Where a collaboration tie was reported by only one party, this was interpreted as asymmetric recognition or recall of the same relationship, following Krackhardt's [11] account of cognitive social structures.

Ties were weighted on a four-point frequency scale (1 = less than once a month, 4 = almost daily); the KT and Collaboration items used slightly different wording for these categories, mapped onto the same scale before analysis.

Because both networks are directed, connectivity between two actors can be defined in two ways. Weak connectivity treats a tie in either direction as sufficient for connection; strong connectivity requires a confirmed tie in both directions [9]. These are applied throughout as Tier 1 and Tier 2 (Table 3), and each answers a different question about the network. Tier 1 uses one definition across both networks and supports direct comparison of overall reach. Tier 2 is interpreted within each network separately, since reciprocity carries different substantive weight in an advice-seeking relationship and in a collaborative one. Divergence between Tier 1 and Tier 2 results for the same network is treated as a substantive finding about the balance between reach and reciprocity.

At the whole-network level, density, mean degree, reciprocity, and mean tie weight are reported descriptively. Component count (K), fragmentation (F), giant- or largest-component ratio, and degree and betweenness centralisation [8] are reported under both tiers, computed on the binarized tie structure.

Cohesive subgroups were identified through clique analysis (minimum size three, Bron-Kerbosch algorithm), again under both tiers: symmetrized cliques admit any directed tie between members, strict reciprocal cliques require a confirmed tie between every pair. At the actor level, out-degree, in-degree, and betweenness centrality are reported for each actor in each network; closeness was not computed, as neither network is fully strongly connected. An actor-level reciprocity ratio is also reported. By cross-analyzing betweenness (above or below the

network median) with second-tier clique membership, participants were classified into four structural roles: core and bridge, pure broker, core member, and isolated. Actors' rankings are compared across the two networks to identify those who are consistently central, central in one network only, or peripheral in both. A supplementary, tier-independent analysis cross-tabulates all directed ties by the functional group of source and target, to examine the composition of cross-group exchange, including the proportion of ties connecting the Business and Technical groups specifically.

Table 3. Summary of the Tier 1 / Tier 2 Connectivity Framework

Tier	Definition	Question It Answers	Applied To
Tier 1 (weak)	A tie in either direction is sufficient for connection.	How broadly does reach extend, regardless of direction or confirmation?	Whole-network K, F, giant-component ratio; symmetrized clique identification
Tier 2 (strong)	A confirmed tie in both directions is required.	How much of the network is embedded in mutually confirmed relationships?	Whole-network K, F, largest strong-component coverage; strict reciprocal clique identification; actor-level role classification

3.4 Data Reliability and Research Ethics

To enhance the reliability and consistency of responses, a briefing session was conducted prior to data collection, during which the questionnaire's content and completion procedures were explained in detail to all participants. Participants also completed a trial run of the questionnaire during this session, serving as a form of cognitive pretesting to clarify ambiguities in question wording and reduce measurement inconsistency.

Participants were informed of the study's purpose, and informed consent was obtained from all before data collection; participation was voluntary and confidentiality of responses was assured. This study was conducted with the approval of the host organization as an internal case study; as such, no separate institutional ethics board approval was sought, and this is noted as a limitation of the study's ethical clearance process.

4. Results and Discussion

4.1 The Results from SECI

This section presents SECI-based findings on knowledge conversion across the project team, organized by the four dimensions: Socialization (S), Externalization (E), Combination (C), and Internalization (I). Results are based on the full project team ($n = 13$). Response categories were item-specific, with category 1 marking the lowest level of the practice described and category 4 marking the highest (Table 4).

The aggregate data reveal higher reported activity in Socialization and Internalization, which secure 84.6% and 74.4% of responses in the upper two categories respectively. Externalization and Combination record the lowest upper-tier frequencies at 56.4%, yet their underlying distributions differ sharply in shape.

Socialization drew the highest share of responses in categories 3 and 4. Informal exchange frequency showed the strongest concentration at the top end, with 7 respondents (53.8%) selecting category 4. Tacit knowledge understanding and joint-experience activities both centered on category 3, chosen by 9 (69.2%) and 8 (61.5%) respondents respectively.

Internalization followed, with 74.4% of responses in categories 3 and 4. Trust in adoption and team learning support each drew a majority into category 3, at 10 respondents (76.9%) and 7 respondents (53.8%). Ratings of the AI team's own learning were more spread, with 4 respondents (30.8%) in category 4 and 2 (15.4%) in category 1.

Externalization and Combination were tied at 56.4%, the lowest share among the four dimensions. Within Externalization, no respondent selected category 4 for the business team's conversion of tacit knowledge into explicit form, or for the business-technology linking mechanism; only 1 respondent (7.7%) selected category 4 for the AI team's explanation clarity. Within Combination, explicit-knowledge quality and technology availability each concentrated in category 3, while process integration spread more evenly across the scale, with 5 respondents (38.5%) in category 2 and 3 respondents (23.1%) at each end. The two dimensions differ in distribution shape despite the tied share: Externalization shows a near-total absence of category-4 responses across all three items, while Combination's spread is concentrated in a single item, process integration.

Table 4. Share of Responses in Categories 3-4, by Dimension

Dimension	% of Responses in Categories 3-4
Socialization	84.6%
Internalization	74.4%
Combination	56.4%
Externalization	56.4%

4.2 The Results from SNA

The KT network recorded 45 directed ties among 18 actors (density = 0.147); the Collaboration network recorded 25 ties (density = 0.082). Mean out-degree and in-degree were both 2.500 in the KT network and 1.389 in the Collaboration network. Overall reciprocity was 35.6% in the KT network and 16.0% in the Collaboration network. Mean tie weight was higher among reciprocated ties than one-directional ties in both networks (KT: 3.062 versus 2.172; Collaboration: 3.750 versus 2.238).

Under Tier 1 (weak connectivity), the KT network formed a single component ($K = 1$; giant-component ratio = 1.000; $F = 0.000$). The Collaboration network split into four components ($K = 4$; giant-component ratio = 0.833; $F = 0.314$). Under Tier 2 (strong connectivity), the KT network split into five components ($K = 5$), the largest covering 77.8% of actors ($F = 0.405$); the Collaboration network split into fifteen components ($K = 15$), the largest covering 22.2% of actors ($F = 0.961$). Degree centralisation was higher for out-degree than in-degree in the KT network (0.343 versus 0.218), and higher for in-degree than out-degree in the Collaboration network (0.287 versus 0.225). Betweenness centralisation was 0.231 in the KT network and 0.038 in the Collaboration network.

Under the symmetrized (Tier 1) definition, ten cliques of size three or more were identified in the KT network, covering 14 of 18 actors, with a largest clique of five members. The Collaboration network yielded seven such cliques, covering 9 of 18 actors, with a largest clique of four members. Under the strict reciprocal (Tier 2) definition, the KT network contained one clique of three members (BU-03, TE-03, TE-05); the Collaboration network met the Tier 2 criterion for no clique (Table 5).

Table 5. Clique Analysis Summary

Measure	KT (T1)	KT (T2)	Collab. (T1)	Collab. (T2)
K (cliques, size ≥ 3)	10	1	7	0
Actors covered (n, %)	14 (77.8%)	3 (16.7%)	9 (50.0%)	0 (0.0%)
Largest clique size	5	3	4	—

TE-05 recorded the highest betweenness in the KT network (0.294), followed by BU-03 (0.259) and BU-02 (0.226). In the Collaboration network, PM-01 recorded the highest betweenness (0.052), followed by BU-03 and TE-02 (0.048 each). Out-degree ranged from 0 to 8 across actors in the KT network and from 0 to 5 in the Collaboration network.

Classifying actors by betweenness and Tier 2 clique membership placed three actors (BU-03, TE-03, TE-05) in the Core and Bridge category for the KT network, with a further six classified as Pure Broker. No actor met the Core and Bridge criteria in the Collaboration network; eight actors were classified as Pure Broker (Table 6).

Table 6 Actor-Level Structural Roles (Tier 2)

Role	KT Network Actors	Collaboration Network Actors
Core + Bridge	BU-03, TE-03, TE-05	None
Pure Broker	PM-01, PM-02, PM-03, BU-01, BU-02, TE-02	PM-01, PM-02, BU-01, BU-03, TE-02, TE-03, TE-04, TE-05
Core Member	None	None
Peripheral/Isolated	PM-04, BU-04, BU-05, SU-01, SU-02, SU-03, TE-01, TE-04, TE-06	PM-03, PM-04, BU-02, BU-04, BU-05, SU-01, SU-02, SU-03, TE-01, TE-06

Seven actors (PM-01, PM-02, BU-01, BU-03, TE-02, TE-03, TE-05) recorded above-median betweenness in both networks. Two actors (PM-03, BU-02) recorded above-median betweenness in the KT network only, and one actor (TE-04) in the Collaboration network only. The KT network contained no isolated actors; the Collaboration network contained three (PM-03, PM-04, SU-03), with no actor isolated in both networks. Mean betweenness by functional group was highest for BU in the KT network (0.118) and highest for TE in the Collaboration network (0.023).

Cross-group ties accounted for 71.1% of all ties in the KT network and 72.0% in the Collaboration network. Ties connecting the Business and Technical groups numbered 13 in the KT network and 7 in the Collaboration network, representing 40.6% and 38.9% of cross-group ties respectively. The realization rate for Business-Technical ties, calculated against the maximum possible number of such ties, was 21.7% in the KT network and 11.7% in the Collaboration network (Table 7).

Table 7. Cross-Functional Tie Composition

Measure	KT Network	Collaboration Network
Within-group ties (n, %)	13 (28.9%)	7 (28.0%)
Cross-group ties (n, %)	32 (71.1%)	18 (72.0%)
BU-TE ties (% of cross-group ties)	40.6%	38.9%
BU-TE realization rate	21.7%	11.7%

4.3 Principal Findings

Considered together, the SECI and SNA results point to a common split between broad, informal exchange and confirmed, structured exchange.

SECI results place Socialization highest among the four dimensions, with 84.6% of responses in categories 3 and 4, and informal exchange frequency drawing the strongest concentration in category 4. The KT network shows a parallel pattern at the whole-network level: under Tier 1 connectivity, all 18 actors sit within a single component ($K = 1$, giant-component ratio = 1.000), so advice-seeking reaches the entire team once direction and mutual

confirmation are set aside.

Externalization and Combination are tied for the lowest share of SECI responses in categories 3 and 4, at 56.4% each, with Externalization showing an almost complete absence of category-4 responses across all three items. The KT network shows a comparable narrowing once reciprocity is required: under Tier 2, K rises from 1 to 5 and the largest strong component covers 77.8% of actors, down from full coverage under Tier 1. Only one clique meets the strict reciprocal definition, comprising BU-03, TE-03, and TE-05. The Collaboration network shows the same narrowing in sharper form: its Tier 1 giant component covers 83.3% of actors, yet no clique meets the Tier 2 definition at all.

SECI's Externalization items address the conversion of business knowledge into explicit form and the clarity of technical explanation between the Business and Technical groups; neither item drew a single category-4 response. The SNA cross-functional composition results show a matching pattern at the structural level. Ties connecting the Business and Technical groups form the largest share of cross-group ties in both networks, at 40.6% in the KT network and 38.9% in the Collaboration network, yet the realization rate for these ties against their theoretical maximum is low in both, at 21.7% and 11.7% respectively.

4.4 Discussion

The convergence between Socialization and Tier 1 reachability fits Nonaka's [3] account of Socialization as grounded in shared context and direct experience. This mode of knowledge conversion does not depend on formal documentation, structured process, or codified language. It can proceed through everyday contact. A single connected component under weak connectivity is a plausible structural counterpart to a dimension that, by its own theoretical description, asks little of participants beyond proximity and willingness to interact.

The joint narrowing of Externalization and Combination in the SECI results, alongside the drop from full reachability to a fragmented reciprocal core in both networks, fits a related theoretical account. Nonaka [3] characterizes Externalization as the most demanding of the four conversion modes, since it requires participants to articulate tacit understanding in a form others can grasp, often through dialogue, analogy, or repeated clarification. Such a process typically depends on sustained, mutually acknowledged exchange. A setting in which most ties run in one direction only, and in which the Collaboration network yields no group of three or more actors with fully confirmed mutual ties, offers a plausible account of why Externalization scores stay low even where Socialization scores are high.

This pattern also speaks to the wider literature on network range and KT. Reagans and McEvily [12] argue that a wide network range eases the movement of knowledge across a group, largely because broad reach exposes actors to more potential sources. The present findings support the reach component of that argument: under Tier 1, the KT network reaches every actor. They also point to a condition that reach alone does not appear to satisfy. Once the criterion shifts from reach to confirmed exchange, coverage falls sharply. Range and reciprocal embeddedness may capture different aspects of a team's capacity to convert knowledge, and a favorable reading of range on its own may understate the difficulty of the conversion process that Nonaka's model describes.

The concentration of low Externalization ratings in the items addressing Business-to-Technical conversion, together with the composition of cross-group ties, points to a boundary specific to the Business and Technical groups. Carlile's [13] account of knowledge boundaries between differing professional practices is relevant here. Carlile [13] distinguishes boundaries that straightforward transfer can cross from boundaries that require translation or transformation, because the groups involved hold different assumptions, vocabularies, and standards for what counts as adequate knowledge. Business and Technical ties form the largest

share of cross-group contact in both networks, yet the share of theoretically possible Business-Technical ties actually realised stays low. This combination fits a pragmatic boundary of the kind Carlile [13] describes. Contact between the two groups is frequent, but converting one group's tacit understanding into a form the other can use appears to demand more than contact alone. BU-03, TE-03, and TE-05, the network's confirmed reciprocal core, may be functioning as the boundary spanners [15] who carry knowledge across this boundary despite limited reciprocal exchange.

Read together, the two strands of data show no clear contradiction. A divergence might have appeared if broad SECI-reported informal exchange had coincided with a fragmented KT network, or if strong Combination scores had coincided with sparse cross-group ties. Instead, the two methods point in the same direction throughout. This agreement across an attitudinal instrument and a relational network instrument lends the observed pattern some credibility as a genuine feature of this team's knowledge-conversion practice.

4.5 Implications

The gap between Tier 1 reach and Tier 2 reciprocity, mirrored in the SECI split between Socialization and Externalization, suggests that reach and reciprocity are separable dimensions of a knowledge network rather than a single underlying quantity. Reagans and McEvily [12] treat network range as a driver of ease of KT; the present findings suggest range captures only part of that ease, with confirmed reciprocity tracking more closely with SECI's account of Externalization as the more demanding conversion process. Structural reachability and relational reciprocity may therefore need to be measured and reported separately when evaluating a network's capacity to support knowledge conversion. The Business-Technical pattern similarly extends Carlile's [13] account of knowledge boundaries: a large cross-group tie share combined with a low realization rate offers a possible network-analytic signature of a pragmatic boundary, worth checking through complementary qualitative work.

Given that reach is broad but confirmed exchange is scarce, effort is better directed at deepening existing ties than at expanding access further. BU-03, TE-03, and TE-05, who form the KT network's one confirmed reciprocal core, are a reasonable starting point for structured knowledge-extraction work. Because the weakest Externalization ratings concentrate in Business-to-Technical conversion specifically, a dedicated translation mechanism between these two groups is likely to address the pattern more directly than a general knowledge-sharing initiative.

5. Conclusion and Future Work

This research exposes critical vulnerabilities in how cross-functional teams transfer knowledge during domain-specific AI development. "The SECI analysis identifies externalisation as the most significant breakdown point. Articulating tacit expertise into explicit, transferable forms remains the project's primary bottleneck. The Business Team's limited capacity to codify experiential knowledge exacerbates this issue. Consequently, a structural disconnect emerges, preventing strong informal socialisation from evolving into durable organisational knowledge assets.

The SNA results reinforce this diagnosis: the KT network is fragmented, asymmetric, and highly centralised. Although a cross-functional core is present, knowledge flow depends disproportionately on a small number of key brokers, most notably BU-03, TE-03, and TE-05, who form the network's confirmed reciprocal core spanning the Business and Technical groups. This dependency creates a pronounced single-point-of-failure risk, undermining both knowledge resilience and the scalability of organizational learning.

As a diagnostic case study of a single organization, this research is subject to a small sample

size and limited generalizability; the findings reflect the specific organizational context examined and should not be assumed to generalize to other settings without further investigation.

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HR Digitalization and Governance as Enablers of Green HRM Systems in Thai Companies

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Abstract

This paper aims to examine the role of corporate governance mechanisms and HR digitalization as key enablers of Green Human Resource Management (Green HRM) systems in Thai companies under the Bio-Circular-Green (BCG) Economic Model and the Thailand 4.0 policy. An integrative literature review was employed as the research methodology. Relevant empirical and conceptual studies published in peer-reviewed journals, international reports, and authoritative institutional publications were systematically identified and selected based on their relevance to Green HRM, corporate governance, HR digitalization, artificial intelligence (AI), ESG, and sustainability. The selected literature was synthesized using thematic analysis to identify key concepts, theoretical relationships, and emerging patterns, which were subsequently integrated into a conceptual framework.

The findings suggest that the SEC Form 56-1 One Report may promote ESG transparency in the Thai capital market. In Thailand's relatively collectivist context, upstream Green HRM practices may support employees' pro-environmental behaviors, although their relative effectiveness requires further validation. AI may serve as an enabling mechanism linking ESG strategies with HR practices, while ethical digital leadership may support responsible AI implementation and sustainable organizational outcomes.

