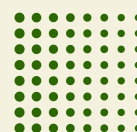




KASETSART
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AT SRIRACHA



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The proceedings of

The 7th Kasetsart University Sriracha Campus International Conference (KUSRC-IC 2025)

August 26, 2025 at Kasetsart University Sriracha Campus

"Green innovation for a Sustainable Future"



The proceedings of the 7th Kasetsart University Sriracha Campus
International Conference (KUSRC-IC 2025)
August 26, 2025

Subject: Engineering and Technology
Subject: Sciences and Applied Sciences
Subject: Economics and Applied Economics
Subject: Humanities and social sciences
Subject: Marine Science and Technology

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Preface

Kasetsart University Sriracha Campus is pleased to announce the 7th Kasetsart University Sriracha Campus International Conference (KUSRC-IC 2025) on the theme “Green Innovation for a Sustainable Future.” The conference will be held in Sriracha Campus, Chonburi, Thailand on August 26, 2025.

The objectives of the conference are to provide a platform for research students, researchers, and professors, to facilitate the exchange of knowledge and experiences among participants, to present research findings on both national and international stages, and to foster networks that may lead to future academic and research collaborations.

The conference will feature oral presentations of outstanding topics, reviewed by esteemed experts. These are categorized in Engineering and Technology, Science and Applied Science, and Humanities and Social Sciences.

The organizing committee of KUSRC-IC 2025 would like to express sincere gratitude to all participated academicians who are presenting their research, as well as to all attendees. Special thank goes to the committee members for their time, dedication, and contribution in making this conference a success.

(Associate Professor Sathaporn Chuepeng, Ph.D.)
Vice president for Sriracha Campus
for president of Kasetsart University
General chair of the conference

Keynote speaker

Dr. Fida Majdoub

LabECAM, ECAM La Salle

Université de Lyon, 69005, Lyon, France

Keynote speech of

“How barium titanate (BaTiO_3) nanoparticles in HDPE (high-density polyethylene) contribute to low friction applications”



Biography:

Dr. Fida Majdoub is an assistant professor of mechanical engineering at ECAM La Salle in France, with almost 10 years of experience in the field. She received her Ph.D. in Mechanical Engineering from Ecole centrale de Lyon in 2013. Her research focuses on the development of new friction laws in different mechanical applications. She has also worked in analyzing the contacts of bearings. Her interest is globally in investigating friction at contacts of various mechanical and bioengineering applications. She received two awards for her Ph.D. research. Dr. Majdoub is passionate about mentoring the next generation of engineers. She teaches mechanics, material science, tribology, and mechanical vibrations courses. Her talk today will focus on how barium titanate (BaTiO_3) nanoparticles embedded in high-density polyethylene (HDPE) can enhance low-friction performance, making the composite suitable for tribological applications.

Title: How barium titanate (BaTiO_3) nanoparticles in HDPE (high-density polyethylene) contribute to low friction applications



Keynote speaker

Dr.Charles Christian David

Senior Scientist,
New Zealand Institute for Bioeconomy
Science Limited.



Keynote speech of

“Beyond the Hype: Unveiling the flaws and contradictions of sustainability.”

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Experienced senior scientist and science director, dedicated to pursuing both fundamental and applied science. Over ten years of experience performing data analytics, developing leading scientific strategies, working with stakeholders to achieve robust and publishable research, and developing international collaborations that bring together the best minds to solve challenging problems.

Education

Ph.D. Bioinformatics and Computational Biology,	2012
University of North Carolina at Charlotte, NC. M.S. Applied Physics,	
University of North Carolina at Charlotte, NC.	2008
M.Ed. Secondary Education, University of Hartford, West Hartford, CT.	2000
Pre-Medical Program , St. Joseph College, West Hartford, CT.	1994
B.A. Physics , University of Hartford, West Hartford, CT	1990
Minor in Geology and Earth Sciences	

Professional Memberships

Biophysical Society	2008 – Present
American Physical Society	



Areas of Expertise

Independent Science Leadership

- Science leadership coherently blended with business acumen.
- Interdisciplinary approaches to global challenges

Modelling and Data Analysis

- Choosing the optimal framework for maximizing understanding
- Critical analysis of underlying assumptions

Statistical Analysis & Machine Learning

- Multivariate Statistics including PCA, Kernel methods, and Neural Networks

Software Design, Unit Testing & Simulation Studies

- Analytic software written in Java, Python, BASH, Perl, and R

Skills

- High Altitude Vision
- Team Building for effective collaborations
- Programming and Algorithm Design
- Workflow Design, Data Management & Analytics, Reproducibility



Conference program
The 7th Kasetsart University Sriracha Campus International Conference
(KUSRC-IC 2025)
"Green innovation for a sustainable future"
August 26, 2025

Time (Thailand Time)	Schedule of activities		
09.30 - 10.00	Registration (Building 13 Physical Education Center)		
10.00 - 10.15	The 7 th Kasetsart University Sriracha Campus International Conference (KUSRC-IC 2025) ceremony		
	Opening remarks by Assoc. Prof. Sathaporn CHUEPENG, Ph.D., Vice President for Sriracha Campus		
	Welcome speech by Mr. Damrong SRIPRARAM, Ph.D., Acting President of Kasetsart University		
10.15 - 10.35	Keynote Speech : "How barium titanate (BaTiO ₃) nanoparticles in HDPE (high-density polyethylene) contribute to low friction applications." Dr. Fida Majdoub ECAM LaSalle Engineering School, France.		
10.35 - 10.55	Keynote Speech : "Beyond the Hype: Unveiling the flaws and contradictions of sustainability." Dr. Charles Christian David Senior Scientist, New Zealand Institute for Bioeconomy Science Limited.		
10.55 - 11.15	Coffee break (PAK PI-RUN hotel)		
11.15 – 12.00	Visit the exhibition in celebration of the anniversary of Kasetsart University Sriracha Campus and enjoy the Kaset Sriracha fair 2025.		
12.00 – 13.00	Lunch (PAK PI-RUN hotel)		
Time (Thailand Time)	Oral Presentation (PAK PI-RUN hotel)		
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17.15 – 17.30	ID 011		
17.30 – 17.45	ID 015		
18.30 - 20.00	Networking night & Certificate awarding ceremony (Holiday Inn & Suites Siracha Laemchabang hotel)		



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The 7th KUSRC – IC International Conference 2025

Subject :

Engineering and Technology

Variation of PLA mechanical properties in one batch printing

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Abstract

This study investigates the variation in mechanical properties of polylactic acid (PLA) parts printed within one batch using fused deposition modeling (FDM) under identical process parameters. Previous studies have shown that factors such as layer height, print orientation, nozzle temperature, and raster angle significantly influence tensile strength and flexural modulus. To isolate these effects, this study controls all process variables and focuses on quantifying the mechanical property differences among PLA samples printed simultaneously under the same settings. Results reveal that even within a single batch, noticeable mechanical variations can occur despite consistent process conditions. These findings underscore the importance of accounting for intra-batch variability, particularly for quality-critical applications in additive manufacturing.

Keywords: PLA, FDM, Mechanical properties, Batch variation

1. Introduction

With the rise of Industry 4.0, additive manufacturing (AM) has emerged as a transformative technology, offering advantages such as material efficiency, design flexibility, and a reduced environmental footprint compared to traditional subtractive manufacturing. Among AM techniques, fused deposition modeling (FDM) is notable for its low cost, ease of operation, and widespread use of thermoplastics like polylactic acid (PLA), which is biodegradable and highly printable.

Previous research has extensively examined how process parameters including layer height, print orientation, nozzle temperature, and raster angle influence the mechanical properties of PLA components. However, limited attention has been paid to the mechanical variation within one batch of prints, where all process settings are held constant. This intra-batch variability may affect the reliability of FDM parts, especially in load bearing or dimensionally critical applications.

This study aims to characterize the

mechanical property variation among PLA parts printed within one batch under identical conditions, offering empirical insights for improving consistency in FDM applications.

2. Materials And Methods

Polylactic acid (PLA) was chosen due to its renewability, biodegradability, and excellent printability. The filament used was commercial-grade PLA (Verbatim, Mitsubishi Chemical Media Co., Ltd., Japan) with the following properties:

Table 1 PLA filament materials properties

Diameter:	1.75 mm
Density:	1.24 g/cm ³
Melt Flow Rate:	8.1 g/10 min (at 210 °C)
Glass Transition Temperature:	58 °C
Weight:	1kg



Figure 1 PLA filament material

Tensile specimens were designed according to the ASTM D638-02 standard. detail as shown in Figure 2

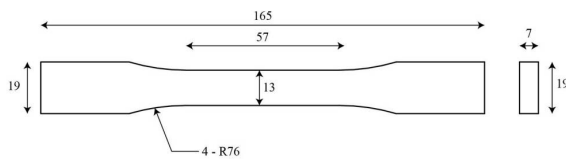


Figure 2 Sample size detail (Unit: Millimeter)

The printing machine is a 3D printer Zortrax M300 Plus from Polish 3D printing equipment manufacturer Zortrax, as shown in Figure 3 below.



Figure 3 Zortrax M300 Plus 3D printing machine

2.1 3D Printing and Storage

Fused Deposition Modeling (FDM) is widely used for its operational simplicity and material efficiency. Mechanical properties of printed parts are significantly influenced by key parameters such as build orientation, raster angle, infill density, layer thickness, and nozzle temperature (Harris, Potgieter, Archer, & Arif, 2019)

Prior studies show that edge build orientation yields superior tensile strength (Daoset, Inglam, Wanchat, & Chantarapanich, 2024; Selvamani et al., 2019), while a raster angle of $\pm 45^\circ$ enhances fatigue life (Shanmugam et al., 2021). Increasing infill density improves interlayer bonding and mechanical strength up to a threshold (Hodzic & Pandzic, 2021), while a layer thickness of 0.2 mm balances efficiency and print quality (Tymrak, Kreiger, & Pearce, 2014)

Nozzle temperature critically affects interlayer adhesion; 210 °C has been shown to optimize mechanical performance for PLA (Ala'aldin Alafaghania, 2017)

To ensure consistent quality and focus on within-batch variations, the samples were printed using a ZORTRAX M300 Plus fused deposition modeling (FDM) 3D printer equipped with a 0.4 mm nozzle, and the printing parameters were kept constant as shown in Table 2.

Table 2 FDM printing parameters

No	Description	Value	Unit
1	Build orientation	Edge	
2	Raster angle	$\pm 45^\circ$	
3	Infill density	70%	
4	Layer thickness	0.2	mm
5	Infill pattern	Patt 0 Grid	
6	Nozzle diameter	0.4	mm
7	Nozzle temperature	210	°C

These settings are based on literature consensus and ensure consistent print quality

across all samples.

After printing (Figure 3) and marking records (Figure 4), all specimens were stored in a climate-controlled chamber under ISO 291 conditions (23 ± 2 °C, $50 \pm 5\%$ RH) prior to testing.

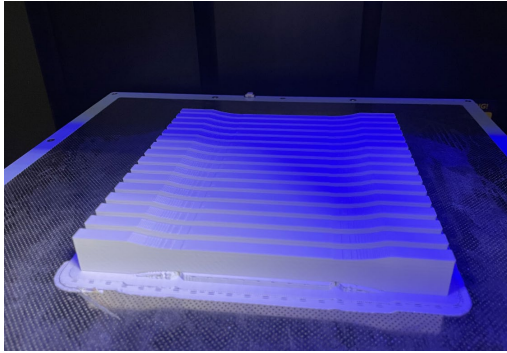


Figure 4 Specimen printing completed



Figure 5 Specimen mark

2.2 Mechanical Testing

Tensile tests were conducted using a universal testing machine (EMIC DL500, Instron Corp., USA) following ASTM D638. A gauge length of 50 mm was used. Testing was performed at 23 ± 2 °C and $50 \pm 5\%$ RH. 12 samples were tested in sequence, as shown in Figure 6; 4 additional samples were retained for future validation. Only tensile properties were considered, as they are the primary mechanical performance indicators for PLA.



Figure 6 Specimen tensile test

2.3 Data Collection and Processing

After the tensile tests of all samples were completed as shown in Figure 7, the mechanical data, including ultimate tensile strength, Young's modulus, and elongation at break, were systematically collected and processed. To ensure data integrity and reduce experimental variability, statistical outlier detection was performed, and outliers were excluded.

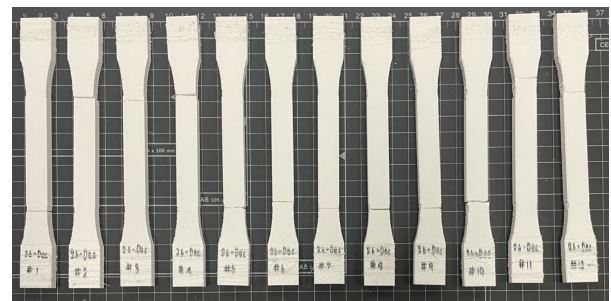


Figure 7 Specimen test completed

3. Results And Discussion

The tensile properties of PLA samples from the same batch and printed under the same parameters were tested. The results are shown in figure 7 below. Although the printing conditions are uniform, there are still obvious differences between the samples.