The proposed conceptual framework contributes to the literature by integrating corporate governance, HR digitalization, AI, and Green HRM into a unified sustainability perspective. The study also provides practical implications for Thai organizations and policymakers in strengthening data governance, HR innovation, and sustainable human resource management to support long-term organizational sustainability and the achievement of the United Nations Sustainable Development Goals (SDGs).

Keywords: Green Human Resource Management (Green HRM); HR Digitalization; Corporate Governance; BCG Economic Model; Artificial Intelligence (AI); ESG Disclosure

1. Introduction

With the acceleration of climate change and the degradation of natural resources, there is a growing expectation that business organizations will contribute to the United Nations Sustainable Development Goals (UN SDGs), in particular Goal 8 (Decent Work and Economic Growth), Goal 12 (Responsible Consumption and Production) and Goal 13 (Climate Action) [4], [5]. Thailand has adopted the Bio-Circular-Green (BCG) Economic Model as a national development strategy to stimulate inclusive and sustainable growth by leveraging biodiversity, innovation and digital transformation [9]. This model is in line with the Thailand 4.0 policy that aims to move Thailand from a middle-income economy to an innovation-driven economy [6]. To achieve these macro-level objectives, the business sector needs to fundamentally transform its strategic orientation, particularly in human capital management, to align HR systems with sustainability priorities. However, aligning HR systems with sustainability priorities is

essential. Nevertheless, the drive towards sustainability in the Thai business sector cannot be achieved solely through voluntary efforts but must also be driven by strong institutional pressures and corporate governance mechanisms of the drive towards sustainability in the Thai business sector cannot be achieved solely through voluntary efforts but also must be driven through strong institutional pressures and mechanisms of corporate governance. One important regulation is the Securities and Exchange Commission (SEC)'s mandatory integrated annual report (Form 56-1 One Report) practice that requires a listed company to disclose Environmental, Social and Governance (ESG) information in a single connected annual report transparently [7]. Empirical evidence suggests that the enforcement of the One Report has significantly improved the quality of ESG disclosures of Thai listed companies, as improved connectivity and conciseness of information are positively correlated with the sustainable growth rates of firms [1]. The governance disclosure of the firms listed in the Market for Alternative Investment (MAI) is associated with a positive market reaction as it reduces information asymmetry and increases investor confidence [11].

On the other hand, negative short-term impacts on investor perceptions have been found for environmental disclosure, with green investments often perceived as cost burdens that put pressure on short-term profitability [11]. Effective Green Human Resource Management (Green HRM) systems are needed to translate macro-level governance and reporting pressures into day-to-day organisational behaviour. Green HRM integrates environmentally sustainable practices into core HR functions aimed at boosting organizational sustainability performance [5]. In the Thai cultural context, it is found that upstream Green HRM practices (green recruitment and environmental training) are most effective in enhancing the environmental commitment and environmental organizational citizenship behavior (Environmental OCB) of employees, while downstream practices (performance appraisal and monetary rewards) are not significantly effective [3]. This pattern reflects the collectivist cultural orientation of Thailand, where group norms and shared values are more important than individual financial incentives [3]. Green HRM systems have been crucial enablers through digital technologies and artificial intelligence (AI). AI enables collection and analysis of ESG data for more accurate reporting. AI also enables the design of personalized learning systems and gamified sustainability interventions to improve employees' environmental literacy [10]. Research has indicated that AI is a mediating mechanism that links ESG goals and Green HRM practices to improved financial performance, especially in terms of return on assets (ROA) and return on equity (ROE) [2]. At the same time, the increasing use of AI in HRM poses risks of algorithmic bias, lack of transparency and possible violations of employee data privacy – risks that have been characterized as the “digital sustainability paradox” [4],[13]. These challenges highlight the importance of ethical digital leadership that can balance innovation with data governance and employee well-being [14]. The relevance of ESG, Green HRM and AI technologies is gaining traction in recent literature. However, most of the existing studies address these components in isolation, creating a gap in integrated knowledge on how these components work together in a developing country like Thailand.

This paper attempts to bridge this gap by synthesizing recent empirical and conceptual work and developing a conceptual framework connecting institutional pressures, digital and AI-enabled Green HRM systems, employee-level outcomes, and firm and market-level performance.

2. Conceptual Framework and Theoretical Foundations

This study employs an integrative literature review to synthesize theoretical and empirical evidence concerning Green Human Resource Management (Green HRM), HR digitalization,

artificial intelligence (AI), digital leadership, corporate governance, ESG disclosure, and organizational sustainability. Relevant literature was identified through Scopus, Web of Science, ScienceDirect, and Google Scholar, covering publications from 2015 to 2025. Additional authoritative Thai regulatory and policy documents were reviewed to capture the institutional context, particularly documents related to the Form 56-1 One Report, Thailand's Bio-Circular-Green (BCG) Economy Model, Thailand 4.0, and national ESG and sustainability policies.

The literature searches employed combinations of keywords and Boolean operators, including "Green Human Resource Management" OR "Green HRM," "HR digitalization" OR "digital HR," "artificial intelligence" OR "AI-enabled HRM," "digital leadership," "corporate governance," "ESG disclosure," "environmental organizational citizenship behavior" OR "Environmental OCB," "organizational sustainability," "sustainable firm performance," and "Thailand." The search strategy was designed to capture studies examining the relationships among digital transformation, human resource management, governance mechanisms, employee environmental behavior, and organizational sustainability.

Studies were included if they (1) directly addressed one or more of the core constructs of the proposed framework; (2) examined theoretical or empirical relationships relevant to Green HRM, HR digitalization, AI, digital leadership, corporate governance, ESG, employee environmental behavior, or organizational sustainability; (3) were peer-reviewed journal articles or authoritative institutional and regulatory documents; and (4) provided sufficient theoretical or empirical evidence to inform the development of the conceptual framework. Studies were excluded if they were duplicates, were unrelated to the principal constructs, focused on digital technology or environmental management without a meaningful connection to HRM, governance, or organizational sustainability, or provided insufficient theoretical or methodological information.

The screening process was conducted in three stages. First, duplicate and clearly irrelevant records were removed. Second, titles and abstracts were screened against the inclusion and exclusion criteria. Third, potentially relevant studies underwent full-text assessment to determine their theoretical and empirical relevance to the proposed framework. The final set of eligible studies was retained for integrative synthesis, with particular attention to studies conducted in Thailand and other organizational contexts that could provide comparative theoretical evidence. The quality and relevance of the selected literature were assessed based on the clarity of research objectives, appropriateness of research design and methodology, adequacy of evidence supporting the conclusions, and relevance to the relationships proposed in the conceptual framework.

The selected literature was subsequently synthesized through thematic analysis and organized into six interrelated themes: (1) Green HRM and employee environmental behavior; (2) HR digitalization and AI-enabled HRM; (3) digital leadership and organizational transformation; (4) corporate governance and institutional pressures; (5) ESG disclosure and stakeholder signalling; and (6) organizational sustainability and firm-level outcomes. Convergent and divergent findings across the studies were compared to identify consistent patterns, theoretical gaps, and context-specific evidence.

Finally, the synthesized evidence was interpreted through the Resource-Based View (RBV), Theory of Planned Behavior (TPB), Ability–Motivation–Opportunity (AMO) framework, Social Exchange Theory (SET), Institutional Theory, and Signalling Theory. Each theoretical perspective was linked to specific constructs and proposed relationships rather than being treated as an independent theoretical explanation. This integrative synthesis provides the theoretical foundation for clarifying the roles of corporate governance, HR digitalization, AI,

digital leadership, Green HRM, employee environmental behavior, ESG disclosure, and organizational sustainability in the conceptual framework presented below.

2.1 Integration of Green HRM, HR Digitalization, and Corporate Governance

The integration of Green HRM, HR digitalization, and corporate governance in the Thai context can be explained by a combination of key theories at the organizational and individual levels. These theories provide the basis for a conceptual framework that links macro-level sustainability policies to micro-level employee behaviors and, ultimately, to firm-level outcomes.

2.1.1. Theoretical Background of Green HRM and Behavior

Resource-Based View (RBV): This theory claims that green human capital and digital capabilities are strategic resources that are valuable, rare, and hard to imitate and thus necessary to gain sustainable competitive advantage (Kurniawan et al., 2025). The use of digital technologies by organizations to support Green HRM systems suggests that these resources are strategic assets that enable adaptation and measurable response to environmental goals [2].

2.1.2. Theory of Planned Behavior (TPB) and AMO Framework (Ability–Motivation–Opportunity)

At the individual level, sustainability goals are achieved by changing the behaviour of the employees in the HR systems [5]. AMO framework explains how organizations can develop employees' ability, increase their motivation and provide opportunity to pursue green activities [3], [5]. Furthermore, Social Exchange Theory (SET) proposes that organizations that invest in employee well-being and equitable support are more likely to have employees reciprocate with pro-environmental organizational citizenship behavior (OCB) [3],[4].

2.2. Institutional theory

Thai firms practice ESG and Green HRM practices because of institutional pressures: coercive pressures by the government regulations (e.g. the One Report policy), normative pressures from industry standards and global ESG frameworks, and mimetic pressures by peers pursuing sustainability goals [6]. These institutional pressures provide the organizational context for the adoption and institutionalization of HR digitalization and Green HRM systems.

2.3 Signalling Theory and Technology as an Intermediary

Signalling Theory: High-quality ESG disclosure, especially governance-related information in the Form 56-1 One Report, is a positive signal to capital markets, reducing information asymmetry between firms and investors and increasing stakeholder confidence [11] This transparent signalling has a direct and positive effect on market reactions and increases sustainable growth rates of firms [1],[11]. Mediating Role of AI and Digital Leadership: From a systems perspective, AI acts as an important mediating mechanism to translate ESG policies into actual Green HRM practices and, in turn, improve organizational financial performance [2]. The digital leadership should guide the technology-driven transformation that integrates innovation and ethics with data governance, balancing organizational efficiency and human well-being [14].

2.4 Proposed Conceptual Framework

Based on the preceding theoretical perspectives, this study develops a conceptual framework that integrates corporate governance, institutional theory, HR digitalization, Green HRM, artificial intelligence (AI), and digital leadership into a coherent multilevel framework.

At the macro level, corporate governance mechanisms, represented by the SEC Form 56-1 One Report, together with institutional pressures arising from the BCG Economic Model and

Thailand 4.0 policy, provide the external drivers encouraging organizations to adopt sustainable HR practices.

At the organizational level, digital leadership facilitates HR digital transformation by promoting the adoption of AI-enabled HR technologies, including e-recruitment, personalized digital learning, gamification, and ESG data analytics. These technologies strengthen Green HRM practices, particularly green recruitment and environmental training.

At the employee level, Green HRM practices enhance employees' environmental commitment, which subsequently promotes environmental organizational citizenship behavior (Environmental OCB), consistent with the Theory of Planned Behavior, the AMO framework, and Social Exchange Theory.

Finally, at the organizational outcome level, employees' pro-environmental behaviors improve ESG disclosure quality, strengthen organizational financial performance, support sustainable firm growth, and contribute to the achievement of the United Nations Sustainable Development Goals (SDGs). Figure 1 summarizes the proposed conceptual framework.

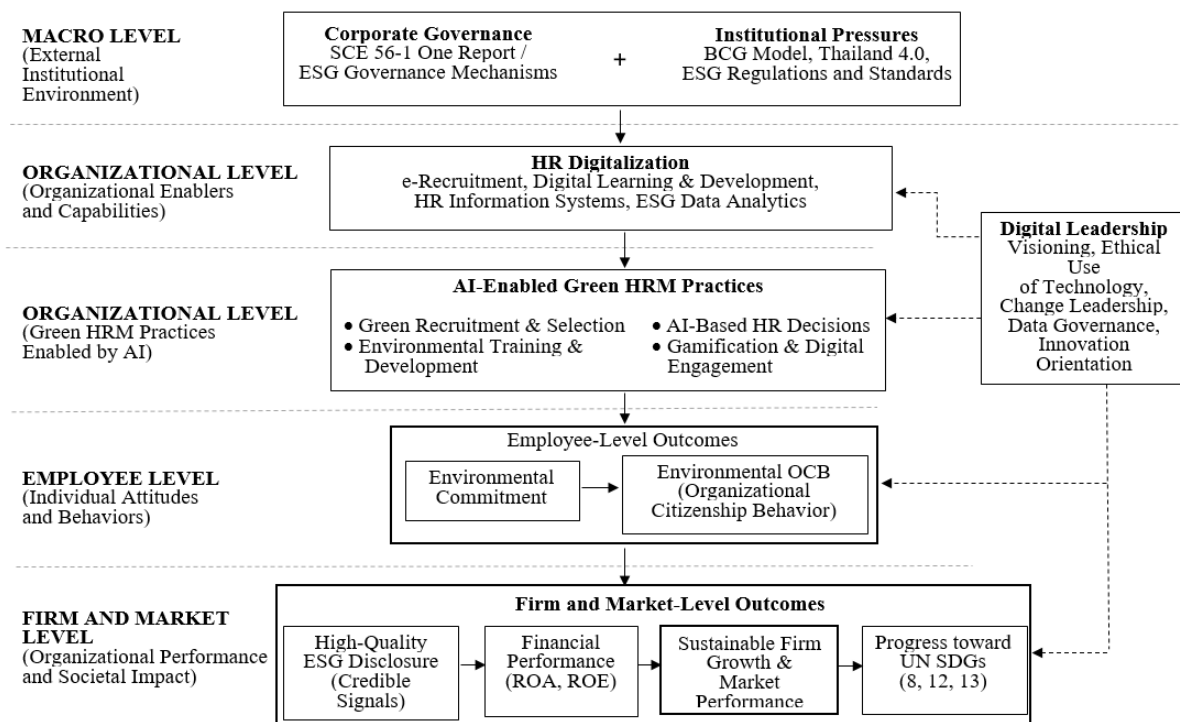


Figure 1 Conceptual Framework of
HR Digitalization and Governance as Enablers of Green HRM Systems in Thai Companies

The proposed framework illustrates a multilevel process linking institutional pressures, organizational capabilities, employee behaviors, and firm-level outcomes. At the macro level, corporate governance and institutional pressures provide external drivers for sustainability-oriented organizational practices. Institutional Theory explains how regulatory, normative, and policy pressures encourage firms to strengthen ESG governance and adopt sustainability-related practices.

At the organizational level, these pressures encourage HR digitalization, which provides the technological infrastructure for implementing AI-enabled Green HRM practices. From the Resource-Based View (RBV), digital technologies and AI-enabled HR capabilities can be viewed as organizational resources that may strengthen the implementation of Green HRM.

Digital leadership plays a facilitating role, supporting HR digitalization and responsible AI adoption through strategic vision, ethical technology use, change leadership, and data governance.

At the employee level, AI-enabled Green HRM practices may enhance environmental commitment, which in turn supports Environmental Organizational Citizenship Behavior (Environmental OCB). These relationships are explained by the AMO framework, Theory of Planned Behavior (TPB), and Social Exchange Theory (SET), which emphasize employee ability, motivation, opportunity, attitudes, and reciprocal responses to organizational practices.

At the firm and market level, employee pro-environmental behavior is expected to contribute to organizational sustainability outcomes, including ESG disclosure quality, financial performance, sustainable firm growth, and progress toward the SDGs. Signalling Theory explains how high-quality ESG disclosure may communicate credible sustainability commitments to investors and stakeholders.

2.5 AI-Enabled Green HRM Practices in the Thai Context

Within the proposed conceptual framework, AI-enabled upstream Green HRM practices represent the primary operational mechanism through which corporate governance requirements and institutional sustainability pressures are translated into employees' pro-environmental behaviors. Supported by HR digitalization and facilitated by digital leadership, these practices enable organizations to integrate sustainability objectives into human resource management while improving organizational capability and long-term competitiveness.

Green Recruitment and Selection. Green recruitment and selection focus on attracting and selecting applicants whose environmental values and sustainability orientation are aligned with the organization's environmental objectives (person–organization fit). Organizations are encouraged to integrate environmental criteria into job descriptions, recruitment policies, and candidate evaluation processes. Through HR digitalization, AI-powered recruitment systems can efficiently screen résumés, identify candidates with sustainability competencies, and support evidence-based recruitment decisions. These technologies improve recruitment efficiency while ensuring that newly hired employees possess values consistent with organizational sustainability goals [10]. For example, Thai Beverage Public Company Limited (ThaiBev) has implemented AI-based e-recruitment platforms together with 360-degree feedback mechanisms to identify and develop employees whose competencies support corporate sustainability strategies [12].

Green Training and Development. Green training and development enhance employees' environmental knowledge, awareness, and competencies necessary for sustainable organizational practices. HR digitalization enables organizations to provide AI-supported personalized learning platforms, digital learning management systems, and gamified sustainability programs that increase employee engagement and facilitate continuous learning [10]. For instance, ThaiBev's Supervisory Development Program (SDP) incorporates real-world sustainability projects related to resource management and waste reduction, allowing employees to apply environmental knowledge in practical organizational settings [12].

Empirical evidence from the Thai private sector indicates that upstream Green HRM practices, particularly green recruitment and environmental training, significantly enhance employees' environmental commitment, which subsequently promotes Environmental Organizational Citizenship Behavior (Environmental OCB) [3]. Within the proposed conceptual framework, these employee-level outcomes constitute the critical link between organizational sustainability initiatives and firm-level performance. HR digitalization and AI technologies strengthen the effectiveness of Green HRM practices, while digital leadership ensures that these technologies are implemented ethically, transparently, and consistently with

organizational sustainability objectives. Consequently, organizations are better able to translate corporate governance requirements and institutional sustainability pressures into improved ESG disclosure, stronger organizational performance, sustainable firm growth, and long-term contributions toward the United Nations Sustainable Development Goals (SDGs).