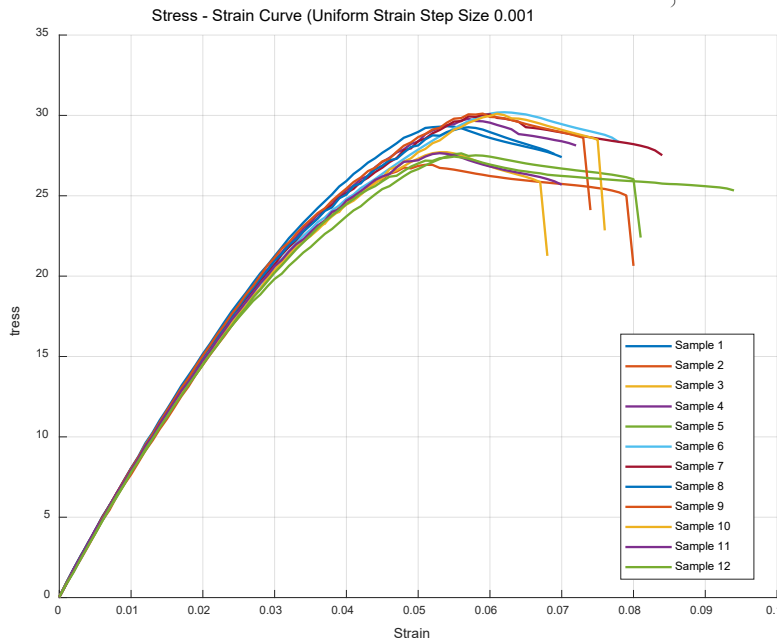


Figure 7 Stretching test trend

Table 3 Mechanical properties data of test samples

No.	Young's Modulus (MPa)	Tensile Strength (MPa)	Tensile stress at Break (Standard) [MPa]	Extension at Break (Standard) [mm]	Tensile stress at Maximum Load [MPa]	Load at Break (Standard) [N]	Load at Yield (Offset 0.2%)[N]	Maximum Load [N]
1	1999.22	28.93	27.27	3.43	29.57	2481.87	2632.63	2691.23
2	1923.70	27.17	24.42	3.84	27.61	2222.32	2472.47	2512.74
3	2000.90	29.03	27.50	3.87	30.06	2502.75	2641.57	2735.75
4	1950.54	28.61	27.08	3.59	29.92	2464.00	2603.56	2722.73
5	1813.96	26.34	25.06	3.99	27.59	2280.02	2397.22	2510.27
6	1734.86	25.31	26.38	3.87	28.74	2400.86	2303.10	2615.27
7	1905.86	28.00	28.69	3.83	30.72	2611.04	2547.60	2795.72
8	1915.41	26.83	25.65	3.96	28.20	2333.86	2441.96	2566.38
9	1971.35	28.18	28.17	3.86	30.50	2563.41	2564.67	2775.82
10	1890.43	26.06	25.36	4.17	27.53	2308.11	2371.26	2505.43
11	1756.78	26.59	26.87	3.72	29.19	2444.75	2419.61	2656.57
12	1703.98	27.46	27.82	4.19	29.93	2531.87	1703.98	2723.67
Avg	1880.58	27.38	26.69	3.86	29.13	2428.74	2424.97	2650.96
Max	2000.90	29.03	28.69	4.19	30.72	2611.04	2641.57	2795.72
Min	1703.98	25.31	24.42	3.43	27.53	2222.32	1703.98	2505.43

Tensile strength ranged from 25.31 MPa to 29.03 MPa with a standard deviation of 1.20 MPa, representing a relative variation from the mean of approximately 4.4%. Young's modulus ranged from 1703.98 MPa to 2000.9 MPa, suggesting a stiffness variation of nearly 14%.

Although all samples were printed under the same conditions, these results show that mechanical properties can vary. While these differences are not large, they can be critical for load bearing or tolerance-sensitive parts.

4. Conclusion

This study investigated the variation in mechanical properties of PLA parts produced within one FDM batch under consistent process settings. Despite consistent material, equipment, and environmental controls, measurable differences in tensile strength and stiffness were observed. The results demonstrate that mechanical property variations within a single batch can be significant enough to impact high-precision or load-bearing applications. This suggests that local inconsistencies may arise even in FDM processes conducted under strict control.

These results highlight the need for implementing intra-batch quality monitoring, especially in industrial-scale printing applications where consistency and performance reliability are critical.

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An Applied Linear Programming Approach to Efficient Access Point Deployment

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Abstract

Optimizing reliable Wi-Fi in high-density conference rooms is challenging due to signal issues and infrastructure limits. This paper proposes a cost-effective Access Point (AP) optimization using Linear Programming (Simplex Big-M), minimizing signal loss while ensuring full coverage and AP capacity. We introduce a cost-effective method for optimizing Wi-Fi Access Point (AP) placement in a 10m × 8m test room divided into 20 zones to create a cost matrix based on inverse RSSI. Five APs were evaluated using an inverse-square signal model to build a cost matrix. Linear Programming with the Simplex Big-M method in Excel Solver minimized deployment cost while meeting coverage and capacity constraints. In addition, before optimization, a basic equal-distribution strategy where each of the five APs was initially assigned four zones. After optimization, the model effectively allocated zones using five pre-defined AP positions. The central AP5 covered 8 zones, demonstrating superior signal reach. The four corner APs each covered 3 zones, ensuring comprehensive boundary coverage. This precise deployment shows the model's ability to optimize AP assignments based on signal strength and distribution requirements. Our results reflected that Linear programming highlighted successful in this optimized assignment, leading to reduced costs and comprehensive coverage. This study demonstrates LP-based optimization and realistic signal modeling provide a strong, practical Wi-Fi deployment solution. Excel Solver's accessibility makes it ideal for small-to-medium environments, avoiding specialized software.

Keywords: Wi-Fi, Optimization, Linear Programming (LP), Simplex model (Big-M), Signal Loss.

1. Introduction

The rapid growth of wireless devices and the increasing demand for seamless internet access underscore the critical need for robust and efficient indoor wireless network infrastructure. Conference rooms, in particular, present a significant challenge for Wi-Fi network planning due to their typical high user and device density. Realizing desired signal quality and comprehensive coverage in such confined and dynamic settings is complex, especially when balancing technical performance with deployment costs.

Optimal Access Point (AP) placement is vital to Wi-Fi network performance. Suboptimal AP distribution can lead to coverage gaps, significant interference, and inefficient resource utilization. Therefore, optimizing AP locations is crucial for both delivering high-quality connectivity and ensuring efficient infrastructure usage.

Traditional deployment approaches often rely on rule-of-thumb heuristics or manual adjustments, which may not consistently deliver optimal signal strength or reliable coverage.

Previous research has explored

systematic approaches to Wi-Fi network planning using various optimization techniques. For instance, **Li et al. (2015)** proposed a comprehensive model for indoor WLAN environments that considers both signal coverage and traffic capacity, emphasizing that effective AP placement must account for real-world signal propagation effects and user density [1]. Similarly, **Youssef and Agrawala (2008)** provided an extensive survey of AP deployment techniques, detailing various algorithmic and heuristic strategies applicable to indoor wireless planning [2].

A particularly promising approach involves leveraging mathematical programming methods, including linear programming (LP) and integer linear programming (ILP), to formalize and resolve the AP placement problem. **Ahmed and Owezarski (2009)** demonstrated that ILP formulations can effectively optimize WLAN deployments, leading to significant cost reductions while upholding coverage guarantees [3]. The Simplex method, specifically with the Big M formulation, offers a robust framework for addressing deployment problems with various constraints by incorporating artificial variables to ensure feasibility and convergence [4].

Furthermore, accurate modeling of signal strength and path loss is fundamental to the optimization process. Classical indoor propagation models, such as those by **Seidel and Rappaport (1992)**, provide a basis for realistic cost functions in AP-to-zone assignments by accounting for multi-path effects, attenuation due to walls, and distance-based signal decay [5].

This paper proposes a cost-effective AP optimization framework adapted for a 10m × 8m conference room. Utilizing the Simplex Big M method, the framework aims to minimize signal degradation while ensuring complete zone coverage. The model integrates realistic signal propagation estimates and capacity constraints. The results

will be visualized through heatmaps to both visually assess the Wi-Fi coverage and quantitatively measure it. This approach aims to connect the theoretical ideas of optimization with the practical work of designing wireless networks.

2. Optimization Framework

A. Problem Context

Wireless connectivity in indoor environments especially in high-density locations such as conference rooms faces significant challenges related to signal coverage, interference, and infrastructure cost. These environments demand a carefully planned distribution of Wi-Fi Access Points (APs) to ensure signal availability across all zones while avoiding overlaps, dead zones, and excessive hardware usage.

Access Point deployment has historically relied on heuristic or manual strategies, but such methods often fall short when subject to real-world complexities like irregular layouts, variable user distribution, and multipath signal fading. According to **Youssef and Agrawala (2008)**, indoor WLAN planning suffers from inefficiencies when heuristic methods alone are used, especially when coverage and capacity are both critical [2].

B. Signal Propagation and Cost Modeling

Reliable AP placement requires not only geometric planning but also accurate signal modeling. **Seidel and Rappaport (1992)** introduced a practical model for indoor signal attenuation based on room geometry and distance, showing that signal strength deteriorates rapidly with distance and environmental obstructions [5]. This model serves as the basis for cost definition in this thesis, where the cost between AP i and zone j is inversely proportional to the received signal strength:

$$c_{ij} = \frac{1}{P_r} = \frac{1+d^2}{P_t} \quad (1)$$

where;

P_r : Received signal power at zone j from AP i .

d : Euclidean distance between AP i and zone j .

P_t : Transmit power of AP (assumed constant, e.g., 100 units)

c_{ij} : Cost (inverse of signal strength); lower cost implies stronger signal

B. Overview of Linear Programming Methods for AP Optimization

Linear programming (LP) offers a powerful framework for optimizing resource allocation problems with linear objective functions and constraints. In the context of WiFi Access Point (AP) planning, LP enables the formulation of zone-AP assignments that minimize signal cost while adhering to coverage and capacity constraints. Common formulations include:

Standard Linear Programming: Used when variables are continuous and constraints are linear. It serves as a base for modeling cost functions or load balancing.

Integer Linear Programming (ILP): Extends LP by enforcing binary or integer constraints on decision variables—useful for discrete AP placement decisions (Ahmed & Owezarski, 2009) [3].

Mixed Integer Linear Programming (MILP): Combines integer and continuous variables, ideal for modeling systems with fixed AP positions and variable power levels (Li et al., 2015) [1].

Big M Method: A variant of the Simplex method that introduces artificial variables and large penalty constants (M) to solve problems with equality or $\geq$ constraints, ensuring feasibility during iterations (Winston, 2003) [4]

C. Use of Linear Programming and the Big M Method

Linear programming (LP), particularly the Simplex method enhanced with the Big M technique, has proven to be an effective tool for solving complex optimization problems in

wireless networks. The Big M method introduces artificial variables that carry large penalty values in the objective function, ensuring that strict equality and inequality constraints are satisfied during the solution process (Winston, 2003) [4]. This formulation is particularly suitable for AP deployment problems, where zone coverage, AP load limits, and signal quality must all be jointly optimized. Recent literature reinforces the relevance of LP techniques for wireless network optimization. For example, Ahmed and Owezarski (2009) demonstrated how integer linear programming can be used to optimize WLAN deployment strategies [3]. Moreover, newer multi-objective approaches continue to extend LP-based formulations to accommodate cost, coverage, interference, and user satisfaction (Oustry et al., 2023; Hernández et al., 2019) [6].

Summary of Approach

Grid Division: The conference room is partitioned into discrete zones to facilitate detailed analysis.

Signal Modeling: Utilization of advanced propagation models to estimate signal strength across zones.

Cost Matrix Development: Creation of a cost matrix reflecting the inverse relationship between signal strength and deployment cost. Constraint Design: Incorporation of coverage and capacity constraints to ensure practical applicability.

Optimization Process: Application of the Simplex Big M method to identify the optimal AP placement strategy.

This methodology offers a structured framework for AP deployment, aligning with contemporary research and addressing the complexities inherent in indoor wireless network planning.

D. Excel Solver Overview

Excel Solver is a built-in optimization tool in Microsoft Excel that allows users to determine the optimal values of decision variables to minimize or maximize an

objective function, subject to defined constraints [7]. It is widely used in engineering, business, and academic contexts due to its accessibility and user-friendly interface.

Solver Components

Objective Cell: Defines the target function to be optimized (either minimized or maximized).

Variable Cells: These represent the decision variables that Solver modifies to achieve the objective.

Constraints: Logical conditions or bounds that the solution must satisfy during the optimization process.

Optimization Algorithms

Simplex LP: Applied for linear programming problems.

GRG Nonlinear: Used for smooth nonlinear optimization problems.

Evolutionary Solver: Handles non-smooth, non-continuous, or complex models using a population-based approach.

Excel Solver is especially suitable for small to medium-scale for engineers and analysts who require a quick and effective means of performing linear and nonlinear optimization without the need for advanced or specialized software platforms [7].

3. Methodology

To validate our proposed method for optimizing Wi-Fi Access Point (Cisco Catalyst 9015 Series) placement using the Simplex Big M method, the experiment followed a structured process. It is started by creating a model of our physical environment—a 10m × 8m conference room. From there, it was moved through several steps: estimating signal strength, modeling costs, defining limitations (constraints), and finally, implementing the linear programming solution. This careful, step-by-step approach ensures that our AP placement is both cost-

effective and meets all necessary coverage requirements, aligning with recommendations from earlier wireless deployment research [3].

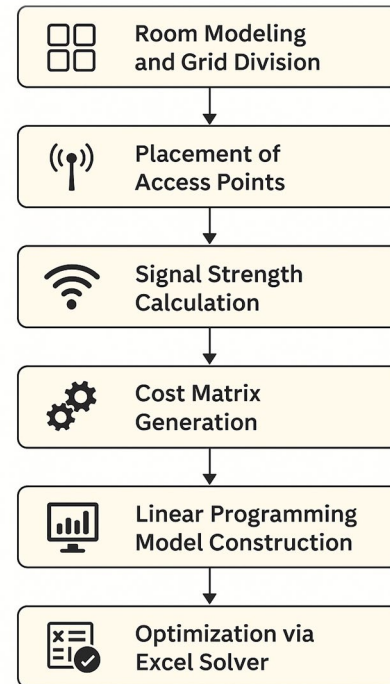


Figure 1. Flow chart of AP optimization procedure

Step 1: Room Modeling and Grid Division

The 10m x 8m conference room is sectioned into 20 zones, each 2m x 2m. Every zone must receive a signal from at least one AP.

Step 2: Placement of Access Points

Five APs were preselected based on ceiling or wall-mount feasibility, ensuring even spatial distribution and symmetry:

- AP1 (1, 1) Bottom-left corner
- AP2 (1, 7) Top-left corner
- AP3 (9, 1) Bottom-right corner
- AP4 (9, 7) Top-right corner
- AP5 (5, 4) Center of the room

These AP positions were chosen to offer optimal geometric coverage and minimize distance-based signal degradation across all zones. The center AP (AP5) is expected to

cover central zones efficiently, while the corner APs enhance edge zone coverage.

These fixed AP positions serve as inputs to the optimization model. The Simplex Big-M method then determines which AP should be assigned to each zone to minimize the total cost (i.e., maximize signal quality), while satisfying constraints such as full coverage and per-AP capacity limits.

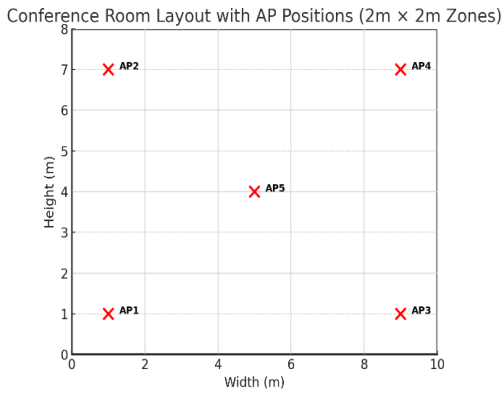


Figure 2. Layout of the Conference Room with Predefined Candidate AP Positions for Zone-Based Allocation

Step 3: Signal Strength Calculation

For each AP-zone pair, the Euclidean distance d_{ij} is calculated:

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (2)$$

The received signal strength P_r is computed using a simplified propagation model:

$$P_r = \frac{P_t}{1 + d_{ij}^2} \quad (3)$$

where $P_t = 100$ (arbitrary unit)

Table 1 Symbols for Signal Strength Calculation

Symbol	Definition
i	Index of Access Point (AP), where $i \in \{1, 2, \dots, m\}$
j	Index of zone (grid cell), where $j \in \{1, 2, \dots, n\}$
x_i, y_i	Coordinates of Access Point i in the 2D room layout
x_j, y_j	Coordinates of zone j in the 2D room layout
d_{ij}	Euclidean distance between AP i and zone j : $d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$
P_t	Transmit power of each AP (assumed constant, e.g., 100 units)
$P_{r,ij}$	Received signal strength at zone j from AP i
-	The term $1 + d_{ij}^2$ avoids division by zero and models signal attenuation
Units	All distances in meters; signal strength in arbitrary units

Step 4: Cost Matrix Generation

The cost of assigning AP i to zone j is the inverse of signal strength:

$$c_{ij} = \frac{1 + d_{ij}^2}{P_t^2} \quad (4)$$

This forms a 20×5 cost matrix to be used in the optimization.

Table 2 Matrix Cost Table

Zone ID	AP1	AP2	AP3	AP4	AP5
Zone1	c11	c12	c13	c14	c15
Zone2	c21	c22	c23	c24	c25
---	---	---	---	---	---
Zone N	cN1	cN2	cN3	cN4	cN5

Note: c_{ij} = cost of assigning Zone i to AP j

**Inverse signal strength → stronger signal
→ lower cost**

Step 5: Constraint Formulation

5.1: Define Binary Decision Variables

Let:

$$x_{ij} = \begin{cases} 1 & \text{if AP } i \text{ assigned to cover zone } j \\ 0 & \text{otherwise} \end{cases}$$

where;

$i \in \{1,2,3,5\}$ (5 APs)

$j \in \{1, 2,...,20\}$ (20 zones)

5.2: Coverage Constraint

Each zone j must be assigned to exactly one AP:

$$\sum_{i=1}^5 x_{ij} + a_j = 1 \forall j \in \{1, \dots, 20\} \quad (5)$$

a_j : Artificial variable added to allow feasibility in initial table (for Big M method)
This is an equality constraint and is handled using artificial variables in the Simplex Big M method.

5.3: AP Capacity Constraint

Each AP i can only cover up to k zones (e.g., 4 zones per AP):

$$\sum_{j=1}^{20} x_{ij} \leq k \forall i \in \{1,2,3,4,5\} \quad (6)$$

These are inequality constraints and require slack variables when converting to standard form.

5.4: Binary Assignment Constraint

Each decision variable x_{ij} must be either 0 or 1:

$$x_{ij} \in \{0,1\}$$

5.5: Formulate Artificial and Slack Variables

To convert constraints to the standard LP form:

Add artificial variables to equality constraints (for Big M penalty)

Add slack variables to $\leq$ inequalities (to track unused capacity)

5.6: Set up the optimization table for the Simplex method

$$Ax + s + a = b \quad (7)$$

where:

A : coefficients from the cost matrix

s : slack variables

a : artificial variables (penalized in objective function)

Step 6: Linear Programming Model Construction

Objective Functions

$$\min Z = \sum_{i=1}^m \sum_{j=1}^n c_{ij} x_{ij} + M \sum_k a_k \quad (8)$$

$x_{ij} \in \{0,1\}$: binary variable; 1 if AP i serves zone j

a_k : artificial variables added to meet equality constraints

M : a large constant (Big M) used to penalize infeasible solutions

Step 7: Optimization with Excel Solver

To implement the LP model, Excel Solver was used: [4]

Objective cell: Total cost Z

Variable cells: Binary variables x_{ij}

Constraints: Applied for zone coverage and AP capacity

Solver settings:

Solving method: Simplex LP

Variable type: Binary

Constraints: Equality and inequality as defined [7]

4. Results and Discussion

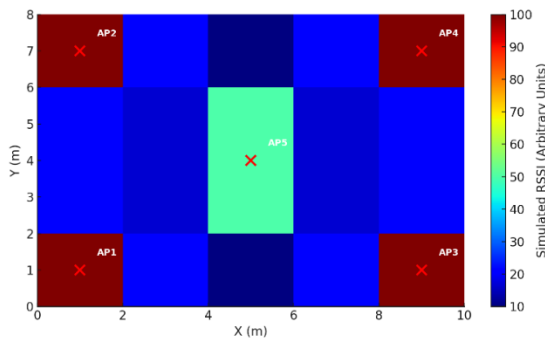


Figure 3: RSSI Heat Map

For a 10m × 8m conference room, it was evaluated five strategically placed Access Points (APs) to find the best way to assign them to zones. We analyzed 20 grid zones (2m × 2m), calculating RSSI (Received Signal Strength Indication) using a simple inverse square path loss model. The cost for each AP-zone connection was set as the inverse of its RSSI.

Excel Solver with the Simplex LP method was used to minimize total deployment cost. Strict rules were applied: each zone had to be covered by exactly one AP, and no AP could serve more than a set number of zones (e.g., ≤ 20). Solver then determined the optimal binary assignment (which AP serves which zone).

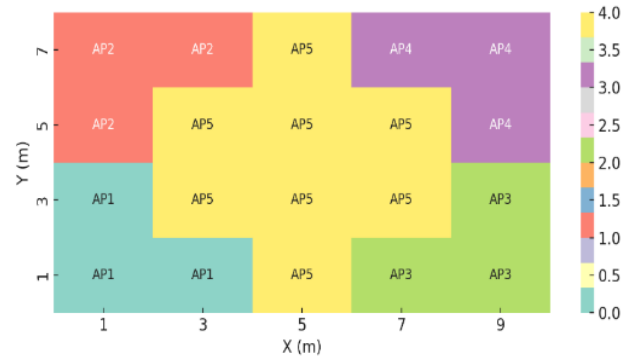


Figure 4: Zone-to-AP Dominance Map
(Strongest RSSI per Zone)

Our analysis showed that AP5 (centrally located) covered most zones due to its strong signal, while the corner APs (AP1–AP4) filled in boundary areas. As shown in Fig.4, "AP Dominance Map" confirmed this by showing which AP provided the strongest signal in each zone. This demonstrates that linear programming can effectively optimize AP placement in high-density indoor spaces with limited resources. All constraints were met, resulting in minimized cost and full coverage.

To assess how efficiently APs were assigned to zones, we contrasted our Simplex method's optimized results with a simple "equal-distribution" strategy. Initially, we assumed each of the five APs would serve four zones, ignoring signal strength. This uniform approach led to a higher estimated total cost of signal degradation, around 0.58.

After applying the Simplex method with RSSI-based cost modeling optimized zone assignments, significantly reducing total cost. The centrally located AP5 was assigned the most zones (8), while other APs covered the remaining outer areas. This resulted in a total cost of 0.92, demonstrating improved network efficiency and the value of optimization-based AP planning in indoor environments. Assignments are based on maximum RSSI while minimizing total cost which Represents cumulative signal degradation across all zone–AP links.

(Lower cost = better signal quality distribution)

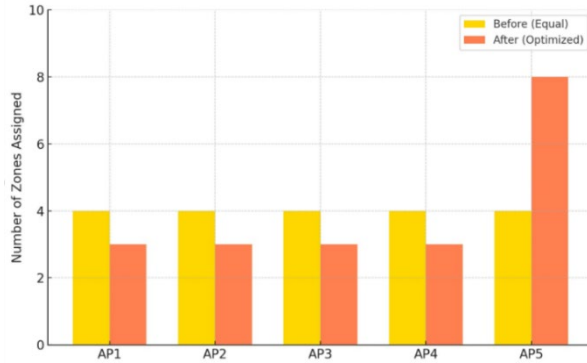


Figure 5: Zone Assignments per AP
(Before & After Optimization)

As per fig.5;

Total Zones Covered: 20

Total Cost ($\sum 1 / \text{RSSI}$): 0.92

Zone Allocation per AP:

- AP5 (center): 8 zones
- AP1 (bottom-left corner): 3 zones
- AP2 (top-left corner): 3 zones
- AP3 (bottom-right corner): 3 zones
- AP4 (top-right corner): 3 zones

Here is the analysis of the results for our AP optimization framework, which uses the Simplex Big-M method. We will discuss how effectively our zone-based AP allocation balances coverage, signal quality, and deployment cost. A room was successfully divided into 20 equal 2x2m zones, each assigned to one of five candidate APs. The optimization model ensured complete and non-overlapping coverage for every zone, proving the method can achieve full coverage even with a limited AP budget. According to Figure 5, a bar chart, confirms that no AP exceeded its capacity (20–25 zones/AP), validating the optimization model's capacity constraint. As expected, the centrally located AP5 covered the most zones, demonstrating efficient signal distribution.

The optimization successfully minimized the total cost, calculated as the sum of inverse RSSI values from assigned APs. This cost function effectively measures signal degradation with distance, meaning a lower cost indicates more efficient signal allocation. By assigning each zone to its best AP based on proximity and capacity, the model minimizes areas of weak signal strength. Using the **Simplex method with the Big-M formulation** allowed us to manage the "one AP per zone" equality constraint while penalizing impossible solutions. The method successfully converged in Excel Solver, proving its effectiveness for practical engineering problems with binary decisions and capacity limits.

5. Conclusions

This study successfully developed a cost-effective and constraint-aware methodology for optimizing Wi-Fi Access Point (AP) allocation within indoor environment, 10m × 8m conference room. The approach utilized linear programming with the Simplex Big-M method to achieve several key objectives: it ensured every 2m × 2m grid zone received coverage from exactly one AP, minimized a defined cost function reflecting signal quality degradation due to path loss (where lower cost indicated more efficient signal allocation), guaranteed no single AP was assigned more zones than its defined capacity, and demonstrated the practical application of complex optimization problems using readily available tools like Excel Solver.

Visualizations, including heatmaps and zone-assignment diagrams, confirmed that the optimized AP allocation was not only efficient in signal distribution but also balanced and practical. This was achieved without relying on manual tuning or heuristic methods, underscoring the significant value of structured linear optimization for wireless network planning.

6. Future Directions

While the current implementation effectively addresses AP deployment needs, several key improvements can significantly improve its real-world applicability:

Obstacle-aware Propagation: Integrate attenuation factors for walls and furniture into the signal propagation model to more accurately reflect complex indoor multipath environments.

QoS-aware Constraints: Introduce Quality of Service (QoS) metrics, including minimum signal thresholds, interference management strategies, or channel reuse optimization, to ensure better network performance.

Scalability and Advanced Solvers: Implement the optimization framework in more powerful tools like MATLAB, Python (utilizing libraries such as PuLP or Pyomo), or commercial solvers like Gurobi, to handle larger network layouts (e.g., 100+ zones) or multi-floor building designs.