3. Discussion

3.1 Corporate Governance as the Institutional Driver of Green HRM

Corporate governance plays a fundamental role in driving organizational sustainability by establishing institutional mechanisms that encourage firms to integrate environmental, social, and governance (ESG) principles into their strategic and operational practices. In Thailand, the Securities and Exchange Commission (SEC) Form 56-1 One Report serves not only as a mandatory ESG disclosure requirement but also as a governance mechanism that motivates organizations to incorporate sustainability into human resource management and organizational decision-making [7]. From the perspective of the proposed conceptual framework, corporate governance creates external institutional pressures that encourage organizations to adopt HR digitalization and AI-enabled Green HRM practices as strategic responses to sustainability challenges. Empirical evidence demonstrates that the implementation of the One Report has significantly improved the quality of ESG disclosures among Thai listed companies, particularly in terms of information connectivity and transparency, thereby contributing to sustainable firm growth [1]. Furthermore, governance-related disclosures have been shown to generate positive market reactions by reducing information asymmetry and strengthening investor confidence [11]. Rather than representing an independent outcome, ESG disclosure reflects the effectiveness of organizational sustainability strategies, including the successful implementation of Green HRM practices supported by HR digitalization and responsible corporate governance. Consequently, organizations that effectively integrate sustainability into their HR systems are more likely to produce credible ESG disclosures, enhance stakeholder trust, and achieve long-term organizational sustainability.

3.2 HR Digitalization and AI as Enablers of Green HRM

Building upon the governance mechanisms discussed above, HR digitalization and artificial intelligence (AI) function as key organizational enablers that strengthen the implementation of Green HRM practices. Rather than replacing traditional HR functions, digital technologies improve the efficiency and effectiveness of environmentally sustainable HR activities, including green recruitment, digital learning, ESG data analytics, and employee engagement initiatives. Iftekhara and Ali [2] demonstrated that AI mediates the relationship between ESG strategies and Green HRM practices, resulting in improved organizational financial performance, particularly return on assets (ROA) and return on equity (ROE). AI-enabled technologies also facilitate personalized learning platforms, digital training systems, and gamified sustainability programs that significantly enhance employees' environmental knowledge and engagement [10]. Practical evidence from leading Thai organizations further supports this relationship. Thai Beverage Public Company Limited (ThaiBev) utilizes AI-driven e-recruitment platforms to align employee competencies with sustainability objectives [12], while PTTEP has developed its enterprise AI platform ("X.brain") to strengthen workforce capability, improve risk management, and support its Net Zero greenhouse gas reduction strategy [8]. These examples illustrate that HR digitalization and AI provide the operational mechanisms through which corporate sustainability strategies are translated into effective Green HRM practices.

3.3 Effectiveness of Green HRM Practices in the Thai Context

The Theory of Planned Behavior suggests that organizational sustainability objectives can be achieved by influencing employees' attitudes and behaviors through effective HR practices [5]. Within the proposed conceptual framework, Green HRM represents the organizational mechanism that transforms corporate sustainability commitments into employee-level environmental behaviors. Empirical evidence from Thailand indicates that upstream Green HRM practices, particularly green recruitment and selection as well as green training and development, significantly enhance employees' environmental commitment, which subsequently promotes Environmental Organizational Citizenship Behavior (Environmental OCB) [3]. Conversely, downstream practices such as performance appraisal and monetary rewards have not demonstrated significant effects. These findings can be explained by Thailand's collectivist cultural orientation, in which employees are more strongly influenced by shared organizational values, social norms, and collective responsibility than by individual financial incentives [3]. Therefore, organizations seeking to strengthen sustainability performance should prioritize upstream Green HRM practices that cultivate environmental values and commitment among employees. Such employee-level outcomes ultimately contribute to stronger ESG performance, organizational reputation, and sustainable competitive advantage.

3.4 Digital Leadership for Sustainable Green HRM

Although digital technologies provide significant opportunities for advancing organizational sustainability, they also introduce challenges associated with algorithmic bias, decision-making transparency, and employee data privacy, commonly referred to as the digital sustainability paradox [4], [13]. These challenges highlight the importance of digital leadership in ensuring that technological innovation supports both organizational performance and ethical governance. Evidence from Southeast Asian organizations demonstrates that digital leadership positively influences sustainable HRM practices ($\beta = 0.61, p < 0.001$), while sustainable HRM significantly improves organizational performance ($\beta = 0.53, p < 0.001$) [14]. Effective digital leaders promote innovation while simultaneously ensuring compliance with ethical standards and data governance regulations, including Thailand's Personal Data Protection Act (PDPA). Within the proposed conceptual framework, digital leadership functions as a strategic capability that facilitates the successful implementation of HR digitalization and AI-enabled Green HRM systems. By balancing technological advancement with employee well-being, organizational transparency, and responsible AI governance, digital leadership enables organizations to strengthen ESG performance, improve stakeholder confidence, and achieve long-term sustainable development.

4. Conclusion and Recommendations

4.1. Conclusion

To move towards sustainability in the Thai business sector, an integrated ecosystem of corporate governance pressures, HR digitalization, and Green HRM is required rather than isolated initiatives. Based on the integrative literature review, this study synthesized empirical findings and theoretical perspectives from recent studies on corporate governance, ESG, HR digitalization, artificial intelligence (AI), and Green HRM to develop a comprehensive conceptual framework. The synthesis demonstrates that these elements are interdependent rather than operating independently, collectively shaping organizational sustainability capabilities. The conceptual framework developed in this research shows how macro-level institutional pressures arising from the BCG Economic Model, the Thailand 4.0 policy, and the mandatory Form 56-1 One Report create the regulatory environment in which Green HRM

systems can be effectively developed and governed. This conclusion is supported by evidence indicating that corporate governance mechanisms not only improve ESG disclosure quality but also encourage organizations to incorporate sustainability principles into human resource management through HR digitalization and AI-enabled practices [1], [2], [7], [11]. At the operational level, AI-enabled Green HRM systems are the mediating mechanism that translates ESG commitments into concrete HR practices and measurable organizational outcomes. The reviewed literature consistently indicates that AI strengthens Green HRM through digital recruitment, personalized environmental training, ESG data analytics, and employee engagement initiatives, thereby enhancing both environmental and organizational performance [2], [10], [12]. In the context of Thailand's collectivist culture, upstream Green HRM practices such as green recruitment and environmental training are the key pathways for fostering environmental commitment and pro-environmental behavior, whereas downstream practices based primarily on performance appraisal and monetary rewards demonstrate limited effectiveness. This conclusion emerged from the synthesis of empirical evidence in the Thai context, which consistently identified environmental commitment as the key mechanism linking Green HRM practices to Environmental Organizational Citizenship Behavior (Environmental OCB) [3]. Ethical digital leadership and effective data governance frameworks supported by PDPA compliance are required to overcome the digital sustainability paradox and enable the responsible use of AI in organizations. Overall, the literature synthesis suggests that sustainable organizational performance is achieved not through the adoption of individual technologies or governance mechanisms alone, but through the strategic integration of corporate governance, HR digitalization, AI-enabled Green HRM, and ethical digital leadership within a coherent organizational sustainability framework.

4.2 Theoretical Contribution

This study contributes to the Green HRM and sustainability literature by developing an integrated conceptual framework that connects corporate governance, institutional pressures, HR digitalization, artificial intelligence (AI), digital leadership, and Green HRM within a single theoretical model. Unlike previous studies that have generally examined these constructs independently, this study synthesizes multiple theoretical perspectives, including Institutional Theory, Resource-Based View (RBV), the Theory of Planned Behavior (TPB), the Ability–Motivation–Opportunity (AMO) framework, Social Exchange Theory (SET), and Signalling Theory, to explain how sustainability objectives are translated from organizational governance into employee-level environmental behaviors and organizational performance.

The proposed framework also extends existing Green HRM research by positioning HR digitalization and AI as organizational enablers that strengthen Green HRM implementation, while identifying digital leadership as a strategic capability supporting the ethical and effective adoption of AI-enabled HR systems. This integrated perspective provides a comprehensive explanation of how governance mechanisms, digital transformation, and human resource management collectively contribute to sustainable organizational development, particularly within the institutional and cultural context of Thailand.

4.3 Practical Implications

The findings of this study provide practical guidance for organizations seeking to strengthen sustainability through human resource management. First, organizations should integrate corporate governance requirements and ESG objectives into HR strategies by adopting HR digitalization and AI-enabled Green HRM practices, particularly green recruitment, environmental training, and digital learning systems. Second, organizations should strengthen digital leadership capabilities to ensure that AI technologies are implemented ethically,

transparently, and in compliance with Thailand's Personal Data Protection Act (PDPA). Third, organizations should recognize ESG disclosure not merely as a reporting obligation but as an organizational outcome reflecting the effectiveness of sustainability-oriented HR practices.

For policymakers and regulators, the proposed framework highlights the importance of promoting integrated policies that simultaneously strengthen corporate governance, digital transformation, and sustainable human resource management. Supporting organizations in adopting AI-enabled Green HRM systems and developing digital leadership capabilities can enhance ESG performance, organizational competitiveness, and progress toward Thailand's BCG Economic Model and the United Nations Sustainable Development Goals (SDGs).

4.4 Recommendations

4.4.1 Organizational Implications

Organisations should focus on integrating upstream Green HRM practices with AI by concentrating on green recruitment and environmental training, supported by AI-based tools for candidate screening, personalized learning and gamified sustainability programmes that align with Thai employees' collectivist values. Furthermore, executives and employees should be measured for performance based on ESG metrics, such as those concerning energy management, employee well-being, and risk management, to enhance accountability. ThaiBev's practice of factoring a portion of its annual performance appraisal to sustainability and risk management metrics is a replicable model. Finally, companies need to take a people-first approach to AI governance by setting up oversight mechanisms to monitor algorithmic bias, compliance with the PDPA, and the protection of employee rights and organizational integrity.

4.4.2 Implications for Regulators

Regulators should further develop and harmonise ESG disclosure standards by guiding listed companies to adopt international frameworks such as the ISSB, TCFD, and the ASEAN Taxonomy. This will keep Thailand attractive to foreign investors. Evidence of short-term negative effects of environmental disclosures on stock prices in the MAI implies that regulatory bodies should develop capacity-building programs to assist small and medium-sized firms to communicate environmental investments as long-term value drivers and not short-term cost burdens.

4.4.3 Suggestions for Further Research

Future research should employ longitudinal and multilevel research designs to explore the joint effects of the quality of One Report disclosure and AI-enabled Green HRM systems on firm performance and employee outcomes over time, overcoming the limitations of cross-sectional research. It is necessary to undertake empirical research to quantitatively assess the extent of gender, age, or educational background bias associated with AI-based recruitment and HR systems in Thailand to inform the development of ethical technology governance frameworks consistent with the PDPA. Finally, future research needs to explore how affordable and accessible digital Green HRM practices can be adopted by small and medium-sized enterprises with limited budgets and IT resources, particularly in light of the evidence that environmental disclosures could harm firms in the MAI.

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A Conceptual Framework for Residual Cigarette and E-Cigarette Odor Management and Hotel Room-Readiness Decisions

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Abstract

Residual cigarette- and e-cigarette-related conditions in hotel guestrooms combine physical or chemical contamination with sensory odor, which are related but not equivalent. Cigarette-derived thirdhand-smoke and vaping residues may deposit on materials, persist, and re-enter the air, although their emissions, chemistry, transformation, and persistence differ. This conceptual paper integrates residual-contamination processes, odor perception, perceived air quality, odor acceptability, and multidimensional hotel room readiness. It compares management approaches by target compartment and presents aerosolized and liquid chitosan formulations as complementary, unvalidated hypotheses derived from filter and functional-material studies. Effectiveness, safety, material compatibility, operational feasibility, and room re-entry must be established before employee acceptance, managerial adoption, or commercialization can be evaluated. The resulting multilevel framework supports comparative environmental, sensory, and hotel-operational research.

Keywords: Thirdhand Smoke; Odor Acceptability; Chitosan Aerosol; Perceived Air Quality; Hotel Room Readiness

1. Introduction

Indoor air quality shapes hotel guests' perceptions of cleanliness, comfort, safety, and service quality; unpleasant odor can undermine confidence even when a room appears clean. Effective air-quality management is associated with perceived room quality, satisfaction, and revisit intentions [1]. Residual cigarette- and e-cigarette-related conditions are especially problematic because they may persist after checkout and delay room preparation.

Routine cleaning and ventilation may not remove substances retained in air, dust, furnishings, or textiles. Tobacco contamination has been detected in designated nonsmoking guestrooms [2], while e-cigarette aerosol constituents can partition into air and surfaces [3]. Contamination is a physical or chemical condition; odor is a sensory perception. Odor neither proves a hazardous concentration nor, when absent, confirms contaminant removal.

Thirdhand-smoke theory explains how cigarette residues remain on surfaces and materials after secondhand smoke dissipates [4] and later re-enter the air through desorption, off-gassing, or resuspension [5]. This source-sink-re-emission-transformation process should not be transferred uncritically to e-cigarettes because their emissions, particles, surface partitioning, aging, and persistence differ.

Hotel room readiness also requires acceptable sensory conditions, cleanliness, safety, amenities, maintenance, service standards, and turnaround time. Odor acceptability-whether an odor condition is suitable for occupancy-is distinct from intensity, hedonic tone, and annoyance

[6]–[9]. Instrumental and sensory evidence are therefore complementary rather than interchangeable.

Existing air-quality, odor-assessment, and hotel-operations models address these issues separately. The proposed framework connects sources, reservoirs, environmental conditions, sensory and instrumental evidence, and room-release decisions while separating the guestroom pathway from post-validation employee and organizational adoption.

Chitosan remains an unvalidated treatment hypothesis. Studies of chitosan-based formaldehyde capture and filtration [10], [11] do not establish the effectiveness or safety of aerosolized or liquid formulations in guestrooms. The contribution is therefore theoretical integration and specification of testable environmental, sensory, safety, operational, and adoption conditions-not a claim of validated treatment.

2. Conceptual Foundations

2.1 Literature Review and Conceptual Synthesis Method

This paper used a structured integrative-review and theory-synthesis approach guided by established integrative-review methodology [12], [13]. The search covered publications from 1989 through July 2026 to include foundational technology-acceptance studies and contemporary indoor-environment research. Search blocks combined terms relating to thirdhand smoke, residual cigarette smoke, e-cigarette residue, vaping-related contamination, re-emission, odor acceptability, perceived air quality, room readiness, chitosan aerosol, safety, and technology adoption. Reference lists of key studies were also examined. Thirty-six sources were retained in the final synthesis.

2.2 Thirdhand Smoke and Residual Vaping-Related Contamination

Thirdhand smoke refers specifically to tobacco-derived chemical and particulate residues that remain after combustible-cigarette smoking has ended and airborne secondhand smoke has dissipated. Residues may deposit on walls, carpets, curtains, bedding, furniture, and dust, creating indoor reservoirs that retain tobacco-related compounds. Deposited nicotine and other compounds may later return to the air through desorption, off-gassing, or dust resuspension and may undergo reactions with indoor oxidants. Surface nicotine can react with ozone, while reactions with nitrous acid may form tobacco-specific nitrosamines [14], [15]. Residues may also be transported on clothing and personal materials into nonsmoking environments [16].

Residual vaping-related contamination represents a separate pathway. E-cigarettes generate aerosol from heated liquid rather than tobacco combustion and therefore differ from cigarette smoke in composition and transformation. Nevertheless, nicotine from e-cigarette aerosol can deposit on indoor surfaces, and deposition and persistence vary by surface and product characteristics [17], [18]. The two pathways may share airborne transport, surface deposition, material retention, and possible re-emission, but combustion-derived soot, many tobacco-specific reaction products, and established thirdhand-smoke chemistry should not automatically be attributed to e-cigarette residues. Long-term transformation, re-emission, and odor relevance are less established for vaping-related contamination.

2.3 Residual Contamination and Residual Odor in Hotel Guestrooms

Residual contamination refers to tobacco- or vaping-derived chemical and particulate substances remaining in indoor air, dust, surfaces, textiles, furnishings, or other materials after smoking or vaping has ceased. Residual odor refers to the sensory perception produced by odor-active compounds in the air. Although contamination may contribute to odor perception, the concepts are not equivalent. A detectable odor does not independently establish contaminant

concentration or safety, while the absence of odor does not confirm that contaminants or material reservoirs have been removed.

Hotels are especially vulnerable because guestrooms experience frequent occupancy changes and must be prepared within limited turnaround periods. Carpets, curtains, mattresses, upholstery, walls, and dust may retain substances after checkout. Ventilation and portable air purification can reduce selected airborne fractions under specific conditions but may leave material reservoirs untreated [19]. Hotels may then apply specialized cleaning, deodorizing products, or additional treatment and may temporarily withhold rooms from sale [20]. Residual odor therefore functions as a sensory and service-quality concern, while residual contamination remains a separate environmental condition requiring appropriate measurement.

2.4 Odor Acceptability, Perceived Air Quality, and Hotel Room Readiness

Indoor environmental conditions are commonly evaluated through both sensory perception and objective measurement. Odor is a central component of this evaluation because it provides an immediate sensory indication of environmental conditions. Perceived residual odor intensity represents perceived strength; hedonic tone represents pleasantness or unpleasantness; odor annoyance represents disturbance; and odor acceptability represents the judgment of whether an odor condition is suitable for the intended use of a space [21], [22]. These are related but distinct constructs. Intensity and hedonic tone may influence acceptability, whereas annoyance is treated as a separate response rather than a component of acceptability.