Real-time or Adaptive Deployment: Apply this framework to reconfigurable AP systems, such as Wi-Fi mesh networks or mobile APs, allowing allocation and configuration to adapt dynamically based on real-time user demand and network conditions.

Acknowledgement

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Sustainable underwater autonomy: real-time docking with YOLOv9-YOLOv12

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Abstract

As demand for autonomous and sustainable marine operations grows, enhancing the performance of autonomous underwater vehicles (AUVs) has become increasingly important. A key challenge is accurately detecting docking stations in complex underwater environments, where visibility, turbidity, and acoustic noise impose significant constraints. In this work, the application of the latest YOLOv9 to YOLOv12 object detection architectures is explored to improve detection accuracy and real-time performance. Experiments were conducted on a public dataset captured in Abisko Lake, Sweden, under realistic underwater conditions. The proposed models are optimized for low-light underwater imagery. Among the evaluated architectures, YOLOv12 achieved the highest mAP@0.5 with a score of 0.995. However, YOLOv11 outperformed others in the more comprehensive mAP@0.5:0.95 metric, attaining a top score of 0.849, demonstrating the capability of modern lightweight detectors for real-time docking tasks. Among the evaluated models, YOLOv10 showed the best balance between accuracy and inference speed, making it the optimal choice for real-time deployment on resource-constrained underwater platforms. By minimizing computational load while maintaining accuracy, the system enables energy-efficient autonomous docking with minimal human intervention. This leads to extended mission durations, fewer surface deployments, and low-impact marine operations. The research highlights how advanced object detection contributes to robust, responsible underwater autonomy and supports the development of future-ready marine systems with reduced environmental footprints.

Keywords: Underwater object detection, YOLOv9-YOLOv12, AUVs, docking station

1. Introduction

Autonomous Underwater Vehicles (AUVs) play a vital role in subsea operations, including pipeline inspection, seabed mapping, marine habitat monitoring, and resource exploration [1],[2]. Their autonomy, mobility, and ability to operate without real-time human control make them ideal for missions in hazardous, remote, or deep-sea environments where traditional methods are costly, risky, or infeasible. The imperatives of climate change mitigation, carbon-neutral logistics, and ecosystem conservation are driving a global shift toward sustainable and

intelligent marine systems. There is increasing demand for scalable underwater robotic solutions that can operate continuously with minimal surface support [3],[4]. Autonomous docking is especially critical in this situation. It allows AUVs to return to a designated station to be retrieved onto a mother vessel for intermediate servicing, such as battery recharging, data downloading, health diagnostics, or maintenance [5],[6].

Despite these advantages, enabling reliable and precise autonomous docking remains a significant technical challenge.

Underwater environments are complex: visibility is often severely limited due to turbidity and low light; optical signals degrade rapidly with depth; and the presence of biofouling and occlusions further complicates perception [7]. In addition, sensor noise and dynamic disturbances such as ocean currents or moving objects introduce uncertainty in localization and path planning. These constraints place high demands on the perception systems of AUVs, particularly the ability to detect and localize docking stations in real-time with high accuracy and robustness. Traditional acoustic localization methods, such as USBL, have low accuracy (e.g., ± 0.3 m within 1,500 m) due to variations in multipath, noise, and sound speed.[8]

This has motivated a growing interest in deep learning-based detection algorithms that are more tolerant of environmental variability and capable of learning abstract features directly from raw sensor data. Among these, object detection frameworks such as the YOLO (You Only Look Once) [9] family have shown promise for real-time applications. Recent versions, from YOLOv9 to YOLOv12, enhance detection performance through improved feature aggregation, attention-based mechanisms, and NMS-free end-to-end architectures [10-13]. These advancements support higher accuracy and lower latency, making them well suited for real-time deployment on embedded and resource-constrained platforms such as AUVs, where efficiency and robustness are essential.

As underwater missions become longer, more complex, and environmentally critical, integrating robust, low-power, and accurate docking detection systems will be essential for advancing autonomous marine robotics. Such integration enhances operational resilience and mission autonomy and contributes to the broader vision of responsible, intelligent ocean stewardship.

2. Materials and Methods

2.1 Dataset

The dataset used in this study is publicly available and was collected during field trials at Abisko Lake, Sweden, as part of underwater visual docking research [14]. It consists of 1,600 images. The resolution of the images is 2048×1536 pixels, capturing an AUV docking station under diverse underwater conditions, including murky water, low-light environments, and varying turbidity. The dataset is divided into training, validation, and testing sets using an 8:1:1 split to ensure reliable evaluation throughout model development.



Figure 1 Example image of AUV docking station

2.2 YOLOv9–YOLOv12-Based Detection Framework

2.2.1 Architectural Overview

The YOLOv9 to YOLOv12 [10-13] represent the most recent advancements in the YOLO object detection family.

YOLOv9 employs the Generalized Efficient Layer Aggregation Network (GELAN), as its backbone architecture. This backbone is complemented by the Progressive Gradient Information (PGI) module, which enhances gradient flow during training through auxiliary gradient branches. The PGI enables deeper networks to converge more effectively by facilitating improved gradient propagation. In inference, YOLOv9 simplifies the architecture by utilizing only a single main branch, which balances computational efficiency with high accuracy.

YOLOv10 introduces a backbone

composed of Rank-Guided Compact Inverted Blocks (CIB) integrated with Cross Stage Partial Networks (CSP). This design leverages rank analysis to reduce redundancy and improve feature extraction efficiency. A key innovation in YOLOv10 is the dual-head label assignment strategy, which enables a one-to-many label assignment during training and a one-to-one assignment during inference, effectively eliminating the need for Non-Maximum Suppression (NMS) and thereby reducing inference latency. Additionally, YOLOv10 incorporates spatial channel decoupled down sampling in the neck to optimize feature representation and employs a lightweight detection head that accelerates inference without sacrificing accuracy.

YOLOv11 further refines the backbone by utilizing the C3K2 module, which reduces the number of parameters while maintaining sufficient network depth for robust feature extraction. The neck architecture is enhanced with Spatial Pyramid Pooling Fast (SPPF) modules combined with Convolution plus Parallel Spatial Attention (C2PSA), which facilitate improved multi-scale feature fusion and better detection of small objects. The detection head in YOLOv11 supports a modular multi-headed design that enables multi-task learning, allowing the network to perform object detection, segmentation, and key point estimation simultaneously.

YOLOv12 adopts the Residual Efficient Layer Aggregation Network (R-ELAN) backbone, which combines residual connections with efficient feature aggregation to maximize representational capacity while minimizing redundancy. YOLOv12 introduces advanced attention mechanisms, including area attention and flash attention, which efficiently capture global contextual information with reduced computational overhead. Architecture also employs large-kernel separable convolutions to expand the receptive field without significantly increasing the

computational cost. Emphasizing scalability and deployment on embedded systems, YOLOv12 incorporates quantization-aware training and layer pruning techniques to reduce model size and accelerate inference.

2.2.2 Training Configuration

All models (YOLOv9-YOLOv12) were trained using identical configuration settings to ensure consistency and comparability. The training used Ultralytics version 8.3.163 and PyTorch version 2.0.1+cu117, and the training was performed for 300 epochs with a batch size of 16 and input image size of 640×640. Early stopping was applied with a patience of 30 epochs.

The mosaic augmentation was enabled at full strength (mosaic: 1.0), with horizontal flipping applied with a 50% probability. The optimizer followed a warm-up phase for 3 epochs with warmup momentum of 0.8 and a bias learning rate starting at 0.1. The detection loss was composed of a box regression loss (weight 7.5), classification loss (weight 0.5), and distribution focal loss (weight 1.5).

3. Results and Discussion

All models, including YOLOv9 and YOLOv12, were assessed on underwater docking imagery captured in Abisko Lake, Sweden, to evaluate their detection performance and real-time suitability. The objective was to determine the optimal model balancing accuracy, inference speed, and computational efficiency for sustainable deployment on AUVs. From the experimental results, YOLOv12 achieved the highest detection accuracy with mean average precision at an Intersection over Union (IoU) threshold of 0.5 (mAP@0.5) of 0.995, demonstrating strong performance in identifying docking stations in visually complex underwater conditions. However, it recorded the lowest inference speed at 175 Frames Per Second (FPS). YOLOv10 offered the most balanced performance, combining high accuracy mAP@0.5 of 0.991 and mean average precision averaged over multiple IoU

thresholds from 0.5 to 0.95 in steps of 0.05 (mAP@0.5:0.95) of 0.846 with the highest inference speed of 256 FPS and the lowest Giga Floating Point Operations Per Second (GFLOPs) at 6.5. These attributes make YOLOv10 especially suitable for real-time applications on energy-constrained embedded platforms. Although YOLOv11 delivered the highest mAP@0.5:0.95 at 0.849, its gain in precision did not translate into significant improvement in efficiency, with moderate FPS (238) and slightly larger parameter size. YOLOv9, while having the smallest model size and moderate FPS (185), showed the lowest detection accuracy, indicating its limitations compared to newer versions, as shown in Table 1.

Table 1 Performance Comparison of YOLOv9 to YOLOv12

YO LO mo- del	mAP @0.5	mAP @0.5: 0.95	FPS	Params (M)	GLOPs
V9	0.965	0.785	185	1.971	7.6
V10	0.991	0.846	256	2.265	6.5
V11	0.949	0.849	238	2.582	6.3
V12	0.995	0.814	175	2.557	6.3

4. Conclusion

This study evaluated the performance of YOLOv9 to YOLOv12 models for real-time docking detection in AUVs, focusing on sustainable underwater autonomy. Results demonstrated that while YOLOv12 achieved the highest mAP@0.5, YOLOv10 offered the best balance between accuracy, processing speed, and computational efficiency. YOLOv10's superior FPS and lower GLOPs make it particularly suitable for deployment on resource-constrained underwater platforms requiring real-time responsiveness. These findings highlight the potential of advanced YOLO architectures to enhance the reliability and sustainability of underwater docking operations, contributing to more autonomous and efficient underwater missions.

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Energy Performance Analysis of Two-Story Residential Buildings Using Building Information Modeling (BIM): A Case Study of a Housing Development Project

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Abstract

Energy consumption in the residential sector is a crucial factor affecting the overall national energy usage, especially in tropical climates like Thailand. This study aims to evaluate the energy performance of two-story residential buildings using Building Information Modeling (BIM) as the primary analytical tool. The case study focuses on a housing unit in a residential development project located in Nakhon Ratchasima Province, with a usable floor area of 175 square meters and a hipped roof covered with concrete tiles. A BIM model was developed using Autodesk Revit 2024 and analyzed through Autodesk Insight to assess energy performance indicators, including Energy Use Intensity (EUI), cooling load, Solar Heat Gain Coefficient (SHGC), and daylight autonomy. A comparative analysis was conducted between the baseline scenario and passive design strategies such as building orientation adjustment, the use of reflective roofing materials, the addition of thermal insulation, and the installation of shading devices. The results indicated a significant reduction in EUI. This study demonstrates the potential of BIM in supporting the design of energy-efficient residential buildings and offers a preliminary framework for the sustainable development of housing design in residential projects.

Keywords: Building Information Modeling, Energy performance, Residential building, BIM simulation, Sustainable design

1. Introduction

Background and Significance of the Problem
At present, energy consumption in the residential sector has shown a continuous upward trend, particularly in Thailand, which is located in a tropical climate zone. Air-conditioning systems and electricity consumption for cooling play a crucial role in daily life. Data from the Ministry of Energy indicates that the residential sector is among the major energy-consuming sectors, which directly affects national energy management and contributes to greenhouse gas emissions that cause global warming. The number of housing development projects in urban and suburban expansion areas is rapidly increasing. Most of the house designs in these projects are typically developed according to

general commercial standards without proper consideration for energy efficiency. This results in unnecessary energy losses and long-term high electricity costs. Therefore, improving house designs to enhance energy efficiency has become an essential issue that requires further study. Building Information Modeling (BIM) technology has been widely recognized as an effective tool to improve the efficiency of building design, construction, and energy performance analysis. Applying BIM in combination with energy simulation software, such as Autodesk Insight, provides a means to accurately assess the impact of various design factors from the early stages of a project. Therefore, this research is significant as it aims to study and compare the energy performance of two-story residential houses in

a housing development project using BIM simulation. The study also seeks to identify passive design strategies that effectively reduce energy consumption and can be practically implemented in residential communities.

1.2 Research Objectives

1.2.1 To create a Building Information Modeling (BIM) model of a two-story residential house.

1.2.2 To analyze energy-related indicators, such as Energy Use Intensity (EUI), Cooling Load, Solar Heat Gain Coefficient (SHGC), and Daylight Autonomy.

1.2.3 To compare the results between the original house design and the passive design strategies.

1.3 Scope of the Study

1.3.1 Building model for the study: A two-story residential house with a usable floor area of 175 m².

1.3.2 Study area: A housing development project in Nakhon Ratchasima Province.

1.3.3 Software used: Autodesk Revit 2024 and Autodesk Insight.

1.3.4 Variables for passive design analysis: Building orientation, fiberglass roof insulation, ceramic coating, reflective glass, and aluminum shading devices (louvers).

2. Literature Review and Related Theories

2.1 Building Location Analysis

Nakhon Ratchasima Province is located at approximately 14.97° N latitude and 102.08° E longitude, situated on the Khorat Plateau, with an average elevation of around 200 meters above sea level. This location results in a climate that is generally hot, with a distinct wet and dry season. The annual average temperature is approximately 26.7 °C (80.1 °F). April is the hottest month, with temperatures reaching 36–37 °C, while December is the coolest month, with temperatures dropping to around 18–19 °C.

The annual rainfall is approximately 1,100–1,150 mm, with the highest rainfall occurring

in September (about 186–235 mm) and the lowest in December (only a few millimeters). The average annual relative humidity is around 65–70%, peaking at 80% during the rainy season [1].

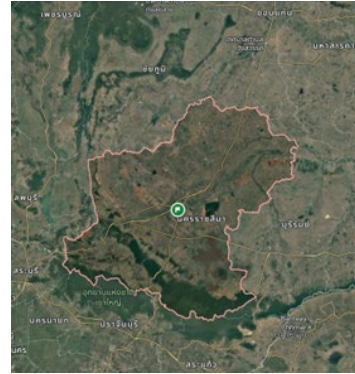


Figure 1. Building Location for Analysis

2.2 Energy Use Intensity (EUI)

Energy Use Intensity (EUI) is an indicator that measures the amount of energy consumed by a building per unit of gross floor area, expressed in kWh/m²·year. It serves as a standardized metric for comparing the energy performance of different buildings or alternative design scenarios.

EUI is a key variable in evaluating energy-efficient building design because it translates the results of energy simulations into a quantifiable figure that can be directly compared with national or international benchmark standards.

$$\text{Equation EUI} = \frac{\text{Annual Energy Consumption (kWh/year)}}{\text{Gross Floor Area (m}^2\text{)}} \quad (1)$$

EUI = Energy Use Intensity (kWh/m²·year)

Annual Energy Consumption = Total energy used by the building in one year (kWh/year)

Gross Floor Area = Total usable floor area of the building (m²)

2.3 Cooling Load

Cooling load refers to the total amount of heat entering a conditioned space—such as an air-conditioned room, cold storage, or indoor

area—which must be removed to maintain the desired temperature and humidity levels. The sources of this heat load include:

1. Heat transfer through external walls, roofs, and windows
2. Heat transfer through internal walls, ceilings, and floors
3. Solar radiation transmitted through windows
4. Heat generated by electrical systems and lighting
5. Heat generated by occupants
6. Heat from machinery and equipment
7. Heat from outdoor air infiltration through openings and from ventilation systems [6]

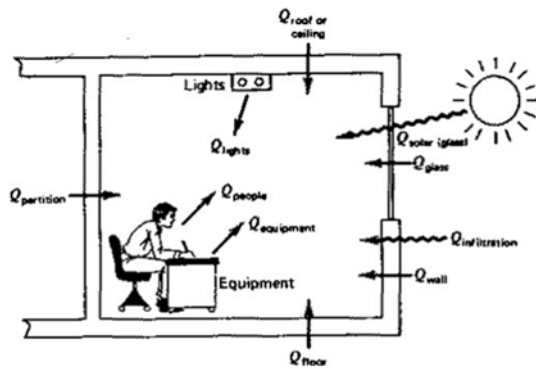


Figure 2. Cooling Load Heat Transfer Through Opaque Walls and Roof

$$\text{Equation } Q = U \times A \times \Delta T \quad (2)$$

Q = Amount of heat transfer (W or kW)

U = Overall heat transfer coefficient (U-value) of the wall or roof ($\text{W/m}^2 \cdot \text{K}$)

A = Surface area of the wall or roof exposed to the outdoor environment (m^2)

ΔT = Temperature difference between indoor and outdoor surfaces ($^{\circ}\text{C}$ or K)

Building Envelope System

The building envelope refers to the protective barrier that separates the outdoor environment from the indoor conditioned space. It includes exterior walls, fenestration (windows and openings), and roofs, all of which significantly affect heat transfer, daylight availability, and moisture protection [9].

Overall Thermal Transfer Value (OTTV)

The Overall Thermal Transfer Value (OTTV) is the average rate of heat gain into a building through its external walls, including both opaque walls and fenestration. It is expressed in W/m^2 and serves as a key index for evaluating how much heat is transmitted through the building envelope into the interior space.

$$\text{Equation OTTV} = (U_w \times (1WWR) \times \Delta T) + (U_f \times WWR \times \Delta T) + (SHGC \times WWR \times SF) \quad (3)$$

U_w = U-value of opaque wall ($\text{W/m}^2 \cdot \text{K}$)

U_f = U-value of fenestration/glass ($\text{W/m}^2 \cdot \text{K}$)

WWR = Window-to-Wall Ratio (ratio of total window area to total wall area)

$SHGC$ = Solar Heat Gain Coefficient of glass

SF = Solar Factor of the wall, based on orientation and shading conditions

Roof Thermal Transfer Value (RTTV)

The Roof Thermal Transfer Value (RTTV) represents the average heat gain through the roof per unit roof area, expressed in W/m^2 . This indicator is widely used to evaluate the thermal performance of roof systems in relation to heat transfer into the building. Lower RTTV values indicate better roof insulation and reduced heat gain, which directly contributes to lower cooling loads and improved building energy efficiency.

$$\text{Equation RTTV} = U_r \times \Delta T + SFr \quad (4)$$

U_r = U-value of the roof ($\text{W/m}^2 \cdot \text{K}$)

ΔT = Temperature difference between outdoor and indoor surfaces ($^{\circ}\text{C}$)

SFr = Solar Factor of the roof, depending on material type and surface color

2.4 Solar Heat Gain Coefficient (SHGC)

The Solar Heat Gain Coefficient (SHGC) is the ratio of the total solar radiation incident on a glazing surface that contributes to heat gain inside the building. The SHGC ranges from 0 to 1, where a lower value indicates that the glass effectively reduces solar heat gain, thereby

lowering the building's cooling load and energy consumption. Conversely, a higher SHGC value indicates greater solar heat admission, which may be desirable for spaces requiring passive solar heating. Typical SHGC values include: Clear float glass: approximately 0.85–0.90 Low-E or reflective glass: approximately 0.20–0.45, commonly used in energy-efficient buildings

$$\text{Equation } Q_{\text{solar}} = A_{\text{glass}} \times \text{SHGC} \times I_{\text{solar}} \quad (5)$$

A_{glass} = Glass area (m^2)

SHGC = Solar Heat Gain Coefficient of glass

I_{solar} = Solar irradiance (W/m^2) based on orientation and time of day

2.5 Daylight Autonomy (DA)

Daylight Autonomy (DA) is an indicator that measures the capability of an indoor space to utilize natural daylight without relying on artificial lighting during daytime. DA is expressed as the percentage of occupied hours during which the illuminance in a specific area exceeds the target illuminance level. The target illuminance is typically defined according to lighting design standards, for example: Residential or general office spaces: 300–500 lux. A higher DA value indicates that the space can rely more on natural light, which contributes to reduced artificial lighting demand and lower overall energy consumption.

$$\text{Equation } DA(\%) = \frac{(t_{\text{daylight}} \geq E_{\text{target}})}{t_{\text{total}}} \times 100 \quad (6)$$

$DA(\%)$ = Daylight Autonomy, expressed as a percentage of occupied hours

$t_{\text{daylight}} \geq E_{\text{target}}$ = Hours when daylight $\geq$ target illuminance (hours/year)

t_{total} = Total annual occupied hours (hours/year)

2.6 Building Location and Orientation in Nakhon Ratchasima Province

Building location and orientation are

critical factors influencing thermal comfort and energy performance. Proper site planning that aligns the building with the solar path, prevailing wind directions, and rainfall patterns in Thailand can significantly reduce cooling loads and electricity consumption. Nakhon Ratchasima Province, located in the northeastern region of Thailand, lies approximately at latitude 14.97°N and longitude 102.08°E on the Khorat Plateau. The climate is classified as Tropical Savanna (Aw) under the Köppen climate classification, characterized by three distinct seasons:

1. Hot season (February–May):

- Average maximum temperature: $35\text{--}37^\circ \text{C}$
- The sun travels almost directly overhead, causing east- and west-facing facades to receive the most solar radiation.
- Orienting the long axis of the building along the north–south direction helps minimize direct solar heat gain.

2. Rainy season (June–October):

- Heavy rainfall occurs under the influence of the southwest monsoon, with wind flowing from southwest to northeast.
- Designing openings along the prevailing wind direction facilitates natural ventilation and reduces indoor heat accumulation.
- Eaves and overhangs are essential for preventing rain penetration, particularly on southwest-facing walls.

3. Cool season (November–January):

- Cooler and drier conditions prevail, with winds blowing from the northeast.
- Buildings can utilize natural ventilation during this period to maintain comfort without mechanical cooling.

By considering seasonal solar exposure, prevailing wind patterns, and rainfall orientation, building orientation strategies in Nakhon Ratchasima can enhance passive cooling and reduce energy consumption, supporting sustainable and energy-efficient residential design.

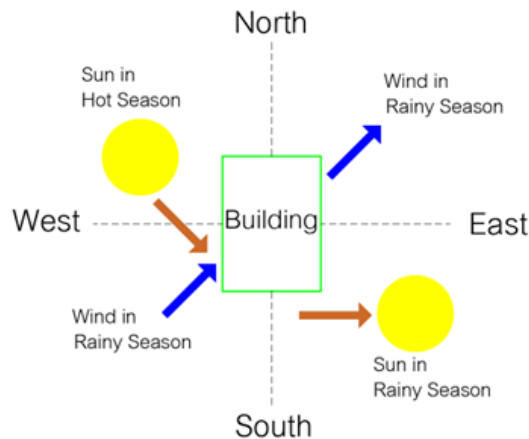


Figure 3. Building Orientation Guidelines

2.7 Building Information Modeling (BIM)

Building Information Modeling (BIM) is a process of creating and utilizing a three-dimensional digital model of a building that systematically integrates both physical and material properties. BIM not only represents the geometric characteristics of a building, such as its shape and dimensions, but also stores detailed information about materials, structural systems, building services, energy performance, and maintenance requirements. BIM has become a critical tool throughout the entire building lifecycle from design and construction to operation, maintenance, and future renovation. In the context of building energy analysis, BIM can be linked with energy simulation software such as Autodesk Insight, DesignBuilder, or EnergyPlus to evaluate key energy performance indicators, including: Energy Use Intensity (EUI), Cooling Load, Overall Thermal Transfer Value (OTTV) / Roof Thermal Transfer Value (RTTV), Daylight Autonomy (DA). The application of BIM in building design allows designers to test and analyze energy-saving strategies during the early design stage, helping to minimize construction errors, enhance energy efficiency, and support accurate engineering decision-making throughout the project.

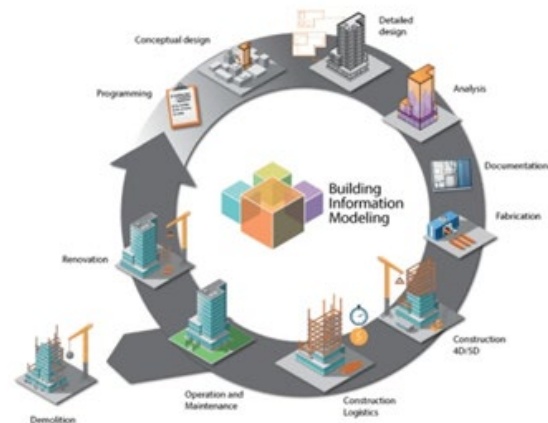


Figure 4. BIM Lifecycle

2.8 Application of BIM in Building Energy Performance Analysis

Autodesk Revit is a widely recognized building design software in the fields of architecture and civil engineering, capable of creating comprehensive Building Information Modeling (BIM) representations that integrate complete building data. This information can then be developed into an Energy Analytical Model (EAM) to evaluate the energy performance of buildings. The BIM-based energy analysis workflow generally involves the following steps:

1. Developing a complete building model in Autodesk Revit, including geometry, materials, and building systems.
2. Converting the model into an Energy Analytical Model (EAM) by defining the building location and climate data through the Energy Optimization settings, ensuring alignment with the real construction site conditions.
3. Exporting the analytical data to energy simulation software such as Autodesk Insight, Green Building Studio, or Energy Plus to calculate key energy performance indicators, including: Energy Use Intensity (EUI), Cooling Load, Solar Heat Gain By using Revit in

combination with energy simulation software, designers can accurately evaluate energy performance during the early design stage, support informed engineering decision-making, and enhance systematic energy-efficient building design.

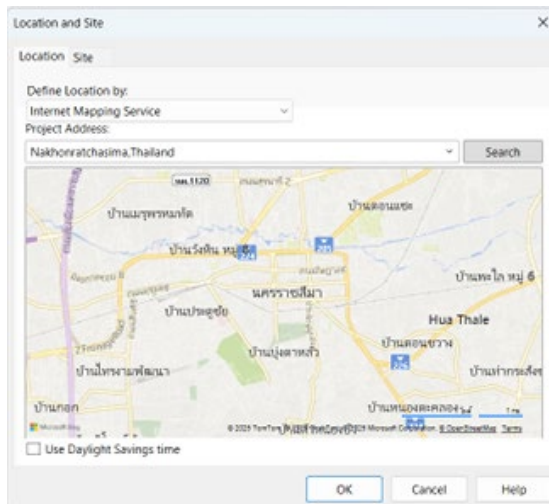


Figure 5. Location Command Panel

3. Research Methodology

This study on energy performance analysis of two-story residential houses using Building Information Modeling (BIM): A case study of a housing development project was conducted through six main steps, as illustrated in Figure 6.