Perceived air quality is a broader subjective evaluation of indoor air and may be influenced by ventilation, airflow, prior experience, individual sensitivity, and contextual expectations [23]. In a hotel guestroom, a weak but recognizable tobacco-related odor may be unacceptable because it conflicts with expectations of cleanliness and freedom from sensory evidence of previous occupants [24], [25].

Hotel room readiness is a multidimensional operational judgment that a guestroom meets the property requirements for release to a subsequent guest. It includes completed cleaning, acceptable sensory conditions, functional amenities, satisfactory physical condition, absence of unresolved safety or maintenance issues, and compliance with service standards. The initial inspection may be performed by housekeeping employees, whereas final classification will be made by a supervisor or manager. A room may be classified as ready for occupancy, requiring additional treatment and reinspection, or temporarily unavailable. Odor acceptability is therefore one antecedent of room readiness rather than its sole determinant.

2.5 Existing Guestroom Odor-Management Approaches

Existing hotel odor-management approaches target different contamination compartments. Ventilation dilutes and removes part of the airborne fraction but does not directly remove contaminants retained in porous materials. Surface and porous-material cleaning addresses exposed reservoirs more directly, although persistent contamination may remain after cleaning or occupancy change [26]. HEPA and other particle filtration target airborne particles, while activated-carbon or other adsorptive media target selected gases; performance depends on airflow, media design, contaminant characteristics, operating time, and maintenance [27]. Ozone methods may transform susceptible compounds but raise concerns regarding incomplete removal, and secondary products [28]. These approaches are complementary rather than interchangeable.

2.6 Chitosan Aerosol as a Plausible Hypothesis

Chitosan contains amino and hydroxyl functional groups that support its use in sorptive, coating, and filtration materials. Chitosan-functionalized particles and chitosan-treated filters

have been investigated for formaldehyde capture, and chitosan has been incorporated into composite filtration media for selected volatile compounds [29].

The proposed aerosol application is therefore a substantial extrapolation and is treated as a plausible hypothesis. Aerosolization also introduces safety questions not addressed by filter studies. Required assessments include droplet-size distribution, airborne suspension and decay, formulation solvents, deposition and persistence of residues on surfaces, employee exposure during preparation and application, guest exposure after treatment, and a defined safe room readiness time. Chitosan may be explored as a complementary odor-management innovation used alongside standard hotel cleaning. Potential application could include an aerosolized formulation designed to interact with the airborne soot, and particles, as well as a liquid chitosan formulation for application to appropriate surfaces or materials. However, the effectiveness, safety, residue formation, material compatibility, and operational feasibility of both formulations must be established through controlled testing before hotel use.

2.7 Technology Acceptance and Organizational Adoption

The Technology Acceptance Model links perceived usefulness and ease of use to intention [30]; extensions add relevance, compatibility, and facilitating conditions [31]–[33], while hospitality research identifies task fit, self-efficacy, and organizational influence [34].

Acceptance should be assessed only after technical and safety validation. Employees evaluate usefulness, ease, workflow fit, and support; managers evaluate verified performance, safety, cost, compatibility, and risk. These outcomes form a post-validation organizational submodel rather than part of the guestroom pathway.

3. Proposed Conceptual Framework

As shown in Figure 1, the proposed framework organizes residual cigarette- and e-cigarette-odor management into environmental, sensory, and operational domains. Smoking and vaping introduce chemical and particulate contaminants into hotel rooms. These contaminants may remain airborne or accumulate on textiles, which function as indoor reservoirs. The reservoirs allow contaminants to persist, undergo chemical transformation, and later return to the indoor air through desorption, off-gassing, or resuspension. The framework therefore extends the source–sink–re-emission–transformation perspective by connecting residual contamination with hotel room-readiness decisions.

Environmental conditions, including ventilation, airflow, temperature, and humidity, may modify contaminant release, dilution, and sensory perception. Residual contamination is subsequently evaluated through two complementary pathways. The first is sensory evaluation through odor acceptability, which reflects whether the perceived room condition is suitable for occupancy. The second is instrumental assessment using selected indoor pollutant indicators, which provides objective evidence regarding components of the contamination. Instrumental measurements support environmental assessment, whereas odor acceptability represents the more immediate service-based criterion used in room-release decisions.

The framework also positions chitosan aerosol as an intervention that may interact with airborne particles or contaminants before they contribute to continuing odor perception. The practical adoption, however, depends on safety, ease of use, treatment time, and compatibility with housekeeping workflows. Operational compatibility therefore links the effectiveness of chitosan aerosol with employee acceptance, managerial adoption, and timely room turnover.

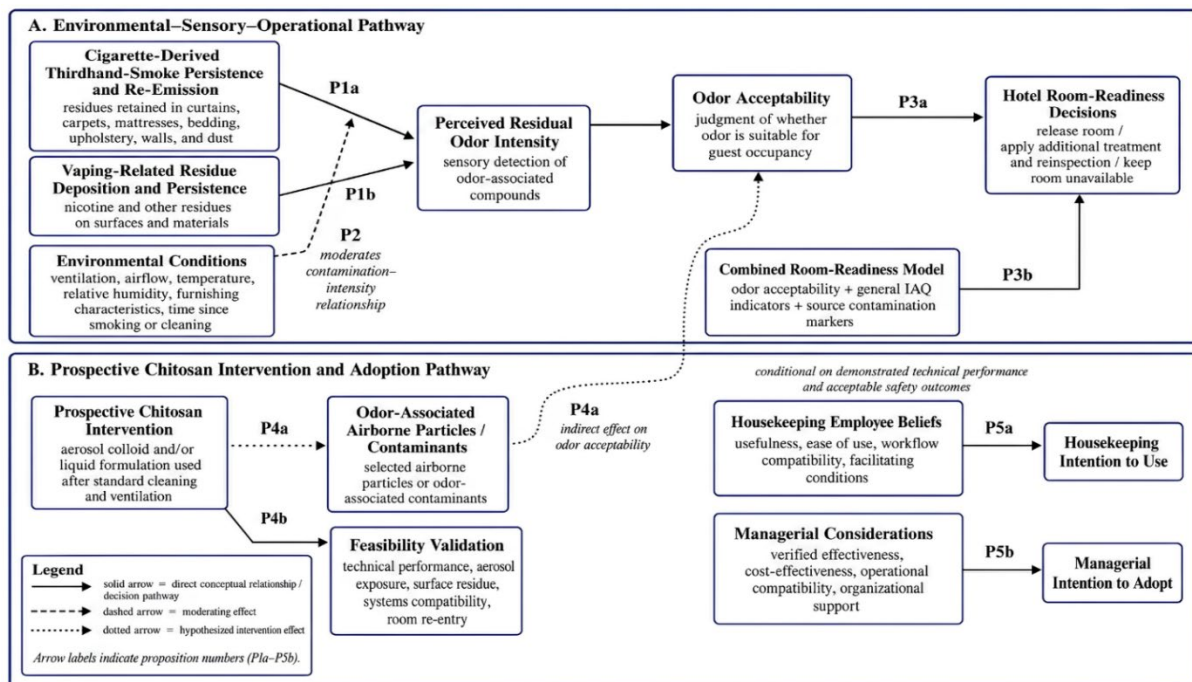


Figure 1. Conceptual Framework for Residual Cigarette and E-Cigarette Odor Management and Hotel Room-Readiness Decisions

4. Conceptual Propositions

Propositions 1–4 define the environmental-sensory-operational model; Propositions 5a and 5b define the post-validation employee and managerial adoption model. This separation prevents room conditions, individual judgments, and organizational decisions from being treated as equivalent.

Proposition 1a: Greater persistence and re-emission of cigarette-derived thirdhand-smoke contaminants are associated with lower guestroom odor acceptability

Residues retained in textiles and dust may release odor-active compounds through desorption, off-gassing, or resuspension [4], [5], [14]–[16]. Re-emission may increase odor intensity and reduce acceptability, but odor is not a direct measure of concentration or safety.

Proposition 1b: Greater deposition and persistence of vaping residues may be associated with lower guestroom odor acceptability

E-cigarette constituents can deposit and persist on surfaces [17], [18]. Because vaping lacks tobacco combustion, soot, transformation, re-emission, and odor pathways require separate source-specific testing.

Proposition 2: Guestroom environmental conditions moderate the relationship between re-emitted odor-active compounds and perceived odor intensity

Ventilation and airflow alter transport and dilution, while temperature and humidity may affect desorption and detection [7], [23]. Similar reservoirs may therefore produce different sensory responses according to environmental conditions and elapsed time.

Proposition 3a: Greater odor acceptability increases the likelihood of room-readiness classification after other operational criteria are considered

Acceptability reflects intensity, hedonic tone, odor identity, and sensitivity [6]–[9], [21], [22]. Final release also requires cleanliness, safety, amenities, physical condition, maintenance, standards, and turnaround; odor is important but not determinative.

Proposition 3b: Combining odor acceptability, general air-quality indicators, and source-linked markers predicts room readiness better than acceptability or a single nonspecific indicator alone

TVOC, PM_{2.5}, and formaldehyde describe general conditions but are not source-specific. Attribution should include matrix-appropriate markers such as air or surface nicotine, tobacco tracers, reaction products, or a vaping profile [35], [36]. Comparative models should evaluate fit and cross-validated classification performance.

Proposition 4a: After cleaning and ventilation, chitosan aerosol may produce additional measurable changes in accessible odor-associated compounds compared with routine treatment and appropriate controls

Material and filter evidence supports possible sorptive interaction [10], [11], [29] but not equivalent guestroom performance. Effects should be limited to airborne or freshly re-emitted targets and should not assume extraction from deep porous reservoirs.

Proposition 4b: Chitosan-aerosol feasibility depends on acceptable technical performance, exposure, residues, material and system compatibility, and room-re-entry outcomes

Droplet behavior, formulation constituents, surface deposition, employee and guest exposure, and re-entry conditions must be validated before hotel pilot testing.

Proposition 5a: After demonstrated performance and safety, usefulness, ease of use, workflow compatibility, and facilitating conditions positively influence housekeeping employees' intention to use chitosan aerosol

Employee evaluation concerns preparation, equipment, training, and fit with cleaning sequences [30]–[34] and must remain separate from measured treatment performance.

Proposition 5b: After demonstrated performance and safety, verified effectiveness, cost-effectiveness, operational compatibility, and organizational support positively influence managers' intention to adopt chitosan aerosol

Managers additionally consider safety, treatment cost, room-closure time, training, equipment, and implementation risk; operational benefits remain empirical outcomes.

5. Discussion

The synthesis separates contamination from odor and cigarette-derived thirdhand smoke from vaping residues. Contamination occurs in air, dust, surfaces, or materials; odor is a sensory response shaped by odor-active compounds, environmental conditions, and sensitivity. Detectable odor does not establish hazardous exposure, and absent odor does not prove contaminant removal. The two source pathways also differ in emissions, transformation, and persistence.

Instrumental indicators characterize environmental change, source-linked markers support attribution, and sensory testing describes room experience. Room readiness further integrates sensory, environmental, physical, safety, service, and timing criteria. Their individual and combined predictive performance must be tested rather than assumed.

5.1 Theoretical Implications

First, the framework extends indoor-air-quality models from current airborne conditions to deposition, material reservoirs, transformation, re-emission, resuspension, and time, while distinguishing cigarette and vaping pathways.

Second, it separates odor intensity, hedonic tone, annoyance, and acceptability and positions acceptability as one readiness antecedent.

Third, it defines room readiness as a multidimensional authorized decision integrating sensory, environmental, cleanliness, safety, amenity, physical-condition, service, and timing criteria.

Finally, it separates the guestroom environmental-sensory-operational model from post-validation employee and managerial adoption, using chitosan only as a hypothesis-generating case.

5.2 Practical Implications

The framework can structure room inspection by distinguishing contamination, odor, acceptability, and multidimensional readiness within a checklist of sensory condition, cleanliness, safety, amenities, physical condition, maintenance, standards, and turnaround.

It also supports layered management: cleaning addresses reservoirs, ventilation airborne fractions, filtration particles or gases, and ozone requires control of exposure and secondary products. No method addresses every compartment.

Chitosan remains a testable adjunct; reduced cleaning, room-closure time, cost, operational benefit, and commercialization are empirical outcomes rather than assumed advantages.

5.3 Limitations

This interdisciplinary synthesis combines definitions, units, methods, and evidence standards that are not directly equivalent; its relationships are theoretical rather than causal.

Evidence is stronger for cigarette thirdhand smoke than vaping residues, whose composition, transformation, and persistence remain uncertain.

Chitosan treatment extrapolates from immobilized materials, with no direct guestroom evidence for aerosol or liquid effectiveness, exposure safety, residues, equipment or material compatibility, or re-entry.

Variation in room volume, furnishings, ventilation, climate, cleaning, elapsed time, and evaluator sensitivity may also limit generalizability across properties and populations.

5.4 Suggestions for Future Empirical Research

Future studies should begin in chambers or mock guestrooms using randomized, controlled, repeated measures and separate cigarette and e-cigarette conditions. Groups should include untreated, routine cleaning and ventilation, an established treatment, chitosan aerosol and/or liquid treatment, and formulation or equipment controls. Measurements should occur at baseline, post-source, post-treatment, proposed re-entry, and delayed follow-up (e.g., 24 and 48–72 h).

Operational studies should record treatment time, labor, repeat cleaning, room closure, release time, cost, and final classification. Only after technical and safety validation should employee acceptance, managerial adoption, and commercialization be assessed using usefulness, ease, workflow fit, facilitating conditions, verified performance, safety, cost-effectiveness, organizational support, reproducibility, compatibility, and incremental value.

6. Conclusion

Residual cigarette and vaping conditions connect environmental contamination, sensory odor, and operational readiness but require source-specific analysis.

The framework links persistence and re-emission with odor intensity, acceptability, instrumental evidence, and multidimensional room classification, while separating guestroom processes from post-validation adoption.

Chitosan aerosol and liquid formulations remain complementary hypotheses derived from material and filter studies; their mechanisms, effectiveness, exposure, residues, compatibility, re-entry, operational value, adoption, and commercialization require staged comparative testing.

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Tourism Narratives and Expected Confidence: A Structural Topic Model of Thailand Tourism Confidence Index Reports

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Abstract

This study examines how institutional text in Thailand Tourism Confidence Index (TTCI) reports complements the numerical index in interpreting tourism conditions and operators' expectations. It has two objectives: to identify the topical structure of TTCI reports and to examine the relationship between expected confidence and topic prevalence. Sixty quarterly reports covering Q1 2010–Q4 2024 were divided into 1,434 paragraph-level documents and analyzed using the Structural Topic Model (STM). Time, quarter, and expected confidence, categorized as below 100 or at least 100, were included as topic-prevalence covariates. The model identified 15 topics in five groups: Reporting on Economic Conditions, Tourist Opinion Surveys, Tourism Operators' Opinions, Tourism Conditions, and Recommendations from the Reports. Compared with reports below 100, those at or above 100 showed significantly greater prevalence of Tourism Promotion and Development, Tourist Satisfaction Survey, Global Economic Conditions, and Forecasts of Tourist Numbers. Conversely, they showed lower prevalence of the COVID-19 Situation, Employment Conditions in Tourism Establishments, Economic Risk Factors, Domestic Risk Factors, Regional Tourism Conditions, Tourism Conditions by Business Type, and Foreign Tourist Opinion Survey. Four topics showed no significant difference. The findings indicate that topic prevalence captures differences in thematic emphasis rather than sentiment or causal relationships, while the text in TTCI reports functions as an economic narrative that provides interpretive context beyond what the confidence index alone can convey.

Keywords: Structural Topic Model; Narrative Economics; Tourism Confidence Index

1. Introduction

The tourism industry plays an important role in Thailand's economy through income generation and employment. However, it is also a complex industry that is highly vulnerable to economic uncertainty. Under such conditions, information reflecting tourism operators' perceptions and expectations is essential for monitoring industry conditions, assessing risks, and preparing measures to address potential changes [1]. The Tourism Council of Thailand (TCT) therefore publishes the TTCI reports quarterly to provide stakeholders with information for preparing appropriate responses to changing conditions [2]. In addition to numerical index values, TTCI reports contain textual information on economic conditions, tourist behavior, tourism operators' opinions, and recommendations for government agencies and businesses.

Within the framework of Narrative Economics, texts communicated through institutional reports may constitute economic narratives that spread and influence macroeconomic behavior [3]. Narratives also serve as frameworks for interpreting facts and as a medium for policy analysis [4]. In TTCI reports, the confidence index provides a quantitative summary of assessments of future conditions, whereas the accompanying text reflects the issues used to

explain and communicate those assessments. The relationship between these two forms of information leads to the following research question: How does the text in TTCI reports explain tourism operators' interpretations of industry conditions and expectations in ways that the confidence index alone cannot convey?

Text analysis has been widely applied in tourism and hospitality research to online reviews, social media content, and destination advertising to understand tourist and market behavior [5]. However, research using textual information from official reports in the tourism field remains limited. This differs from economics and finance, where institutional documents such as corporate reports, economic news, and central bank statements have been widely analyzed to identify contexts, risks, and factors that may not be captured by quantitative indicators [6].

Topic modeling is a natural language processing technique that identifies latent topic structures from patterns of word co-occurrence, thereby enabling the systematic summarization and interpretation of large document collections. It is based on the concept that each document comprises multiple topics in different proportions, as proposed in the Latent Dirichlet Allocation (LDA) model [7]. The Structural Topic Model (STM) extends conventional topic models by incorporating document-level metadata directly into model estimation. It therefore enables the analysis of both latent topics and the relationship between document characteristics and topic prevalence [8]. This feature makes STM suitable for analyzing TTCI reports, as the study seeks both to identify their topical structure and to examine the relationship between topic prevalence and tourism operators' expected confidence.

Based on the research gap and question outlined above, this study has two objectives: (1) to analyze the topical structure of text in TTCI reports and (2) to examine the relationship between tourism operators' expected confidence and topic prevalence in these reports. The study extends tourism text analysis from tourist-generated data to institutional text while linking topical structure with an indicator of economic expectations. The findings can help tourism agencies and tourism operator organizations interpret report content alongside index values, understand the issues and concerns emphasized under different confidence levels, and support industry monitoring and the identification of policy priorities that reflect tourism conditions.

2. Research Methodology

2.1 Data

This study used 60 quarterly TTCI reports covering Q1 2010–Q4 2024, collected from the Tourism Council of Thailand's website. Because their layouts and section structures varied over time, the textual content and expected-confidence index values were manually extracted, excluding front and back covers, tables, and figures. To accommodate the multiple themes contained in each report, the text was divided into 1,434 paragraph-level documents and linked to quarterly metadata comprising a sequential time index, quarter, and expected confidence. Using 100 as the benchmark for the normal confidence level in the TTCI [2], expected confidence was classified as below normal for values below 100 and as normal or above for values of at least 100. Each category comprised 30 quarters.

2.2 Text Preprocessing

Thai-language text was preprocessed using Python and the PyThaiNLP library [9]. Numbers, symbols, and special characters irrelevant to topic interpretation were first removed. The text was then tokenized using the dictionary-based NewMM algorithm, after which Thai stop words and single-character tokens were removed to reduce noise. The remaining tokens were rejoined with spaces and transformed into the document, vocabulary, and metadata structures required for STM estimation.

2.3 STM Estimation and Analysis

Topic modeling was conducted using the *stm* package in R following the procedures proposed by Roberts et al. [10]. Candidate models with the number of topics (*K*) ranging from 3 to 30 were evaluated using semantic coherence, exclusivity, held-out likelihood, residuals, and the lower bound. After determining the number of topics, the model was estimated over 20 runs to select the most appropriate solution and assess model convergence. Topics were interpreted and labeled by jointly examining the highest-probability, FREX, lift, and score terms. For conciseness, Table 1 reports only the FREX keywords. Mean topic prevalence across documents was then used to compare the relative prominence of topics in the reports, thereby addressing the first research objective.

To address the second research objective, topic prevalence was modeled as a function of document-level metadata as follows:

$$\theta_{dk} \sim t_d + quarter_d + expected_ttci_d \quad (1)$$

; where θ_{dk} denotes the prevalence of topic (*k*) in paragraph-level document (*d*); t_d denotes the sequential time index of the report; $quarter_d$ denotes the quarter in which the document was published; and $expected_ttci_d$ denotes the expected confidence category associated with the document.

The time index ranged from 1 to 60. Quarter was represented by dummy variables, with the first quarter as the reference category. Expected confidence was coded as 1 when the index was at least 100 and 0 when it was below 100, with the latter serving as the reference category. The associations between the covariates and the prevalence of each topic were estimated and evaluated at statistical significance levels of 0.10, 0.05, and 0.01. The coefficient for expected confidence therefore represents the adjusted difference in topic prevalence between reports with expected confidence at or above the normal level and those below the normal level, controlling for the time trend and quarterly differences.

3. Results

3.1 Topic Structure of TTCI Reports

After preprocessing the 60 TTCI reports, comprising 1,434 paragraph-level documents, the number of tokens decreased from 372,759 to 296,166, representing a reduction of 20.55%. No document contained zero tokens after preprocessing, and the resulting vocabulary comprised 3,414 terms. The evaluation of candidate models with the number of topics ranging from 3 to 30 indicated that the 15-topic model (*K* = 15) provided an appropriate balance among semantic coherence, exclusivity, held-out likelihood, residuals, and topic interpretability. Following 20 model runs, the selected model achieved a semantic coherence score of -48.42 and an exclusivity score of 9.36, while also demonstrating satisfactory convergence.

As shown in Table 1, the analysis identified 15 topics in the TTCI reports, which were organized into five main groups. The first group, Reporting on Economic Conditions, comprises Economic Risk Factors, the COVID-19 Situation, Global Economic Conditions, and Domestic Risk Factors. The second group, Tourist Opinion Surveys, comprises the Tourist Satisfaction Survey, Tourist Behavior Survey, and Foreign Tourist Opinion Survey. The third group, Tourism Operators' Opinions, comprises Regional Tourism Conditions, the Tourism Confidence Index, and Tourism Conditions by Business Type. The fourth group, Tourism Conditions, comprises Employment Conditions in Tourism Establishments, Forecasts of Tourist Numbers, and Tourism Conditions during Festival Periods. The final group, Recommendations from the Reports, comprises Tourism Promotion and Development and Recommendations for Tourism Operators.

Table 1 Topic Groups, Labels, FREX Keywords, and Mean Topic Prevalence in TTCI Reports

Topic Group	Topic	FREX Keywords	Mean Topic Prevalence (%)
Reporting on Economic Conditions	3. Economic Risk Factors	ถดถอย, หนี้, ปัจจัยเสี่ยง, ครัวเรือน, Festival, ยุครณ, หนี้เสีย, รายจ่าย, ภาระ, คนจีน	3.38
	4. COVID-19 Situation	ฉีดวัคซีน, วัคซีน, โดส, ถักตัว, นิด, เปิดรับ, ผู้ป่วย, อินดีคชั่นรับ, แพร่เชื้อ, ระลอก	4.80
	7. Global Economic Conditions	สหรัฐฯ, ขยายตัว, สกุล, น้ำมันดิบ, โลก, การส่งออก, อ่อน, เศรษฐกิจ, อัตราแลกเปลี่ยน, ธนาคารกลาง	3.50
	9. Domestic Risk Factors	ทางการเมือง, อย่างไรก็ดีตาม, ลบ, ปัญหา, สภาพเศรษฐกิจ, ผลกระทบ, อุทกภัย, การแข่งขัน, ที่สูง, รุนแรง	8.18
Tourist Opinion Surveys	2. Tourist Satisfaction Survey	คะแนน, ความพอใจ, ความพึงพอใจ, การเที่ยว, รถไฟ, คมนาคม, ชม, การปรับปรุง, การคมนาคม, สถานที่	5.17
	8. Tourist Behavior Survey	จุดหมาย, ไปเที่ยว, เลือก, ระบุ, นิยม, ชาวไทย, ส่วนตัว, ความนิยม, ความสะดวก, ที่พัก	7.59
	12. Foreign Tourist Opinion Survey	ค่าใช้จ่าย, ทริป, เชื้อสาย, ชาวต่างชาติ, อเมริกา, สภา, ประเทศ, เอเชียตะวันออกเฉียงใต้, เอเชีย, เที่ยว	4.27
Tourism Operators' Opinions	5. Regional Tourism Conditions	ภาคใต้, ภูมิภาค, ภาคเหนือ, ตะวันออกเฉียงเหนือ, ตะวันตก, ตะวันออก, ดิกว่า, สถานการณ์, กลาง, ที่ผ่านมา	7.74
	13. Tourism Confidence Index	ปกติ, ประเมิน, ดัชนี, คำว่า, ผู้ประกอบการ, ความเชื่อมั่น, ผู้ประกอบการธุรกิจ, ธุรกิจท่องเที่ยว, ระดับ, ค่าการณ์	13.60
	15. Tourism Conditions by Business Type	ของที่ระลึก, ผลประกอบการ, ประเภท, ร้าน, ธุรกิจ, ร้านอาหาร, สถานบันเทิง, สปา, สวนสนุก, ของฝาก	5.94
Tourism Conditions	1. Employment Conditions in Tourism Establishments	พนักงาน, สถานประกอบการ, รายได้, ทักษะ, ปิดกิจการ, แรงงาน, ทำการ, ถาวร, จ้างงาน, ชั่วโมง	9.27
	10. Forecasts of Tourist Numbers	ล้าน, คน, ทั้งปี, เพิ่มขึ้น, ปี, ต่างชาติ, บาท, คาด, เอเชีย, เอเชีย	12.01
	14. Tourism Conditions during Festival Periods	วันแม่, วันอาสาฬหบูชา, วันหยุด, สงกรานต์, เทศกาล, สุก, ตรุษจีน, ปีใหม่, วันเฉลิมพระชนมพรรษา, คริสต์มาส	4.32
Recommendations from the Reports	6. Tourism Promotion and Development	ภาษี, มาตรฐาน, รถ, พัฒนา, ส่งเสริม, สาธารณะ, จัดทะเบียน, มากยิ่งขึ้น, สนามบิน, IT	6.90
	11. Recommendations for Tourism Operators	ขยะ, ฝึกอบรม, ทรัพยากร, จัดสรร, กำจัด, ทำลาย, แพร, วิชาชีพ, น้ำ, แก้ปัญหา	3.35

Note: FREX keywords are presented in their original Thai form to preserve the model output.

Regarding mean topic prevalence, the Tourism Confidence Index had the highest prevalence, consistent with the primary purpose of TTCI reports to present the results of tourism operator confidence surveys. Forecasts of Tourist Numbers had the second-highest prevalence, whereas Recommendations for Tourism Operators had the lowest. These findings indicate that although the reports are primarily structured around the confidence index and forecasts, they

also contain diverse content concerning tourism conditions, risks, opinions, and recommendations.

3.2 Association Between Expected Confidence and Topic Prevalence

The analysis used reports with expected confidence index values below 100 as the reference group and compared them with reports having values of 100 or higher, while controlling for the time trend and quarterly differences. Figure 1 presents the estimated coefficients of expected confidence for the prevalence of all 15 topics. A positive coefficient indicates that a topic had greater prevalence in reports with expected confidence at or above the normal level, whereas a negative coefficient indicates that it had lower prevalence than in reports with expected confidence below the normal level.

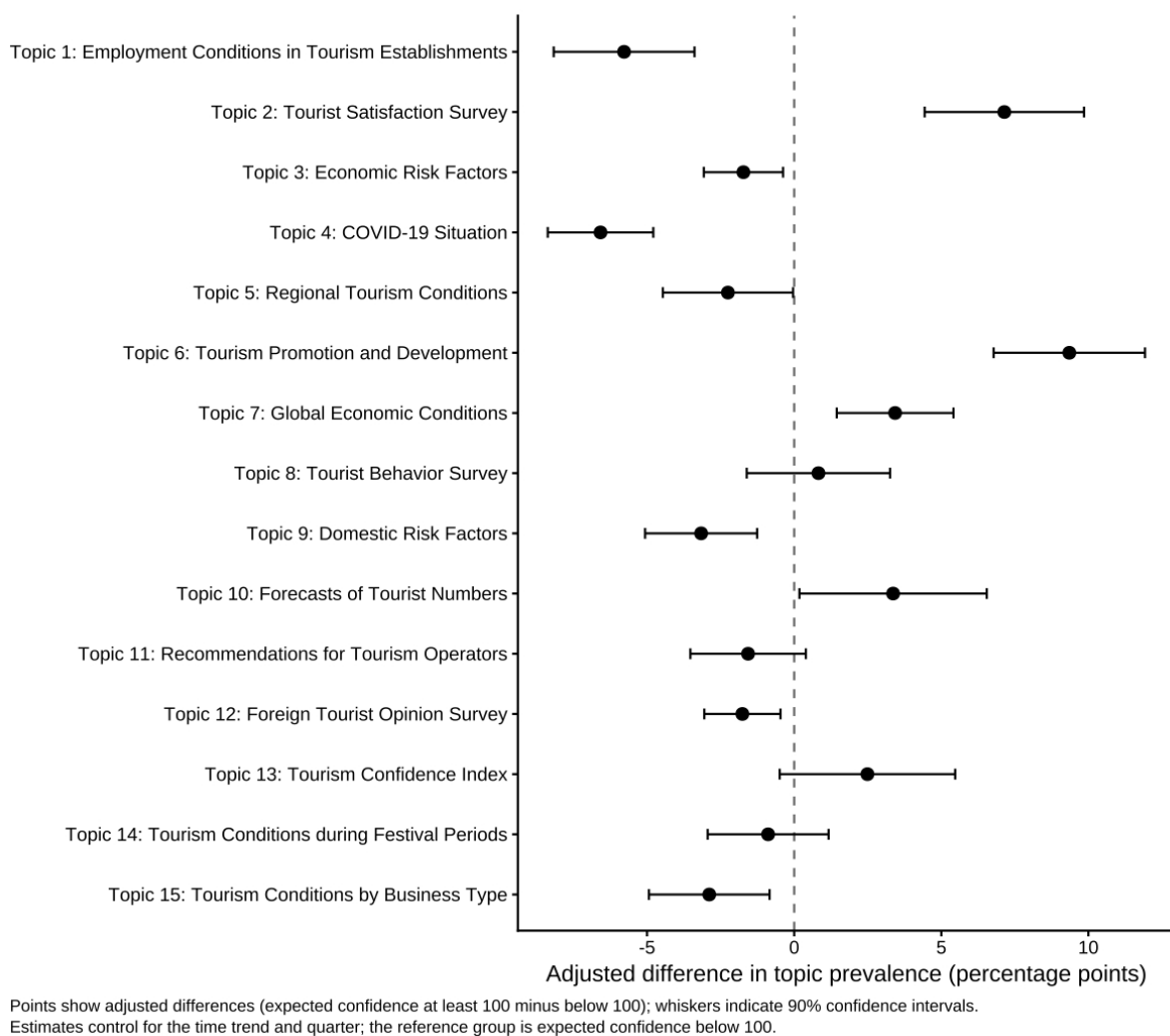


Figure 1 Estimated Differences in Topic Prevalence by Expected Confidence Level

As shown in Figure 1, compared with the below-normal confidence group, reports with expected confidence at or above the normal level had higher estimated prevalence of four topics: Tourism Promotion and Development (9.36 percentage points, $p < 0.01$), Tourist Satisfaction Survey (7.14 percentage points, $p < 0.01$), Global Economic Conditions (3.43 percentage points, $p < 0.01$), and Forecasts of Tourist Numbers (3.40 percentage points, $p < 0.01$).

0.10).

Conversely, reports with expected confidence at or above the normal level had lower estimated prevalence of seven topics: the COVID-19 Situation (6.58 percentage points, $p < 0.01$), Employment Conditions in Tourism Establishments (5.77 percentage points, $p < 0.01$), Domestic Risk Factors (3.16 percentage points, $p < 0.01$), Tourism Conditions by Business Type (2.89 percentage points, $p < 0.05$), Regional Tourism Conditions (2.26 percentage points, $p < 0.10$), Foreign Tourist Opinion Survey (1.77 percentage points, $p < 0.05$), and Economic Risk Factors (1.71 percentage points, $p < 0.05$).

No statistically significant differences by expected confidence level were found for the Tourist Behavior Survey, Recommendations for Tourism Operators, Tourism Confidence Index, or Tourism Conditions during Festival Periods. Overall, reports with below-normal confidence placed greater emphasis on crises, risks, employment, and business conditions, whereas those with confidence at or above the normal level placed greater emphasis on tourism promotion, tourist satisfaction, global economic conditions, and forecasts of tourist numbers. These differences represent variations in thematic emphasis and do not indicate positive or negative sentiment within individual topics.

4. Discussion

Regarding the first research objective, the analysis identified 15 topics organized into five groups: Reporting on Economic Conditions, Tourist Opinion Surveys, Tourism Operators' Opinions, Tourism Conditions, and Recommendations from the Reports. These findings can be compared with Liu et al. [11], who applied STM to 192 CEO open letters from 152 companies included in Fortune's World's Most Admired Companies 2020 and classified 14 topics into four groups: Resilience, Social Support, Values-Centered, and Preventive Measures. Both forms of communication contain elements related to interpreting circumstances and proposing responses. In particular, Tourism Conditions and Recommendations from the Reports are comparable to the Resilience and Preventive Measures categories. However, Social Support and Values-Centered did not emerge as distinct groups in the TTCI reports, which instead contained specific groups concerning economic conditions, tourist opinions, and tourism operators' opinions. These differences reflect the roles of the communicators. CEOs communicate as leaders of individual companies and therefore emphasize organizational responses, support, and values, whereas the Tourism Council of Thailand communicates as a central private-sector organization that collects information and represents the tourism industry as a whole.

Regarding the second research objective, expected confidence was associated with differences in the emphasis placed on topics within the reports. Reports with below-normal confidence contained greater prevalence of the COVID-19 Situation, Employment Conditions in Tourism Establishments, risk factors, and business conditions. In contrast, reports with confidence at or above the normal level placed greater emphasis on Tourism Promotion and Development, Tourist Satisfaction Survey, Global Economic Conditions, and Forecasts of Tourist Numbers. These findings are partially consistent with Shi and Chen [12], who incorporated employment status as a covariate in an STM and found that former employees discussed negative topics more frequently than current employees, particularly bullying, compensation, and the working environment. Their findings demonstrate that respondent or document characteristics can be associated with the issues emphasized in textual content. Similarly, topics concerning crises, risks, and employment were more prevalent in TTCI reports when expected confidence was low. Nevertheless, topic prevalence represents the emphasis placed on an issue and does not directly indicate the sentiment expressed within that topic.

Thus, the greater prevalence of Global Economic Conditions when confidence was at or above the normal level does not necessarily mean that the reports evaluated global economic conditions positively. Furthermore, these associations should not be interpreted as causal because the textual content and confidence index values were obtained from reports covering the same periods and may reflect common underlying conditions.