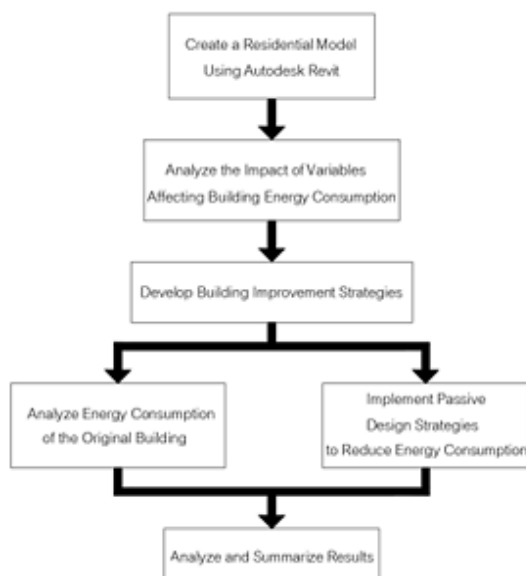


Figure 6. Research Procedure Flowchart

3.1 Development of a Residential Building Model Using Autodesk Revit for Energy Performance Analysis

This research focuses on creating a residential building model using Autodesk Revit to analyze the energy performance of the house. A standard housing prototype from a development project in Nakhon Ratchasima Province [4] was selected, as shown in Figure 7, which is designed to accommodate the modern lifestyle of residents. During the research process, a three-dimensional Building Information Modeling (BIM) model was developed, incorporating architectural, structural, and material data. This model was then used for energy performance analysis, including: Energy Use Intensity (EUI), Cooling Load, Energy-saving potential. The integration of BIM modeling with energy analysis supports the design of more energy-efficient residential houses, providing insights for improving energy performance in housing developments.



Figure 7. Residential Building Model

3.2 Analysis of the Impact of Variables Affecting the Energy Consumption of the Original Building

In this study, the impact of building orientation and positioning on energy consumption was analyzed using Autodesk Revit to develop a Building Information Modeling (BIM) model for energy simulation. The initial building orientation was set at 0° facing north, with the front facade oriented toward the north. The orientation was then rotated clockwise in 90° increments to analyze

the following positions: East: 90°, South: 180°, West: 270°. Energy performance indicators were evaluated for each orientation, including: Energy Use Intensity (EUI), Cooling Load, Solar Heat Gain Coefficient (SHGC), Daylight Autonomy (DA). The analysis results indicated that the west-facing and south-facing facades contributed the highest energy loads, suggesting that these orientations require targeted passive design improvements to enhance overall building energy performance.

3.3 Development of Building Material Improvement Strategies

This part of the research focuses on analyzing building surfaces that receive intense solar exposure during the afternoon, which leads to heat accumulation and increased cooling loads. The improvement strategies were developed using solar radiation analysis as a guideline for selecting and modifying building materials. The analysis was conducted using the Solar command within Autodesk Insight, which functions as an add-in for Autodesk Revit. This tool enables the evaluation of solar energy impact on building surfaces, providing a visualization of solar radiation intensity on each facade. By identifying areas with high solar heat gain, it becomes possible to determine the most critical building surfaces for passive design intervention. Following the solar analysis, passive design improvement scenarios were created and compared with the original building model to determine the optimal building material modifications that result in maximum energy savings.

3.4 Analysis of Building Material Energy Performance for Energy Reduction

This step of the study focuses on evaluating the energy-saving potential of building materials by analyzing the effect of adding or modifying materials on the building's energy performance. The investigation targeted the facades exposed to the highest solar radiation, which contribute to maximum heat accumulation and increased cooling loads. These areas were selected for passive design

interventions to reduce energy consumption. In this research, four material improvement strategies were studied: Adding 3-inch fiberglass insulation to the ceiling beneath the roof, Applying ceramic coating to exterior walls, Replacing windows with reflective glass, Installing aluminum shading devices (louvers). The analysis compared the energy performance of the original building with modified building scenarios, including improvements to two critical facades-west and south-which receive the highest solar radiation. This comparative study identifies which material modifications contribute most effectively to energy savings and cooling load reduction in the residential building.

Table 1. Building Improvement Strategies

Improvement Study	Improvement Scenario	Ceiling + 3" Fiberglass Insulation	Ceramic Coating	Reflective Glass	Aluminum Sunshade
West & South Facades	1	/	/	/	/
	2	/	/	/	/

4. Results and Discussion

This study analyzed the energy performance of a two-story residential building using Building Information Modeling (BIM) for a housing development case study. The research examined the impact of building orientation and positioning through four orientation scenarios and proposed building improvement strategies to reduce energy consumption. The improvements targeted the facades with the highest energy demand, which were identified as the west and south orientations. The analysis results are divided into two main parts as follows.

4.1 Analysis of the Impact of Building Orientation on Energy Consumption

The impact of building orientation and positioning on energy consumption was evaluated using Autodesk Revit by simulating the cooling load for four different orientations of the building. The initial orientation was set at 0° (north-facing facade), and the model was then rotated clockwise in 90° increments to analyze the following orientations: 0° (North-facing),

90° (East-facing), 180° (South-facing), 270° (West-facing). The BIM-based energy simulation results identified the orientations with the highest and lowest cooling loads, providing a clear basis for targeting passive design improvements. The west-facing facade (270°) demonstrated the highest solar heat gain and cooling demand, while the north-facing facade (0°) exhibited the lowest energy load.

Table 2. Building Orientation and Energy Consumption

Building Orientation	Azimuth (°)	Energy Intensity (kWh/m ²)	Use
North	0	63,398	
East	90	65,233	
South	180	65,397	
West	270	66,435	

4.2 Results of Passive Design Building Material Improvements

In this study, the Solar command in Autodesk Insight served as a key tool for analyzing and evaluating the impact of solar radiation on the building. Insight operates in conjunction with the Building Information Modeling (BIM) model created in Autodesk Revit, enabling accurate 3D simulation of solar radiation on building surfaces. The Solar analysis workflow begins with the following steps: Set the building location (Latitude and Longitude) to match the actual project site. Define the building orientation according to the design configuration. Adjust date, time, and seasonal conditions to simulate the sun path and solar position [7]. The program then calculates the solar radiation (kWh/m²) received on each building surface using weather data from the EPW (EnergyPlus Weather File). The output of the Solar command is presented as a heat map overlaid on the building surfaces, which visually identifies areas with high and low solar exposure. This analysis provides guidance for passive building material improvements by pinpointing the facades and roof areas most affected by solar heat gain.

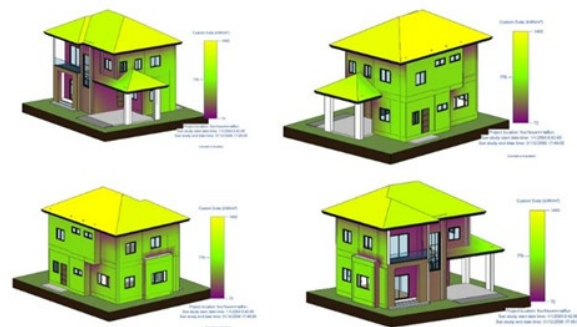


Figure 8. Solar Analysis Using the Solar Command

The solar radiation analysis revealed the following annual solar exposure on each building facade: North facade (front of the building): 1,470 kWh/m², East facade: 1,480 kWh/m², South facade: 1,503 kWh/m², West facade: 1,511 kWh/m². The west facade exhibited the highest solar radiation, followed by the south, east, and north facades, respectively [5]. Based on these results, the south and west facades were selected as the primary focus for passive building material improvement strategies, aiming to reduce solar heat gain and overall energy consumption.

4.3 Results of Passive Design Building Material Improvement Analysis

The results of the two passive building material improvement strategies, as described in Section 3.4, were evaluated to determine their impact on building energy performance. The analysis focused on the building orientations with the highest cooling load, identified in the earlier simulation, to implement targeted passive material modifications [10]. The Autodesk Revit Heating and Cooling Load analysis was used to evaluate: Cooling Load (kWh/year), Solar Heat Gain Coefficient (SHGC), Daylight Autonomy (DA). When the improved building models were compared with the original building model, the energy performance indicators demonstrated an average reduction of approximately 15% in cooling energy demand. This result confirms that passive material strategies including insulation, reflective coatings, and shading devices significantly enhance building energy efficiency.

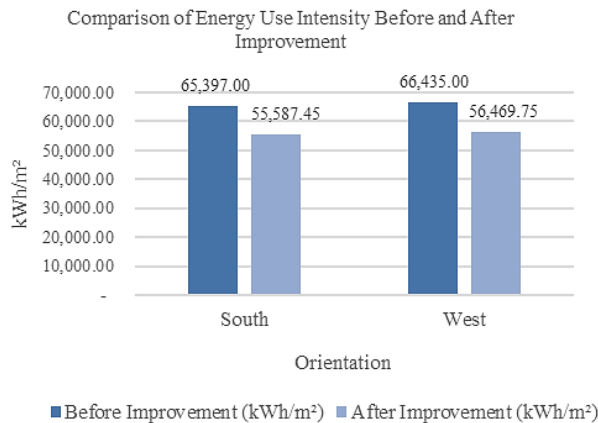


Figure 9. Comparison of Energy Use Intensity (EUI)

5. Conclusion

5.1 Impact of Building Orientation on Energy Consumption

The orientation and positioning of the building significantly influence the energy performance of residential houses, as reflected in the Energy Use Intensity (EUI) and cooling load. The BIM-based energy simulation using Autodesk Revit demonstrated that building orientation is a key factor in determining energy consumption patterns. By identifying the facades most exposed to solar radiation, the study established a foundation for passive design improvements, which provide effective strategies for reducing energy demand.

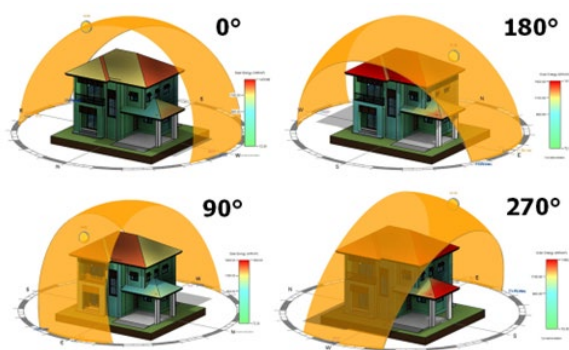


Figure 10. Building Orientation Used for Energy Analysis

The analysis indicated that rotating the building from the highest cooling load orientation to the lowest results in a notable reduction in annual energy consumption,

emphasizing the importance of optimal building orientation in residential energy-efficient design.

5.2 Results of Passive Design Building Material Improvements

The study of building material modifications to enhance energy efficiency revealed that the most effective material improvements for the analyzed two-story residential prototype included: Adding 3-inch fiberglass insulation to the ceiling beneath the roof, Applying ceramic coating to exterior walls, Replacing clear glass with reflective glass, Installing aluminum sunshade louvers. When all four improvements were applied across the building, the annual energy consumption of the air-conditioning system was reduced by approximately 15%. Energy simulation results using Autodesk Revit demonstrated that focusing passive material improvements on the south and west façades, which receive the highest solar radiation, is sufficient to achieve a significant reduction in energy use without requiring full building modification. This approach highlights the cost-effectiveness of targeted passive design strategies in residential projects.

5.3 Summary of Experimental Energy Performance Analysis

This research analyzed the energy performance of a two-story residential house using Building Information Modeling (BIM) as a simulation tool. The case study was a 175 m² housing prototype with a hipped roof and concrete roof tiles, located in Nakhon Ratchasima Province, Thailand. The orientation analysis showed that the west-facing facade (270°) received the highest solar radiation and consequently produced the highest cooling load, while the north-facing facade had the lowest energy demand. The implementation of passive design strategies, including: 3-inch fiberglass ceiling insulation, Ceramic-coated exterior walls, Reflective glass windows, Aluminum sunshade louvers, significantly reduced solar heat gain and air-

conditioning load. Energy simulation results revealed that improving the two most solar-exposed facades (south and west) led to an annual energy reduction of approximately 15% compared to the original condition. These findings demonstrate that the integration of BIM with passive design principles provides an effective and practical method for enhancing residential building energy performance in hot and humid tropical climates.

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Influence of Macadamia Shell Biochar Properties on Rinse-Off Facial Mask Performance

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Abstract

This research explores the potential of biochar derived from macadamia shells—an agricultural byproduct from the Doi Tung Development Project in Chiang Rai Province—as a sustainable ingredient for rinse-off facial masks. Biochar from macadamia shells was compared with activated carbon produced from industrial coconut shells in terms of surface area, porosity, and oil absorption capacity. Characterization results indicated that macadamia shell biochar possessed a high surface area and porous morphology suitable for adsorption-based applications. Sixteen rinse-off facial mask formulations containing various ratios of macadamia biochar and activated carbon were developed and tested. The formulation with macadamia biochar showed effective oil absorption while maintaining skin compatibility. Cytotoxicity assays confirmed its safety for cosmetic use in accordance with industrial standards. While activated carbon remains a popular choice due to its adsorption efficiency, its production involves energy-intensive activation processes and higher costs. In contrast, macadamia-derived biochar offers a lower-cost, environmentally friendly alternative with promising functional performance. These findings suggest that macadamia shell biochar is a viable and sustainable material for application in rinse-off skincare formulations.

Keywords: Biochar, Macadamia shell, Rinse-off mask, Adsorption, Skincare product

1. Introduction

The pursuit of sustainable and low-impact materials for cosmetic formulations has led to growing interest in biochar, a carbon-rich material produced through biomass pyrolysis. With its high surface area, porosity, and functional groups, biochar exhibits potential for use in rinse-off facial masks that target oil control and skin purification. Macadamia nut shells, a lignocellulosic waste abundant in northern Thailand, offer a sustainable feedstock for biochar production. Their utilization aligns with circular economic principles. Although activated carbon is widely used for its high adsorption capacity, it typically involves complex activation processes and higher production costs. Hence, Biochar offers a low-cost and more sustainable alternative.

This study compares macadamia shell biochar with commercial coconut shell activated carbon in terms of physicochemical properties, oil adsorption, and cytotoxicity. It also evaluates rinse-off mask formulations using varying macadamia shell biochar and commercial coconut shell activated carbon (BC:AC) ratios, highlighting the potential of macadamia shell biochar as a safe, eco-friendly cosmetic ingredient.

2. Materials and Methods

Macadamia shell biochar used in this study was sourced as an agricultural byproduct from the Doi Tung Development Project (Royal Initiative), located in Mae Fah Luang District, Chiang Rai Province, Thailand. This biochar served as a primary functional ingredient in the rinse-off facial

mask formulations. All other materials, including activated carbon derived from coconut shells and cosmetic-grade chemicals, were provided by Cosmania Laboratories Co., Ltd. The cosmetic base formulation consisted of kaolin, bentonite, titanium dioxide, hydroxyethyl acrylate, butylene glycol, polysorbate 60, ethylhexyl palmitate, glycerin, allantoin, niacinamide, collagen, sodium hyaluronate, and phenoxyethanol. Each of these ingredients was selected for its specific functional role in the formulations, such as oil absorption, emulsion stabilization, skin hydration, and product preservation, contributing to the overall efficacy, texture, and safety profile of the rinse-off facial mask.

2.2 Sample Preparations

2.2.1 Preparation of Biochar

The raw macadamia shells underwent initial coarse grinding using a mechanical grinder to reduce their size for further processing. For particle size refinement, the ground material was subjected to milling in a low-speed ball mill for 72 hours. After milling, the biochar was oven-dried at 80 °C for 2 hours to eliminate residual moisture. The dried biochar was subsequently sieved into three particle size fractions using stainless steel sieves with mesh sizes of 325 ($\leq 45 \mu\text{m}$), 400 ($\leq 37 \mu\text{m}$), and 500 ($\leq 25 \mu\text{m}$), respectively [1]. The equipment employed in this preparation process included a low-speed ball mill for particle size reduction, an electric oven for drying, and mesh sieves for size classification. A mortar and pestle were also used for supplementary manual grinding where necessary. These preparation steps ensured that the macadamia shell biochar met the particle size and moisture requirements suitable for incorporation into cosmetic formulations. Although the macadamia shell biochar was initially classified into three particle size groups BC1 ($\leq 45 \mu\text{m}$), BC2 ($\leq 37 \mu\text{m}$), and BC3 ($\leq 25 \mu\text{m}$), the distinction between these fractions was not clearly

reflected in the subsequent performance evaluations. Due to potential overlapping during sieving and limitations in material uniformity, the effect of particle size could not be reliably assessed. As such, the comparative analysis in this study focuses primarily on formulation composition based on biochar-to-activated carbon ratios, rather than particle size variation.

2.2.2 Preparation of Rinse-Off Mask Formulations

For cosmetic formulation, the prepared macadamia shell biochar from each particle size fraction was labeled as BC1 ($\leq 45 \mu\text{m}$), BC2 ($\leq 37 \mu\text{m}$), and BC3 ($\leq 25 \mu\text{m}$). The commercial activated carbon from coconut shell was labeled as AC. These carbon materials were incorporated into rinse-off facial mask formulations based on a clay-based mask system. The base ingredients included 63.90 g of kaolin, 10 g of bentonite, 5 g of titanium dioxide, and 0.60 g of hydroxyethyl acrylate, which were initially blended using a mortar and pestle until a homogeneous mixture was achieved. Subsequently, a total of 5 g of carbonaceous material was added into each formulation using different BC:AC ratios across 16 distinct formulations, as described in Table 1. After achieving a uniform blend, the remaining cosmetic ingredients were sequentially added and mixed thoroughly, including 2.50 g of butylene glycol, 2.50 g of polysorbate 60, 3 g of ethylhexyl palmitate, 5 g of glycerin, 0.10 g of allantoin, 1 g of niacinamide, 0.20 g of collagen, 0.20 g of sodium hyaluronate, and 1 g of phenoxyethanol. The entire formulation process was conducted manually using a mortar and pestle to ensure consistent texture and proper dispersion of all ingredients. The proportions of macadamia shell biochar and activated carbon from coconut shell used in the formulations are shown in Table 1.

Table 1. Proportions of Macadamia shell biochar and Activated carbon from coconut shell in Rinse-off mask formulations.

Formula	Sample	Composition(wt%)	
		BC	AC
1	BC1	5.00	-
2	BC1+AC	4.00	1.00
3	BC1+AC	3.00	2.00
4	BC1+AC	2.00	3.00
5	BC1+AC	1.00	4.00
6	BC2	5.00	-
7	BC2+AC	4.00	1.00
8	BC2+AC	3.00	2.00
9	BC2+AC	2.00	3.00
10	BC2+AC	1.00	4.00
11	BC3	5.00	-
12	BC3+AC	4.00	1.00
13	BC3+AC	3.00	2.00
14	BC3+AC	2.00	3.00
15	BC3+AC	1.00	4.00
16	AC	-	5.00

2.3 Characterization

The physicochemical properties of both the macadamia shell biochar and commercial activated carbon from coconut shell were characterized using various analytical techniques. Scanning electron microscopy (SEM) was employed to investigate surface morphology and particle aggregation, while Fourier transform infrared spectroscopy (FTIR) was used to identify surface functional groups. Surface area and pore size distribution were determined using a BET surface area analyzer. An iodine number analysis was conducted according to ASTM D4607 to evaluate the adsorption capacity. In addition, the cytotoxicity of the macadamia shell biochar was assessed via MTT assay on L929 fibroblast cells to ensure its biocompatibility for cosmetic applications.

The oil absorption capacity of the rinse-off mask formulations was evaluated using a standardized setup with cosmetic-grade virgin coconut oil (VCO) as the test medium. Each formulation (n = 16) was assessed by placing 5 grams of mask powder on a filter paper inside a funnel connected to a separating funnel containing 20 mL of

virgin coconut oil (VCO). The oil was gradually released over the powder for 20 minutes, allowing full saturation. A measuring cylinder placed beneath the funnel was used to collect the unabsorbed oil. The difference in oil volume before and after the test was recorded to determine the amount absorbed. Each formulation was tested in quintuplicate to ensure reproducibility [2]. The average oil absorption and standard deviation were calculated and used for statistical comparison using one-way ANOVA.

3. Results and Discussion

Microstructural Analysis

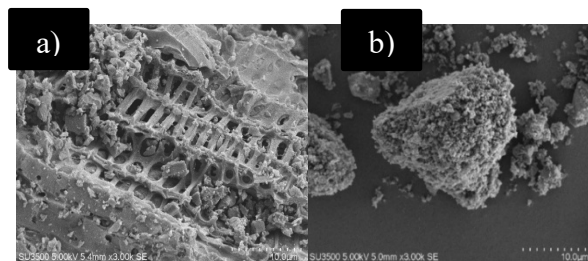


Figure 1. (a) SEM Image of Macadamia shell biochar and (b) Activated carbon from coconut shell at 3,000× Magnification.

The microstructure of macadamia shell biochar and activated carbon from coconut shell was examined using a scanning electron microscope (SEM) under low vacuum mode at an accelerating voltage of 5 kV with secondary electron (SE) detection at 3,000× magnification, as shown in Figure 1(a) and (b).

Figure 1(a) reveals that the macadamia shell biochar particles exhibit aggregation behavior, likely due to high surface atom density that facilitates van der Waals interactions, leading to particle adhesion [3]. Electrostatic charges on the particle surface may further enhance this attraction, especially among fine particles with high surface area-to-mass ratios [4].

In contrast, Figure 1(b) shows that activated carbon from coconut shell possesses a well-defined, open pore structure with clearly

distinguishable pores. This morphology results from physical or chemical activation processes that develop micro- and mesopores. Such a porous architecture contributes to high surface area and pore volume, making it suitable for adsorption applications involving organic compounds and heavy metals [5].

Functional Group Analysis

As shown in Figure 2, the FTIR spectrum of macadamia shell biochar exhibits prominent absorption bands at $\sim 3400\text{ cm}^{-1}$ and $\sim 1595\text{ cm}^{-1}$, corresponding to hydroxyl groups and aromatic C=C stretching, respectively. These functional groups suggest a strong potential for hydrogen bonding and organic adsorption, consistent with the findings of Trung et al. (2020), who reported that macadamia-based biochar exhibits high adsorption capacities due to abundant surface functional groups [6]. In contrast, the FTIR spectrum of activated carbon from coconut shell displays a dominant carbonyl (C=O) peak at $\sim 1700\text{ cm}^{-1}$, aligning with the study by Nuryana et al. (2020), which attributed this to the high degree of carbonization in coconut shell-derived carbons. This structure results in more defined C=O functionalities but fewer active surface groups overall [7].

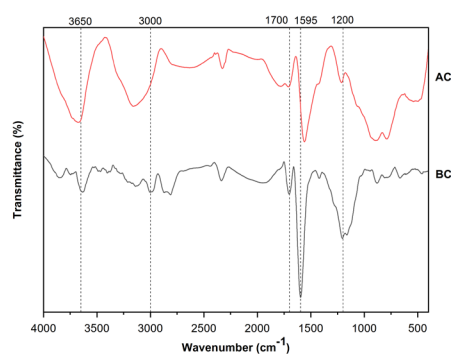


Figure 2. FTIR spectra of Macadamia shell biochar and Activated carbon from coconut shell.

Surface Area Analysis

Surface area and porosity were analyzed using the Brunauer–Emmett–Teller (BET) method. The BET surface area of activated carbon from coconut shell was

found to be $816.14\text{ m}^2/\text{g}$, while macadamia shell biochar exhibited a surface area of $320.83\text{ m}^2/\text{g}$. The high BET value of the activated carbon from coconut shell reflects a well-developed microporous structure formed through activation processes [8], which corresponds with the microstructure shown in Figure 1(b), characterized by abundant and continuous pores. Such a structure is favorable for high-efficiency adsorption applications, including water purification, air filtration, and pollutant removal. In comparison, the BET surface area of macadamia shell biochar, though lower, remains sufficient for effective adsorption of impurities and excess oil from the skin. Its moderate surface area reduces the risk of over-adsorption of natural skin oils, thereby minimizing the potential for dryness or irritation [9].

Iodine Number Analysis

The iodine number analysis performed according to ASTM D4607 revealed that activated carbon from coconut shell exhibited an iodine value of 991 mg/g , while macadamia shell biochar showed a value of 350 mg/g . The iodine number serves as an indicator of the material's adsorption capacity, with higher values reflecting greater surface area and the ability to adsorb small molecules effectively [10], making high-iodine materials suitable for water and air filtration applications. However, in cosmetic applications such as rinse-off facial masks, the iodine value of 350 mg/g in macadamia shell biochar is considered appropriate, providing sufficient adsorption of excess oil and impurities without over-drying or irritating the skin. Additionally, macadamia shell biochar offers a milder surface texture compared to the more aggressive behavior of high iodine activated carbon from coconut shell, making it a favorable ingredient for gentle yet effective skincare formulations.

In Vitro Cytotoxicity Analysis of Macadamia Shell Biochar

The cytotoxicity of macadamia shell biochar was evaluated using the MTT assay on L929 mouse fibroblast cells, conducted by the Research Office, Faculty of Dentistry, Mahidol University. The results showed that cell viability remained above 70% across all tested concentrations (1.25–10.00%), with values ranging from 83.4% to 102.5%. These findings indicate that the macadamia shell biochar is non-cytotoxic according to ISO 10993-5 standards and is therefore suitable for use in cosmetic formulations, particularly rinse-off facial masks.

Oil Absorption Performance Analysis of Rinse-Off Mask Formulations

The oil absorption performance of the rinse-off mask formulations containing macadamia shell biochar with different particle sizes (BC1, BC2, BC3) was compared to that of commercial activated carbon from coconut shell (AC). The reference formulation containing only AC (Formula 16) exhibited the highest oil absorption at 59.5%. Among the biochar-based groups, the average absorption values were similar: BC1 at $45.90 \pm 6.68\%$, BC2 at $44.46 \pm 7.29\%$, and BC3 at $45.72 \pm 5.62\%$, as shown in Figure 3

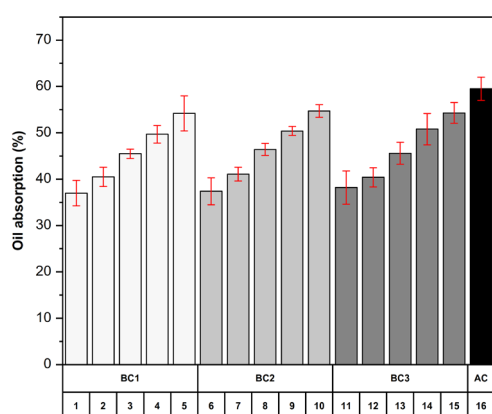


Figure 3. Oil absorption (%) of rinse-off mask formulations containing Macadamia shell biochar (BC1–BC3), compared with coconut shell activated carbon (AC)

Increasing the proportion of AC in the BC–AC combinations (Formulas 1–15) resulted in a consistent upward trend in oil absorption across all macadamia shell biochar types. Notably, formulations with a BC:AC ratio of 1:4 (Formulas 5, 10, and 15) demonstrated the highest absorption values within each group, closely matching the performance of the AC-only reference. Conversely, formulations containing only macadamia shell biochar (Formulas 1, 6, and 11) showed the lowest oil absorption in each group, suggesting that while biochar possesses inherent adsorption potential, its efficiency is significantly enhanced when combined with activated carbon from coconut shell. No statistically significant differences were observed among the macadamia shell biochar particle size groups (BC1, BC2, and BC3). The one-way ANOVA results confirmed statistically significant differences among the 16 formulations ($F = 43.68$, $p = 8.81 \times 10^{-28}$), validating the influence of BC:AC ratio on oil absorption efficiency. These results are summarized in Table 2.