Considering both research objectives together, the Tourism Confidence Index was the principal topic, with the highest mean prevalence and relatively consistent representation across the reports. In contrast, topics concerning risks, crises, employment, promotion, and forecasts varied with expected confidence. These findings demonstrate an advantage of STM, which can identify latent topics and examine how their prevalence varies with document-level metadata [8]. Transforming qualitative text into quantitative information also enables hidden structures and patterns to be extracted, providing a more detailed understanding of important tourism issues than the numerical index alone [5]. Following Roos and Reccius [4], the text in TTCI reports can therefore be understood as functioning as a narrative that frames facts and supports policy analysis rather than directly driving economic behavior. The confidence index quantitatively summarizes the direction of confidence, whereas the accompanying text identifies the issues used to interpret and communicate that confidence.

5. Conclusion and Recommendations

5.1 Conclusion

This study applied STM to 1,434 paragraph-level documents extracted from 60 quarterly TTCI reports covering 2010–2024. The analysis identified 15 topics organized into five groups: Reporting on Economic Conditions, Tourist Opinion Surveys, Tourism Operators' Opinions, Tourism Conditions, and Recommendations from the Reports. Expected confidence was also associated with differences in topic prevalence. Below-normal confidence was associated with greater emphasis on crises, risks, employment, and business conditions, whereas confidence at or above the normal level was associated with greater emphasis on tourism promotion, tourist satisfaction, global economic conditions, and forecasts of tourist numbers. These findings demonstrate that the accompanying text provides context concerning the issues emphasized under different confidence levels that the numerical index alone cannot convey. However, the identified associations should not be interpreted as causal relationships.

5.2 Recommendations for Applying the Findings

(1) The Tourism Council of Thailand and other organizations involved in preparing TTCI reports can use the 15-topic structure as a framework for developing a thematic summary to accompany the index each quarter. Such a summary would indicate which conditions, risks, or development approaches receive emphasis and enable readers to interpret the index alongside the context provided by the report.

(2) The Tourism Authority of Thailand, the Ministry of Tourism and Sports, relevant government agencies, and tourism operator organizations can use differences in topic prevalence across confidence levels as a framework for monitoring conditions and prioritizing issues for planning and operations. Employment, risks, and business conditions should receive particular attention when confidence is low, whereas development, promotion, and tourist satisfaction may be considered when confidence is at or above the normal level. These findings should inform decision-making rather than be treated as causal evidence.

5.3 Recommendations for Future Research

(1) Future research should expand the data sources to include documents from other tourism organizations, such as the Tourism Authority of Thailand, the Ministry of Tourism and

Sports, and tourism business associations. This would allow comparisons of whether topical structures and thematic emphasis differ according to the roles and sources of the documents.

(2) Topic prevalence derived from text analysis should be further incorporated as variables in econometric or forecasting models and examined in relation to the confidence index, tourist numbers, or tourism revenue. Quarterly topic prevalence and confidence index values could be used to assess whether textual information provides additional explanatory or predictive information about tourism conditions.

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Labor Productivity in Aging Society: The Role of Older Workers across Sectors and Provinces in Thailand

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Abstract

This study investigates how the share of older workers affects labor productivity across Thai provinces and economic sectors, addressing two objectives: to assess the presence and magnitude of spatial dependence in the age–productivity relationship, and to examine whether the effects differ across the agricultural, industrial, and service sectors. Using balanced panel of all 77 provinces from 2014 to 2023, labor productivity is measured as gross provincial product (GPP) per active worker, and older workers as individuals aged 45 and over, covering both formal and informal workers. Data is drawn from the National Statistical Office's Labor Force Survey. The analysis applies Spatial Autoregressive (SAR), Spatial Error (SEM), and Spatial Durbin (SDM) models with queen-contiguity weight matrices, with model selection guided by AIC and BIC. Results show that the older-worker share exerts a consistently negative and significant effect on labor productivity in the aggregate economy and in all three sectors, with the largest penalty in industry. Spatial spillover effects are confirmed for all sectors. Skill decomposition shows high-skilled older workers are positively associated with productivity. Transmission channel analysis indicates that human capital mitigates the adverse aging effect in services and industry, whereas greater internet use intensifies it, suggesting technological substitution rather than complementarity for older workers in Thailand.

Keywords: Older Workers; Labor Productivity; Spatial panel regression

1. Introduction

Thailand's demographic transition has been exceptionally rapid, taking only about two decades (2002–2024) to move from an aging to an aged society. The number of people continuing to work beyond the conventional retirement age has increased steadily, with its share of total employment rising most sharply in the North and Northeast. In 2024, over 5.3 million people aged 60 and over remained employed, including 3.0 million in agriculture, 1.7 million in services, and 0.6 million in industry. Workforce aging has prompted growing interest in labor productivity effects of older workers.

Whether this shift rises or lowers labor productivity remains unsettled. The empirical evidence is mixed, with effects depending on how labor productivity is measured and, on the sector, and context in which older workers are employed [1], [2]. Moreover, most studies of workforce aging and labor productivity focus on national or firm-level average effects and neglect the spatial dimension. Yet provincial productivity depends not only on local conditions but also on neighboring provinces through labor migration, technology diffusion, and trade [3], [4]. In Thailand, Tipayalai (2025) finds that a larger share of older workers is negatively associated with provincial economic performance [5], but sectoral spatial evidence remains scarce, and little is known about how older workers affect labor productivity differently across agriculture, industry, and services. This study addresses that gap to inform policies for allocating older workers to the sectors in which they are most productive.

Following the World Health Organization threshold and the occupational-health literature, which treats age 45 as the point at which work ability and employability begin to require active attention [6], this study defines “older workers” as individuals aged 45 and over. This definition covers workers in both the pre-retirement and post-retirement stages of their careers and includes those in formal and informal employment.

Accordingly, the study pursues two objectives: first, to investigate the spatial dependence in the relationship between the share of older workers and labor productivity across Thai provinces; and second, to examine the differential effects of older workers on labor productivity across the agricultural, industrial, and service sectors.

In terms of scope, the study uses a provincial panel of all 77 provinces for the period 2014 - 2023. Labor productivity is measured as gross provincial product (GPP) per active worker, both in aggregate and disaggregated by sector, while the age structure and skill composition of the workforce are drawn from the Labor Force Survey. The analysis applies spatial autoregressive (SAR), spatial error (SEM), and spatial Durbin (SDM) models with queen-contiguity weight matrices, benchmarked against conventional panel regression to capture interprovincial dependence and spatial spillover effects.

The structure of this paper is as follows. Chapter 2 reviews the theoretical and empirical literature on older workers, labor productivity, and their spatial transmission. Chapter 3 presents the conceptual framework, spatial econometric methodology, the model specification, and the data. Chapter 4 reports and interprets empirical results, and Chapter 5 discussion with the study's conclusion and limitations.

2. Literature Review

The relationship between older workers and labor productivity is theoretically ambiguous and empirically unsettled. Human capital theory holds that education, training, and experience are forms of capital that raise productivity [7], [8]; for older workers, this capital is multidimensional, since some physical and cognitive capacities decline with age while firm-specific knowledge, expertise, and professional networks accumulate [9], [10]. The net effect therefore depends on task content and on continued investment in training and can be sustained where workplaces adapt job design and support intergenerational knowledge transfer [11], [12].

Empirically, this ambiguity is borne out. A systematic review by Viviani et al. (2021), covering 74 studies, found that 41% of the evidence reported no significant difference in productivity between older and younger workers. In comparison, 31% of the studies concluded that younger workers were more productive, while 28% found that older workers exhibited higher productivity. The evidence ranges from productivity declines in technologically dynamic or physically demanding settings [9], [13] to stable or rising productivity in tasks that reward experience and interpersonal skills [1], [14]. The effect thus appears contingent on how productivity is measured and on the sectoral and national context, a contingency that motivates the sector-disaggregated approach adopted in this study.

This microeconomic evidence is increasingly interpreted through the demographic-dividend framework, which links a population's age structure to economic growth [15]. The first, or labor-supply, dividend arises as a rising working-age share raises the economic support ratio, a mechanism to which attribute roughly one-third of East Asia's income growth; it is transitory and dissipates as populations age. The second, or capital-accumulation, dividend is potentially permanent and operates as the anticipation of longer lives induces greater saving and investment in physical and human capital [16]. More recently, a third, or “longevity,” dividend has been identified, arising from the untapped productivity of healthy older workers rather than from an expanding labor-force share [17]; its realization depends precisely on the

age–productivity relationship examined here. This framing is directly relevant to Thailand, whose first dividend is estimated to have closed around 2011 [18], and where a rapidly growing older population continues to rely on family transfers and on continued work under thin pension coverage [19].

Parallel literature emphasizes that these effects are not spatially uniform. Building on first law of geography and demonstration that ignoring spatial dependence yields biased and inefficient estimates, recent studies show that the productivity effects of aging vary across regions and spill over to neighbors through labor mobility, technology diffusion, and agglomeration economies [20], [3], [4]. Two transmission channels are commonly emphasized. The first is human capital, proxied by average years of schooling, through which older workers generate spillovers via tacit knowledge, mentoring, and labor-market linkages [21], [22]. The second is technological adoption, proxied by information and communication technology (ICT), which conditions the age–productivity relationship: greater ICT intensity tends to attenuate the labor productivity losses associated with an aging workforce [23], [24].

Taken together, this body of work suggests that the effect of older workers on productivity is heterogeneous, sector-specific, and spatially interdependent. Yet evidence on the spatial and sectoral effects of older workers remains thin, particularly for developing economies. This study addresses that gap, and in doing so speaks to whether Thailand can convert its aging workforce into a source of continued, spatially balanced growth.

3. Research Methodology

3.1 Conceptual framework

This section develops the theoretical framework and hypotheses guiding the empirical analysis of how the share of older workers affects labor productivity.

H1: The share of older workers and labor productivity exhibit spatial dependence. Provincial economies are interconnected through labor mobility, technology diffusion, trade, and shared infrastructure. Consequently, the labor productivity associations of workforce aging may spill across provincial boundaries [25], [26].

H2: The effect of older workers on labor productivity operates partly through the human capital channel and the technological innovation channel. Older workers possess accumulated experience, tacit knowledge, professional networks, and mentoring capacity, although some formal skills may depreciate as production requirements change. Human capital is proxied by average years of schooling. Technology adoption, measured by the Provincial internet usage rate, may also mediate the relationship, while technology diffusion from neighboring provinces may facilitate or constrain local productivity gains [27].

H3: The share of older workers negatively impacts agricultural and industrial sector, while positively affecting the services sector. The expected effect varies with sectoral task composition. Agriculture and industry rely more heavily on physical capacity, mechanization, and adaptation to technological change, which may disadvantage older workers [28], [29]. By contrast, services place greater value on experience, interpersonal skills, and accumulated knowledge, which tend to remain stable or improve with age [30].

3.2 Methodology: Spatial Econometrics

The spatial weight matrix W employs queen contiguity: $w_{ij}=1$ if provinces i and j share a boundary or vertex, and 0 otherwise (including $i = j$). The raw contiguity matrix is row-standardized by dividing each element by its row sum ($\sum_{j=1}^n w_{ij} = 1$ for all i), so that the spatial lag represents a weighted average of neighboring values [31]. One province (Phuket) has no contiguous neighbor and is assigned a zero spatial lag. To examine spatial patterns in labor

productivity and the older-worker share before formal estimation, this study applies two complementary measures of spatial autocorrelation. Global Moran's I statistics assesses whether a variable is clustered, dispersed, or randomly distributed across the study area:

$$Global\ Moran's\ I_t = \frac{n}{\sum_{i=1}^n \sum_{j=1}^n w_{ij}} \left[\frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij} (X_i - \bar{X})(X_j - \bar{X})}{\sum_{i=1}^n (X_i - \bar{X})^2} \right] \quad (1)$$

; where n is the number of observations (provinces), $\bar{X}$ is the mean value of the variable, X_i is the value of a variable at a particular location, X_j is the value of a variable at another location, and w_{ij} is an element of binary spatial weight matrix. Values close to 1 indicate positive spatial autocorrelation, values close to -1 indicate negative autocorrelation, and values near 0 imply spatial randomness. Because Global Moran's I provide only an overall summary, this study also applies to the Local Indicators of Spatial Association (LISA) to identify statistically significant clusters and outliers at the individual province level [32]:

$$Local\ Moran's\ I_i = \left(\frac{X_i - \bar{X}}{s_0} \right) \sum_{j=1}^n w_{ij} (X_j - \bar{X}), s_0 = \sum_{i=1}^n \frac{(X_i - \bar{X})^2}{n} \quad (2)$$

; where $I_i > 0$ indicates positive local spatial autocorrelation (or spatial clusters), implying that a province is surrounded by provinces with similar values. These locations are categorized as either High-High clusters (hot spots) or Low-Low clusters (cold spots). In contrast, $I_i < 0$ reflects negative local spatial autocorrelation (or spatial outliers), identifying provinces whose values differ markedly from their neighbors [33].

To formally test the hypotheses while accounting for spatial dependence, this study estimates three spatial panel regression models following LeSage and Pace (2009): the Spatial Autoregressive Model (SAR), the Spatial Error Model (SEM), and the Spatial Durbin Model (SDM), all departing from ordinary least squares (OLS) which assumes independent errors.

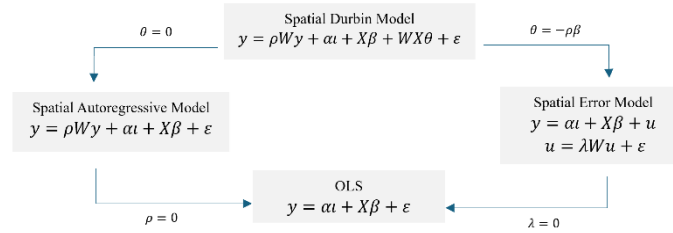


Figure 1 The relationships between different spatial dependence models adapted from a figure in Elhorst (2014, p.9) [34]

The SAR spatial lag of the dependent variable (ρ) captures output spillovers across provinces; omitting ρ yields biased and inconsistent OLS estimates. The SEM models spatially correlated error term (λ) captures common unobserved provincial shocks; OLS remains unbiased but inefficient with invalid standard errors. The SDM extends the SAR by adding spatial lags of all explanatory variables (θ), allowing neighboring provinces' characteristics to directly affect local productivity. The SDM nests the SAR when $\theta = 0$ and approximates the SEM under the restriction $\theta = -\rho\beta$ (Figures 1).

The baseline specifications build on work by Aiyar et al. (2017)¹ in (3), fitting the growth in real output per worker on the share of older workers, the youth and the old dependency ratios, and fixed effects. The present study departs from that framework in two respects: it models the level of ln (GPP per active worker) rather than the growth rate, and it focuses on Thai provinces rather than countries, a choice motivated by the absence of a reliable provincial capital series. The aggregate equation is:

$$\ln y_{it} = \alpha_0 + \beta_1 OldWorker_{it} + \beta_2 YADR_{it} + \beta_3 OADR_{it} + \beta_4 yearedu_{it} + \beta_5 internet_{it} + \mu_i + \varepsilon_{it} \quad (3)$$

; where y_{it} denotes GPP per active workers; *OldWorker* is the share of older workers aged 45 years old and above to the active workers; *YADR* and *OADR* are the young-age and old-age dependency ratios, respectively; *yearedu*_{it} is average years of schooling; *internet*_{it} is the ratio of internet users to the total population; μ_i province fixed effects; and ε_{it} is the error term. The coefficient β_1 is the parameter of central interest, capturing the semi-elasticity of labor productivity with respect to the older worker share.

To examine sectoral heterogeneity, Equation (4) is estimated separately for agriculture, industry, and services. The sector-specific counterpart is:

$$\ln y_{it}^s = \alpha_{it}^s + \beta_1 OldWorker_{it}^s + \beta_2 YADR_{it} + \beta_3 OADR_{it} + \beta_4 yearedu_{it} + \beta_5 internet_{it} + \mu_i + \varepsilon_{it} \quad (4)$$

; where superscript $s \in \{\text{Agriculture (A), Industry (I), Services (S)}\}$; y_{it}^s is GPP per worker in sector s ; and $OldWorker_{it}^s$ is the share of older workers within sector s .

Model selection among the SAR, SEM, and SDM specifications follows a goodness-of-fit approach using the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), with lower values indicating a better-fitting model. Once the preferred spatial model is identified, two transmission channels are examined through interactions of the older-worker share with (i) average years of schooling (human-capital channel) and (ii) internet penetration (technology channel). A supplementary specification disaggregates the workforce into high-, mid-, and low-skill tiers (ISCO-08 occupation groups) to assess whether skill composition modifies the productivity association [35].

3.3 Data

This study examines Thai provincial-level data from 2014 to 2023. Data are obtained from government agencies, including the Office of the National Economic and Social Development Council (NESDC) and National Statistical Office (NSO). Table 1 shows variable description.

Table 1 Variable Description

Variable(s)	Description
Gpp_pact	GPP per active worker, where an active worker is defined as an employed individual aged 15 years and above.
Oldwork_ratio	Share of workers aged 45+ to total active workers
YADR	Ratio of population aged 0–14 to population aged 15–59
OADR	Ratio of population aged 60+ to population aged 15–59
yearedu	Average years of schooling, population aged 15+
internet_ratio	Ratio of internet users to the total population
skilled labor	Share of older workers in high/mid/low occupation groups

¹ Aiyar et al. (2017) studies the effect of the aging of the workforce (the share of the total workforce aged 55–64 years) on labor productivity (real output per worker) using a panel of major EU28 countries from 1950 to 2014. They find that workforce aging reduces growth in labor productivity, mainly through its negative effect on TFP growth.

Note: Skill groups follow ISCO-08 classification in [35]: high = managers, legislators, professionals, technicians; mid = clerks, service workers, plant/machine operators; low = craft workers, agricultural workers, unskilled workers. These are occupation-based categories, not measures of educational attainment.

4. Results

4.1 Hot Spots and Cold Spots

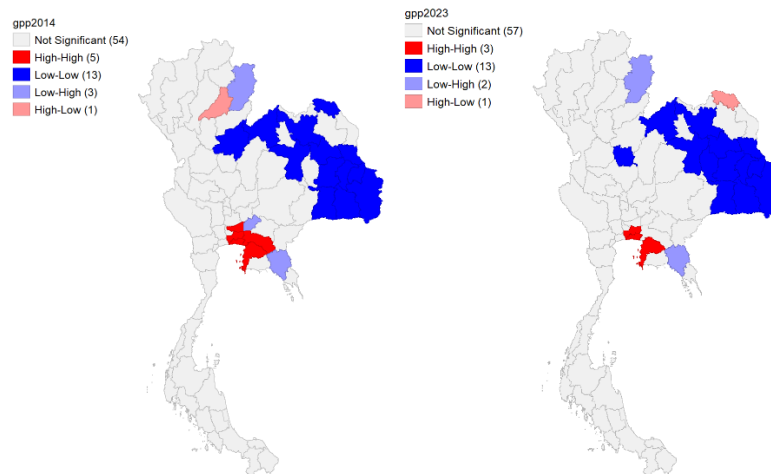


Figure 2 Local Indicators of Spatial Association of GPP per active workers in 2014 and 2023

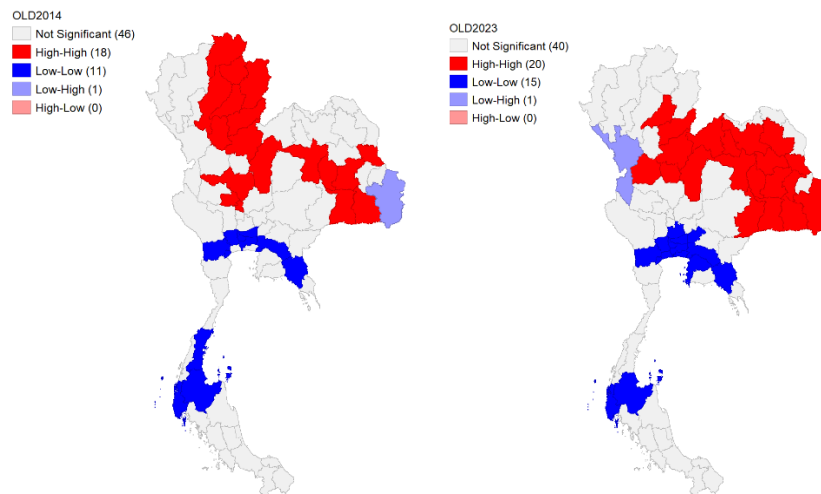


Figure 3 Local Indicators of Spatial Association of Older-worker share in 2014 and 2023

Global Moran's I for GPP per worker was 0.208 in 2014 and declined to 0.141 in 2023, both positive, indicating moderate but weakening spatial clustering of labor productivity over the study period. For the older-worker share, spatial clustering was substantially stronger and intensified over time, with Global Moran's I rising from 0.624 in 2014 to 0.756 in 2023, indicating that the geographic concentration of aging workers became more pronounced across Thai provinces during this decade.

The LISA maps (Figures 2 and 3) reveal a clear geographic mismatch between where labor productivity is high and where the workforce is oldest. High-High productivity clusters are concentrated in the central region around Bangkok, with five provinces forming such clusters

in 2014, declining to three by 2023. Low-Low clusters are concentrated in the northeastern region, stable at 13 provinces across both years. The spatial pattern of the older-worker share is essentially the inverse: High-High clusters of aging are in the northern and northeastern regions (18 provinces in 2014, expanding to 20 in 2023), while Low-Low clusters of aging are in the central and southern regions (11 to 15 provinces over the same period). These results confirm that older workers and labor productivity are spatially dependent but geographically divergent, providing a *prima facie* case for the spatial econometric analysis that follows.

4.2 Spatial Panel Regression

Table 2 presents the descriptive statistics for all variables used in this study. The average GPP per active worker at the aggregate level (*gpp_pact*) is 196,189 baht. Among sectors, industry records the highest average productivity (349,187 baht) but also the greatest dispersion, driven by capital-intensive provinces in the Eastern Economic Corridor, while agriculture records the lowest. The older-worker share averages 47.68%, meaning that close to half of Thailand's provincial workforce falls within the older-worker age range over the study period. Because the GPP per active worker variables have considerably larger values than the ratio variables, these productivity measures are transformed using the natural logarithm.

Table 2 Descriptive statistics

Variable	Unit	Mean	Std. Dev	Min	Max
<i>gpp_pact</i>	Thai baht	196,189	217,543	33,688	1,547,238
<i>Oldwork_ratio</i>	Proportion	0.4768	0.0820	0.1981	0.6275
<i>YADR</i>	Proportion	0.2848	0.0630	0.1153	0.4527
<i>OADR</i>	Proportion	0.2790	0.0890	0.0880	0.5302
<i>yearedu</i>	Year	7.89	0.99	5.36	11.21
<i>internet_ratio</i>	Proportion	0.6014	0.2148	0.17	0.9699
<i>gpp_agri</i>	Thai baht	76,572	75,230	13,616	817,099
<i>gpp_indus</i>	Thai baht	349,187	709,743	16,655	5,939,476
<i>gpp_serv</i>	Thai baht	232,095	159,470	43,890	1,162,008

Table 3 reports the estimation results from spatial and non-spatial panel models. The Hausman test supports the use of the fixed-effects specification. Because the panel fixed-effects model is estimated by OLS, its log-likelihood values are not directly comparable with those of the maximum-likelihood spatial models. Among the spatial specifications, the SDM provides the best fit, as indicated by the highest log-likelihood and the lowest AIC and BIC values.

Because the SDM contains a spatial lag of the dependent variable, reported coefficients are not marginal effects. Table 3b decomposes the average direct, indirect (spillover), and total associations from the SDM using Delta-method standard errors. A 1-percentage-point increase in the older-worker share is associated with a 0.57% reduction in labor productivity within the province. Negative spatial spillovers increase the magnitude of the total association to more than four times that of the direct effect alone. By contrast, the significant total associations of internet use and education are driven almost entirely by indirect spatial spillovers. These findings support H1 by demonstrating spatial interdependence between older workers and labor productivity across Thai provinces.

Table 3 Estimation results of older workers on labor productivity (Aggregate GPP)

Variable	Panel FE	SAR	SEM	SDM
<i>Oldwork_ratio</i>	-1.2013*** (0.1966)	-0.9024*** (0.1879)	-0.7469*** (0.2112)	-0.4599** (0.2064)
<i>YADR</i>	0.6350*** (0.1790)	0.6611*** (0.1679)	0.8623*** (0.1839)	1.0113*** (0.1794)

OADR	0.5513*** (0.1519)	0.2438* (0.1471)	0.0620 (0.1882)	-0.7322*** (0.1992)
yearedu	-0.0341** (0.0155)	-0.0211 (0.0146)	-0.0055 (0.0158)	-0.0121 (0.0152)
internet_ratio	0.3119*** (0.0409)	0.2387*** (0.0393)	0.3072*** (0.0442)	0.0307 (0.0792)
Spatial ρ	—	0.3655*** (0.0438)	—	0.3079*** (0.0447)
Spatial λ	—	—	0.3931*** (0.0469)	—
Spatial Cross-regressive ($W \times \text{Oldwork_ratio}(\theta)$)	—	—	—	-1.2755*** (0.3273)
sigma_e	—	0.0822*** (0.0022)	0.0822*** (0.0022)	0.0674*** (0.0024)
Observation	770	770	770	770
Log-likelihood	824.254	735.906	734.560	778.030
AIC	-1636.5	-1,457.8	-1,455.1	-1,532.1
BIC	-1608.6	-1,425.3	-1,422.6	-1,476.3

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

SDM is preferred: AIC = -1,532.1 (lowest); LR test SAR $\rightarrow$ SDM: $\chi^2(5) = 84.25$, $p < 0.001$.

Table 3b Average direct, indirect, and total associations (SDM, Aggregate GPP)

Variable	Direct	Indirect	Total
Oldwork_ratio	-0.5704*** (0.2023)	-1.9104*** (0.4090)	-2.4808*** (0.4421)
YADR	0.9266*** (0.1742)	-1.4648*** (0.3972)	-0.5382 (0.4090)
OADR	-0.6207*** (0.1895)	1.9267*** (0.2925)	1.3059*** (0.2557)
yearedu	-0.0202 (0.0151)	-0.1398*** (0.0320)	-0.1600*** (0.0353)
internet_ratio	0.0535 (0.0756)	0.3940*** (0.1066)	0.4475*** (0.0908)

Note: Delta-method standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Direct = own-province association; Indirect = spillover via WX and spatial-multiplier channels combined; Total = Direct + Indirect.

Tables 4 and 4b report the sectoral SDM estimates and their direct and indirect effects. The share of older workers is negatively associated with labor productivity in all three sectors, with the largest effect on industry and the smallest in services. In agriculture, a positive indirect effect partly offsets the negative direct effect, suggesting beneficial knowledge spillovers from neighboring provinces. In services, the association operates mainly through the direct effect, whereas industry exhibits substantial negative direct and spillover effects. Among the control variables, the YADR is positively associated with productivity across sectors, while internet use has a significant positive effect in industry. H3 is therefore partially supported, as the predicted negative association is observed in agriculture and industry, but also in services.

Table 4 Sectoral SDM Estimates

Variable	Agriculture	Services	Industry
Oldwork_ratio (by sector)	-4.6262*** (0.3742)	-2.8658*** (0.2497)	-7.8374*** (0.5608)
YADR	1.1436*** (0.4149)	1.1645*** (0.2190)	1.0198*** (0.3435)
OADR	0.9187** (0.3637)	-0.1201 (0.1983)	0.1641 (0.3138)
yearedu	-0.0884** (0.0361)	-0.0889*** (0.0187)	0.0070 (0.0287)

internet_ratio	0.0242 (0.1817)	0.1231 (0.0963)	0.2787* (0.1509)
W× Oldwork_ratio (θ)	2.6359*** (0.6689)	0.9602** (0.4630)	-1.3207 (1.1214)
Spatial ρ	0.0615 (0.0535)	0.1238** (0.0488)	0.2057*** (0.0482)
N	770	770	770
Log-likelihood	205.671	645.978	331.140
AIC (SDM)	-387.3	-1,268.0	-638.3
BIC (SDM)	-331.6	-1,212.2	-582.5

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 4b: Sectoral decomposition of spatial direct, indirect, and Total Associations

Variable	Agricultural Direct	Agricultural Indirect	Services Direct	Services Indirect	Industry Direct	Industry Indirect
Oldwork_ratio (by sector)	-4.5939*** (0.3718)	2.4406*** (0.6699)	-2.8486*** (0.2482)	0.6649 (0.4799)	-7.9811*** (0.5598)	-3.5001*** (1.2416)
YADR	1.1358*** (0.4113)	-0.5854 (0.7463)	1.1331*** (0.2152)	-1.2151*** (0.4085)	0.9443*** (0.3345)	-1.8377*** (0.6879)
OADR	0.9169** (0.3596)	-0.1410 (0.5316)	-0.0969 (0.1941)	0.9001*** (0.2905)	0.1810 (0.3036)	0.4125 (0.4977)
yearedu	-0.0868** (0.0359)	0.1207** (0.0588)	-0.0912*** (0.0184)	-0.0877*** (0.0291)	0.0038 (0.0281)	-0.0784 (0.0488)
internet_ratio	0.0270 (0.1795)	0.2163 (0.2098)	0.1290 (0.0941)	0.2273** (0.1090)	0.2863** (0.1457)	0.1852 (0.1806)

Note: Delta-method standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 5 examines human-capital and technology channels through interactions term. Education mitigates the negative productivity association in services and industry, whereas internet use intensifies it in industry but modestly mitigates it in agriculture. H2 is supported as both transmission channels are operative.

Table 5 Transmission channel Analysis

Variable	Total GPP	Agriculture	Services	Industry
A. Direct effects (estat impact)				
Aging variable (direct)	-0.5077** (0.2070)	-4.7157*** (0.3937)	-2.9769*** (0.2527)	-8.1781*** (0.5689)
YADR (direct)	0.8850*** (0.1800)	1.2352*** (0.4123)	0.9118*** (0.2158)	0.8480** (0.3356)
OADR (direct)	-0.6562*** (0.1919)	0.9138** (0.3584)	-0.0993 (0.1906)	0.1250 (0.3016)
B. Interaction coefficients (raw)				
Oldwork_ratio (by sector) × yearedu	0.1279 (0.0990)	-0.0061 (0.2151)	0.9441*** (0.2200)	1.7911*** (0.5061)
Oldwork_ratio (by sector) × internet_ratio	0.0852 (0.2668)	0.8604* (0.4868)	-0.8914 (0.6931)	-4.1495*** (1.4033)
C. Spatial parameters				
W× Oldwork_ratio (θ)	-1.1902*** (0.3327)	2.1215*** (0.7003)	0.8672* (0.4642)	-0.8341 (1.1404)
Spatial ρ	0.3085*** (0.0446)	0.0572 (0.0536)	0.1300*** (0.0482)	0.2009*** (0.0481)
N	770	770	770	770
AIC	-1,531.2	-389.5	-1,290.3	-646.9

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Direct effects in Panel A are evaluated without interactions as a baseline reference.

Table 6 presents the skill decomposition based on occupation groups. Agriculture is excluded because older agricultural workers are concentrated in low-skill occupations, providing insufficient variation to estimate skill-specific spatial effects. High-skill older

workers are positively associated with labor productivity in the aggregate, services, and industry, consistent with their contributions to knowledge transfer and mentoring. By contrast, the adverse association is concentrated among mid-skill older workers, while low-skill direct effects are statistically insignificant.

Table 6 Skill-level decomposition

Variable	GPP Direct	GPP Indirect	Services Direct	Services Indirect	Industry Direct	Industry Indirect
High-skill older workers	1.3400*** (0.5020)	-1.8810 (1.2570)	1.1040*** (0.2550)	-2.0320*** (0.5250)	1.6340*** (0.4490)	0.3070 (1.0810)
Mid-skill older workers	-0.7050*** (0.2030)	-2.0240*** (0.4350)	0.0860 (0.1640)	-0.9650*** (0.3380)	0.1860 (0.1510)	-0.8560** (0.3580)
Low-skill older workers	-0.2530 (0.4160)	-1.6720 (1.0340)	-0.0860 (0.2900)	0.6170 (0.6550)	0.4030 (0.2910)	0.0090 (0.7580)

Note: Delta-method standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5. Discussion

5.1 Conclusion and Implications

This study examines whether workforce aging is associated with labor productivity differently across Thai provinces and sectors. Three findings emerge. First, older-worker share is associated with lower labor productivity across the aggregate economy and all three sectors, most severely in industry, though agriculture benefits from positive spillovers from neighboring provinces. Second, high-skilled older workers are positively associated with labor productivity. Finally, education mitigates the negative association in services and industry, whereas internet use intensifies it in industry, suggesting that digital transformation has benefited younger workers more than older workers.

Several policy priorities emerge. Targeted retraining should support older workers in transitioning to higher-skilled roles, where the productivity gains from upskilling are greatest. Flexible work arrangements, hiring incentives, and age-supportive technologies can help retain experienced workers in industry and services. Continued investment in education is also important, particularly in provinces dominated by these sectors. As the productivity effects of workforce aging extend across provincial borders, implementation should be coordinated regionally.

5.2 Limitations

The main concern is potential endogeneity of the older-worker share: productive provinces attract younger migrants, lowering their older-worker share while raising productivity, whereas lagging provinces lose youth to out-migration, generating reverse causality and spatial sorting. Fixed effects and the spatial models mitigate but do not eliminate this simultaneity; instrumenting the age structure with its long lag is a useful extension.

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Futuristic Food Systems Driving the Bio Circular Green Economy Framework through the Processing and Formulation of *Wolffia globosa*

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Abstract

As global food security faces increasing pressures from rapid population growth, land degradation, water scarcity, and the environmental burdens of traditional agriculture, there is an urgent need to transition toward sustainable, resource-efficient protein alternatives. This paper critically reviews *Wolffia globosa*, the world's smallest flowering aquatic plant, through the lens of the Bio-Circular-Green (BCG) economy model. Bridging the gap between botanical utility and sustainable economy, this review demonstrates how the unique biological traits of *W. globosa* directly fulfill the core pillars of the BCG model. Nutritionally, it serves as a nutrient-dense superfood yielding 20-45% dry-weight protein with a complete essential amino acid profile, high dietary fiber, healthy omega-3 fatty acids, and essential bioactive micronutrients. Under the Bioeconomy pillar, advanced processing techniques such as enzymatic hydrolysis and ultrasound-assisted extraction, convert this biomass into functional peptides and protein isolates suitable for human foods, functional snacks, and pet nutrition. Within the Circular Economy framework, *W. globosa* thrives in closed-loop aquatic systems and agricultural wastewater side-streams, drastically reducing freshwater consumption and eliminating arable land competition. From a Green Economy perspective, transitioning from local pond harvesting to automated, renewable-energy-powered vertical biorefineries minimizes carbon footprints while driving down production costs to achieve true economies of scale. Ultimately, this paper highlights the innovativeness of *W. globosa* as a superfood whose nutritional density and commercial adaptability serve as a primary engine for sustainable economic growth and global food security.

Keywords: *Wolffia globosa*; Bio-Circular-Green (BCG); Plant-Based Protein, Superfood

1. Introduction

The global food system faces immense pressure because the world population is expanding rapidly and is projected to reach nearly ten billion by mid-century. This growth increases the demand for high-protein products, demonstrating that current agricultural methods cannot keep up with future needs [1]. Concurrently, essential natural resources are disappearing, leading to severe shortages of agricultural land due to expanding cities and soil degradation. Furthermore, water security has become a critical challenge because traditional farming consumes a disproportionate number of freshwater resources [2]. This major gap between production capacity and available resources requires an urgent shift in global agriculture to prevent severe food shortages.

In response to these growing food demands, modern diets rely far too heavily on livestock farming to meet daily protein needs. However, this heavy reliance on meat products creates massive resource waste because animals require vast amounts of energy, water, and crop feed to produce a relatively small amount of human food [3]. The pressure from this livestock

industry also causes widespread biodiversity loss, damages natural habitats, and destroys primary forests for cattle grazing. Because animal farming requires substantially more resources than plant-based foods, it seriously threatens global environmental stability and planetary boundaries [2]. To address this imbalance, the global food system must urgently shift away from traditional meat production and focus on sustainable plant alternatives.

Beyond excessive land use, traditional livestock production causes severe environmental damage and operates as a primary driver of global warming by releasing massive amounts of greenhouse gases. The animal farming industry, particularly cattle raising, releases huge quantities of harmful methane and nitrous oxide gases into the atmosphere [4]. Furthermore, raising farm animals consumes vast amounts of clean freshwater, which worsens water shortages in many arid regions and strains local reserves. This production cycle also generates large volumes of agricultural waste that run off into nearby lakes and rivers, causing severe water pollution and eutrophication [3]. Therefore, switching to sustainable future foods with small environmental footprints is necessary to protect global ecosystems.

Alongside these severe ecological damages, the rising financial costs of traditional farming create major economic barriers that directly threaten global food security and supply chains. Constantly changing prices for synthetic fertilizers, energy, animal feed, and farming land make traditional meat production highly vulnerable to inflation and market shocks [5]. These rising costs hit vulnerable populations the hardest, making it difficult for them to purchase affordable, high-quality nutrition and worsening global dietary imbalances. Additionally, the financial costs of environmental damage are increasingly added to production bills through new carbon taxes and resource fees [4]. As a result, developing new protein sources with very low input costs is essential to bypass these economic barriers and stabilize food supplies worldwide.

To solve these connected environmental and economic problems, the central objective of modern agricultural science must focus on developing sustainable alternative food sources. Transitioning to these new, non-traditional foods allows the global food industry to produce essential nutrients without using up huge amounts of land and water [5]. These innovative alternative foods must offer rich nutritional profiles while requiring minimal land, water, and energy, thereby ensuring they do not harm nature. By setting up efficient, low-carbon production systems, these alternative resources can reliably supply high-quality protein to feed the growing world population [1]. Ultimately, discovering and scaling up these resource-efficient crops is the best pathway to achieve long-term food security while actively restoring damaged ecosystems.

2. The Bio Circular Green Economy Model Framework

The Bio-Circular-Green (BCG) model is an integrated economic framework designed to promote sustainable and inclusive growth. So, the economy can continue to thrive constantly as well as help boost sustainability. First, bioeconomy refers to utilizing biological resources to their fullest potential while maintaining environmental balance [6]. It involves technology to increase production efficiency, creating innovative and high-value goods. It is important to use biological resources as they are renewable, which means they produce a lower net of carbon footprint, mitigating greenhouse gas emissions. This means that it is manageable to create high-value products even when using natural resources. The bioeconomy vision is to apply sustainably sourced biomass, including residual biomasses such as crop residues, industrial side-streams, and food waste, estimated by the FAO worldwide to be one-third of the product produced [7], as well as organic municipal waste, by transforming it into value-added products [8].

Second, the approach of the circular economy pillar includes using resources as efficiently

as possible, and the materials used must be recyclable [6]. This is important as reusing and recycling resources can prevent shortages and decrease waste, making it better for both humans and animals. Many industries, like the agricultural sector, consume energy in various forms while simultaneously generating agricultural waste and wastewater, remaining a major contributor to carbon emissions [9]. To resolve the problem of dwindling economic resources, it is necessary to develop an integrated perspective of the economy, namely, a circular economy. In this regard, a circular business perspective helps achieve sustainable growth by treating economic waste as a useful economic resource [10].

Third, the green economy is an economic system that involves creating innovations and managing social conditions to minimize environmental impact [6]. The Environment Management Group points out that the green economy is seen to: (1) reduce carbon emissions and pollution; (2) enhance energy and resource efficiency; and (3) prevent the loss of biodiversity and ecosystem services. This is done by limiting government spending in areas that deplete natural capital through removing harmful subsidies and incentives, promoting investment and spending in areas that stimulate a green economy, and establishing a sound regulatory framework to accelerate progress towards a green economy and equitably allocate costs and benefits across key economic actors. This guides people to switch to alternative renewable energy and resources which provide better benefits to the environment [11].

In conclusion, combining these three pillars can help solve global food problems and transform modern agriculture. This is done by switching to using natural resources which are renewable, rather than depleting scarce resources. Additionally, this model enables companies to create closed-loop systems that minimize waste, recycle water, and reuse raw agricultural materials to promote greater sustainability. Lastly, it positively benefits the environment by using renewable resources which are less harmful to the atmosphere because they release less greenhouse gas, contributing less to climate change and global warming.

3. *Wolffia globosa*: Biological Foundations, Nutritional Value, and Agricultural Potential

Wolffia species represent the world's smallest and most structurally reduced flowering plant species. Among the five duckweed genera, members of the genus *Wolffia* are uniquely rootless, completely lacking true stems and leaves. Instead, their microscopic morphology consists of an extremely simplified body containing only a single leaf-like frond, one stamen, and one gynoecium. Because of this simplified structural plan, *Wolffia* species are easy to cultivate in laboratory settings and complete their entire life cycle rapidly. Crucially, the unique reproductive strategy of *Wolffia* species drives fast asexual budding, enabling the rapid accumulation of biomass and allowing them to achieve wide distribution across various aquatic habitats [12]. Beyond laboratory environments, *Wolffia* species demonstrate exceptional growth kinetics in natural aquatic ecosystems, particularly across Asian countries like Thailand, where it is known locally as "watermeal", "phum", "kai-phum", or "Green Caviar" and has long been harvested for traditional dishes. In the context of Thailand's transition into an aging society facing rising non-communicable diseases (NCDs), *Wolffia* has gained growing recognition as a health-promoting "superfood" within the expanding global health and wellness economy [13].

Recognized under circular bioeconomy principles for its low environmental impact, *Wolffia* biomass contains 40-45% dry-weight protein alongside essential vitamins and minerals, serving as an ideal functional alternative to animal protein that mitigates NCD risks while delivering high vegetative growth efficiency with biomass doubling times of 1.0 to 2.3 days [14]. From a community-based agricultural perspective, *Wolffia globosa* is cultivated through integrated, low-cost farming systems that utilize local water bodies and agricultural side-streams. At local levels, cultivation originated naturally in clay treatment ponds used for tofu

production wastewater. Producers manage dedicated earthen ponds to achieve high yields, harvesting up to 50 kilograms of fresh biomass daily. To ensure safety, marketability, and compliance with Good Agricultural Practices (GAP), the raw harvested biomass undergoes ozone sterilization and controlled drying processes, transforming fresh watermeal into high-value dried products suitable for long-term storage and distribution [13].

W. globosa exhibits an exceptional nutritional value comprising high-quality protein, dietary fiber, low starch, healthy lipids, essential minerals, and key phytochemicals. Evaluation of 16 *Wolffia* samples indicates a dry-weight protein content of 20-30%, with all species and clones showing an excellent essential amino acid profile that complies with WHO reference standards for human nutrition [14]. Its carbohydrate fraction consists of a relatively low starch content (10-15%) alongside approximately $26.2 \pm 1.2\%$ dietary fiber, which supports cardiovascular health by helping to manage total and LDL cholesterol levels. Furthermore, *W. globosa* contains 1-5% total lipids featuring healthy omega-3 fatty acids, specifically alpha-linolenic acid (ALA) and stearidonic acid (SDA), maintaining a favorable omega-6 to omega-3 ratio below 1:1. Micronutrient analyses reveal that *Wolffia* is rich in potassium and iron while remaining low in sodium, containing vital trace elements like manganese, zinc, and copper, as well as bioactive compounds including lutein, beta-carotene, zeaxanthin, vitamin E, and phytosterols [14]. *W. globosa* also contains substantial stable levels of bioactive vitamin B12 compounds including hydroxocobalamin, five deoxyadenosylcobalamin and methylcobalamin without containing inactive pseudo B12 forms. Clinical research demonstrates that long term consumption of *W. globosa* effectively increases serum vitamin B12 concentrations in humans establishing it as a viable plant-based source of this essential nutrient [15].

Building upon these inherent nutritional and agronomic strengths, *Wolffia globosa* is increasingly recognized as a multi-functional ingredient for advanced food technology, functional foods, and nutraceutical applications. Beyond raw biomass, processing techniques such as enzymatic hydrolysis, ultrasound-assisted extraction, and biotransformation enhance its techno-functional properties, including protein solubility (>80%), emulsification, and foaming capacity, which enable its seamless integration into clean-label matrixes such as plant-based meat analogs, dairy substitutes, and high-protein extruded snacks. Furthermore, bioactive peptides, phenolic extracts, and phytosterols derived from *W. globosa* demonstrate key therapeutic potential, including antioxidant, anti-inflammatory, antimicrobial, and antihypertensive (ACE-inhibitory) activities, alongside clinically demonstrated postprandial glycemic regulation. Coupled with international regulatory approvals such as Novel Food authorization by the European Food Safety Authority (EFSA) and Generally Recognized as Safe (GRAS) status by the U.S. FDA, *W. globosa* is strategically positioned as a safe, highly sustainable, and commercially viable protein powerhouse for next-generation global food systems [16].

4. Business Aspects and Food Application Innovations

As an evolved traditional food with numerous nutritional benefits, *W. globosa* can be combined with various food products to develop nutritious snacks and foods to tackle malnutrition. For instance, clinical research comparing the postprandial glucose peak of replacing dinner with either a kai-phum green shake or a carbohydrate/protein/calorie yogurt shake demonstrated that the kai-phum shake elicited a lower postprandial glucose peak. This depicts *W. globosa* as an emerging alternative plant protein source containing rich nutrients and offering beneficial postprandial glycemic effects, making it a great option for vegetarians seeking high-protein alternatives [17]. Furthermore, research proves that *W. globosa* is appreciated for its taste, texture, aroma, and nutritional content.

W. globosa can significantly convert traditional, heavily carbohydrate-based foods that lack adequate protein, micronutrients, and antioxidants into functional, nutritious options. Examples include pasta and the popular Thai snack Khanom Khai Nok Krata, where *W. globosa* can be incorporated while preserving the snack's sweet aroma, crispy exterior, and chewy interior [18]. Additionally, yogurt is a convenient staple food to modify with *W. globosa*, improving its baseline nutritional value while maintaining desirable taste, texture, and a refrigerated shelf life of up to two weeks [19] [20]. Another food innovation developed by researchers is protein hydrolysate-fortified porridge made from *W. globosa*. This high-protein functional food is especially suitable for elderly people because the protein is hydrolyzed into smaller peptides, making it easier to digest and absorb while providing enhanced nutritional benefits [21]. Beyond human nutrition, *W. globosa* can be applied to animal food, including dry kibble, wet food, high-protein treats, and functional pet snacks for dogs and cats. By providing essential vitamins and minerals, adding *W. globosa* to pet food prevents malnutrition and related diseases, ultimately helping to increase animal lifespan.

5. *Wolffia globosa* as Futuristic Food and Economics of Scale

Achieving economies of scale for *Wolffia globosa* requires transitioning from traditional, manual harvesting in open ponds to automated industrial biorefineries and controlled production systems. Manual collection and small-scale cultivation limit volume yield, increase labor costs, and result in inconsistent biomass quality. By deploying automated harvesting, continuous-flow dewatering, and controlled bioreactor or indoor vertical farming systems, large-scale facilities can dramatically boost areal biomass output while tightly controlling environmental parameters [23]. This industrial transition significantly lowers unit production costs, making *W. globosa* protein cost-competitive with conventional terrestrial crops.

Scaling up production through industrial vertical hydroponic systems preserves core environmental benefits while increasing overall biomass output. Conventional protein sources like soybeans and livestock require vast areas of arable land and high freshwater consumption. In contrast, closed vertical hydroponics and recirculating aquatic farms optimize vertical space and recycle water without competing for fertile agricultural land [24]. This structural efficiency allows scaled-up production to achieve exponential protein yields per hectare without driving deforestation, soil degradation, or land-use conflicts.

Industrial-scale production further reduces environmental and operational costs by integrating renewable energy infrastructures directly into cultivation facilities. Powering water circulation pumps, environmental sensors, and energy-intensive post-harvest processing steps such as drying and sterilization, with solar panels or wind turbines minimizes reliance on fossil fuels. Furthermore, utilizing closed-loop nutrient recirculation alongside renewable energy inputs drastically lowers overall greenhouse gas emissions, establishing a near-zero carbon footprint throughout the manufacturing cycle [22].

Achieving economies of scale provides a clear roadmap for integrating *W. globosa* into global commercial markets as an affordable and accessible staple food. Lowered manufacturing costs enable watermeal to transition from a regional delicacy into a mainstream functional ingredient used in everyday foods, functional beverages, and alternative protein matrices. This cost-effective, high-volume output directly fulfills the core directives of the BCG economy model by turning aquatic bio-resources into high-value functional protein while conserving natural ecosystems [25].

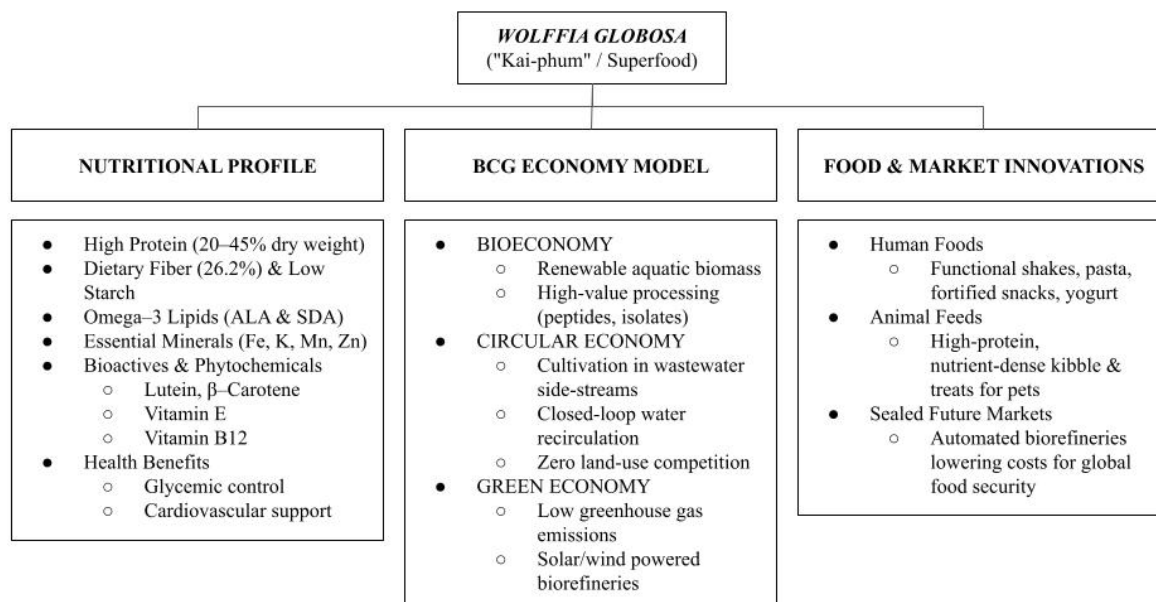


Figure 1. *Wolffia globosa* attributes and Bio-Circular-Green (BCG) economy integration

6. Conclusion

Addressing the global food crisis demands a paradigm shift away from resource-intensive animal agriculture toward innovative, sustainable plant proteins. As demonstrated across biological, nutritional, economic, and technological dimensions (Figure 1), *Wolffia globosa* (kai-phum) stands out as a next-generation superfood perfectly suited to meet this challenge. Its rapid growth kinetics, minimal land and water requirements, and capacity to thrive in recirculating side-stream systems make it an ideal engine for the Bio-Circular-Green (BCG) economy model. Nutritionally, *W. globosa* delivers high-quality protein, essential lipids, dietary fiber, and protective antioxidants, offering distinct functional benefits such as glycemic control and cardiovascular support. The versatility of *W. globosa* across food application innovations, ranging from traditional dish fortification and dairy alternatives to pet nutrition, proves its readiness for broad consumer adoption. Furthermore, scaling up production from localized community farming to automated, renewable-energy-powered biorefineries provides a clear pathway to lowering production costs and achieving true economies of scale. By aligning environmental sustainability with economic feasibility and regulatory readiness, *Wolffia globosa* represents a scalable, accessible, and high-impact solution for global food security, human health, and ecological restoration.

7. References

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