Table 2. One-way ANOVA summary for oil absorption performance of 16 rinse-off mask formulations.

Source of Variation	Sum of Squares (SS)	df	Mean Square (MS)	F-value
Between Groups	149.25	15	9.95	43.68
Within Groups	14.58	64	0.23	–
Total	163.83	79	–	–

Figure 4 shows the prototype of the rinse-off facial mask containing macadamia shell biochar, illustrating its real-world application potential.



Figure 4. Prototype 10 g of rinse-off facial mask containing macadamia shell biochar as the functional ingredient.

4. Conclusion

The findings indicate that macadamia shell biochar possesses a porous structure and sufficient surface area suitable for adsorbing pollutants. FTIR analysis confirmed the presence of hydroxyl (-OH), carbonyl (C=O), and ether (C-O) functional groups, which are known to enhance adsorption performance. BET analysis revealed that the surface area of macadamia shell biochar was $320.83 \text{ m}^2/\text{g}$, compared to $816.14 \text{ m}^2/\text{g}$ for activated carbon from coconut shell. These results correspond with iodine numbers of 350 mg/g and 991 mg/g , respectively, indicating higher molecular-level adsorption capacity for the activated carbon from coconut shell. The MTT cytotoxicity assay conducted on L929 fibroblast cells demonstrated that macadamia shell biochar maintained cell viability above 70% across all tested concentrations, meeting ISO 10993-5 biocompatibility standards. One-way ANOVA revealed that differences in oil absorption among the 16 rinse-off mask formulations were statistically significant ($F = 43.68$, $p = 8.81 \times 10^{-28}$), confirming that formulation composition had a measurable effect on adsorption efficiency.

In conclusion, biochar derived from macadamia shells represents a safe, effective, and sustainable alternative for use in rinse-off facial masks. It demonstrates adequate oil adsorption capacity suitable for skincare

applications while contributing to the valorization of agricultural waste. Furthermore, its lower production cost compared to commercial coconut shell-based activated carbon highlights its potential for industrial-scale development.

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Effects of Different Force Magnitudes for Second Molar Uprighting with Miniscrew Anchorage: A Finite Element Method

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Abstract

This study aims to evaluate the effects of different force magnitude for uprighting mesially tipping mandibular second molars using a single pulling force by the use of Finite Element Method. Forces of 30 g, 70 g, 110 g, 150 g were applied from a button at distal surface to miniscrew anchorage at retromolar pad. The von Mises stress in periodontal ligament (PDL), and initial displacement of second molars were evaluated. At orthodontic force 30 g, 70 g, 110 g and 150 g, the maximum von Mises stress in PDL were distributed on the mesial side of distal root of the second molars' PDL, with the maximum stress values were 0.0083, 0.019, 0.029, 0.038 Mpa, respectively. The initial displacement of mesially tipping second molar was mesial part of root and crown were buccal tipped, distal part of crown was distal tipped and intruded, and mesial part of crown was distal tipped and extruded. A force of 70 g was found suitable for uprighting mesially tipping mandibular second molars using miniscrew anchorage without exceeding the safe stress threshold in the PDL.

Keywords: Finite Element Method, mesially tipping mandibular second molar, miniscrew anchorage, molar uprighting

1. Introduction

The permanent first molars are the earliest erupting teeth in the permanent dentition. Their prolonged presence in the oral cavity makes them highly susceptible to decay, often resulting in early loss when oral hygiene is inadequate. This premature loss frequently causes the second molars to tip mesially, while premolars may drift distally.[1]

Various techniques have been developed for molar uprighting, including Niti coil spring[2] and cantilever spring[2, 3], which are widely used in orthodontic treatment. However, due to the dense mandibular cortical bone and the buccolingually broad roots of second molars, a strong anchorage control is needed for molar uprighting.[4] Therefore, miniscrew eliminate the reaction forces usually applied on the anchor teeth and

preventing unwanted tooth movement and anchorage loss.[4, 5]

Orthodontic force should be regulated such that stress in the periodontal ligament (PDL) remains under the critical limit of 26 kPa to avoid irreversible tissue damage.[6]

The Finite Element Method (FEM) is a computational technique used to estimate mechanical values and obtain approximate solutions. Known for being noninvasive and reproducible, FEM has become a valuable tool in addressing structural and biomechanical challenges.[7]

Although molar uprighting is usually routine in orthodontic practice, limited limited studies have explored optimal force levels and the stress responses within the PDL, especially when using a single pulling force mechanic anchored by miniscrews. This study aims to evaluate the effects of different

force magnitudes for uprighting mesially tipping mandibular second molars using a single pulling force applied from a button on the distal surface of the tooth toward a miniscrew anchorage in order to determine the optimal force magnitude that does not exceed the PDL stress threshold of 26 kPa, using Finite Element Method.

2. Material & Methods

A mandibular model was generated from a CT scan (Spectral CT 7500, Philips, USA), with DICOM data encompassing the mandible at a 0.6 mm slice thickness. These files were processed using 3D Slicer (open-source software) to develop a three-dimensional mandibular structure. Additional dental components — first and second premolars, first molar, and mesially tipping second molar — were modeled using VISI (Vero Software, UK).

The second molars were designed to tip mesially at an angle of 57°, which is measured from the occlusal plane and long axis of second molars, based on the average inclination described by Hong et al.[8] in patients missing mandibular first molars. Miniscrews were inserted at retromolar pad at a distance of about 5 mm from button on second molars at the same level of occlusal plane. The size of the miniscrew was 12 mm in length and 2 mm in diameter. (Figure 1)

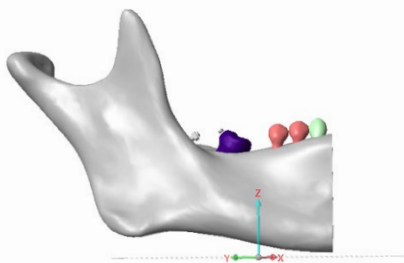


Figure 1 Generated Model

The assembled models were imported into Patran (MSC Software, USA) to generate the finite element mesh before being analyzed in Marc Mentat (MSC Software, USA).

A tetrahedral mesh was created using the following parameters: 0.8 mm for cortical bone, 0.5 mm for cancellous bone, and 0.2 mm for teeth, PDL, and miniscrews. The final model comprised 603,996 elements and 139,669 nodes. All materials were modeled as homogeneous, isotropic, and linearly elastic. Table 1 specify the material properties.[9, 10]

Table 1 Properties of materials

	Young's modulus (MPa)	Poisson's ratio
Teeth	19613.3	0.15
PDL	0.6668	0.49
Cortical bone	13700	0.26
Cancellous bone	1370	0.3
Stainless steel	200000	0.3

All bony parts of geometric model and miniscrews were set as having no relative displacement and assumed that miniscrews and bone contact were fully anchoring. Forces of 30 g, 70 g, 110 g, 150 g were applied from the center of head of the buttons on second molars to center of head of miniscrews, according to previous studies have reported variable force applications from 50 g to 150 g.[11-13] The von Mises stress in PDL, and initial displacement of second molars were evaluated. The magnitude of each parameter measurement was presented visually using a gradient color column, where a yellow color means the highest value and a deep blue color means the lowest value of each parameter, respectively.

3. Results

3.1 Equivalent von Mises Stress of PDL

At orthodontic force 30 g, 70 g, 110 g and 150 g, the maximum von Mises stress in the PDL was distributed on the mesial side of the distal root of the second molars (Figure 2), with the maximum stress values of 0.0083, 0.019, 0.029, 0.038 Mpa, respectively. The maximum von Mises stress in the PDL showed a corresponding increase as the orthodontic force increased.

The 70 g was the optimal force of this study because the maximum stress level was 0.019 MPa, which less than Lee et al.'s recommended stress threshold of 26 kPa[6]

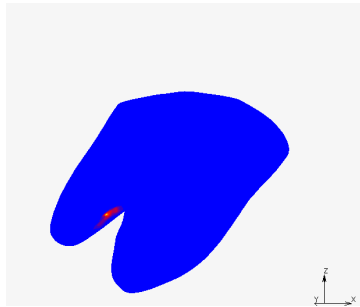


Figure 2 stress distribution at PDL

3.2 Initial displacement of mesially tipping second molar

As the optimal force was 70 g, initial tooth displacement of second molar under 70 g of force was chosen to analyze and presented with different colors (Figure 3), according to the magnitude of tooth displacements was measured in the x, y, and z-axes. Displacement directions were categorized along three axes:

- X-axis (buccolingual): positive = lingual, negative = buccal
- Y-axis (mesiodistal): positive = distal, negative = mesial
- Z-axis (vertical): positive = extrusion, negative = intrusion

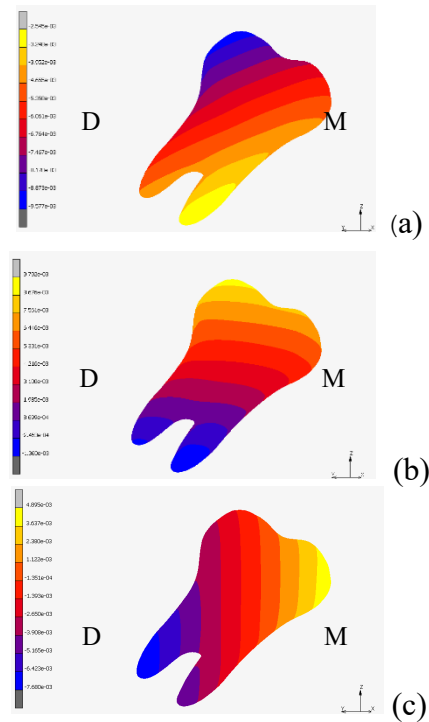


Figure 3 Initial displacement in all axes
(a) X-axis (b) Y-axis (c) Z-axis

The maximum initial displacement values in each axis were shown in Table 2.

Table 2 maximum initial displacement values

Maximum initial displacement (mm)		Location	Direction
ΔX	-0.0025	Mesial root	Buccal direction
ΔY	0.010	Distolingual cusp	Distal direction
ΔZ	0.0045	Mesial cusp	Extrusion direction

Overall, mesially tipping second molar showed mesial part of root and crown were buccal tipped, distal part of crown was distal tipped and intruded, and mesial part of crown was distal tipped and extruded.

4. Discussion

Previous literature supports the use of miniscrews for molar uprighting.[4, 5, 11, 12] However, there is no agreement regarding the ideal force magnitude for uprighting non-impacted, mesially tipping mandibular second molars. Studies have reported variable force applications. Gracco et al.[12] used 150 g of force with a miniscrew in an edentulous area and NiTi open coil spring. Giancotti et al.[11] used a retromolar miniscrew and a NiTi closed coil spring with 50g force. Kittichaithanakoon et al.[13] found 80 g was an optimal force magnitude to upright impacted second mandibular molar by Finite Element Method. This study identifies 70 g as the optimal force when uprighting mesially tipping second molars using a single pulling force from a button at distal surface to miniscrew anchorage approach, as it generated a von Mises stress of 0.019 MPa, which is below the threshold associated with PDL damage.[6] The maximum von Mises stress in PDL were distributed on the mesial side of distal root of the second molars' PDL (Figure 2). The von Mises stress distribution in PDL was similar pattern at all force but the stress values were increased when the forces were increased.

This study revealed that the initial displacement of mesially tipping second molar as mesial part of root and crown were buccal tipped, distal part of crown was distal tipped and intruded, mesial part of crown was distal tipped and extruded. Since the force was applied from the button to the miniscrew and did not pass directly through the second molar's center of resistance, it generated a moment, leading to unavoidable side effects in both the bucco-lingual and vertical directions. In some cases, extrusion was unwanted movement, such vertical displacement could be problematic, potentially leading to premature contacts, occlusal trauma, or open bite. Thus, the position of the miniscrew and button should be carefully considered to achieve an appropriate force direction. Moreover, full

arch orthodontic brackets bonding with rectangular archwires may help control all directions and provide better tooth movement of the molar.

However, this study examined a tooth with a single degree of mesial tipping. In reality, second molars can exhibit various degrees of mesial tipping. Therefore, further studies of comparing second molar with different tipping angles are recommended. Additionally, since it is not possible to directly measure stress distribution within tooth structures in a clinical setting, the Finite Element Method is used to simulate these conditions. Nevertheless, it does not fully reflect actual clinical conditions. Moreover, differences in each individual's biological response and how their teeth react to orthodontic forces must also be considered.

5. Conclusion

Based on our Finite Element Method, A force of 70 g was found suitable for uprighting mesially tipping mandibular second molars using miniscrew anchorage without exceeding the safe stress threshold in the PDL. The maximum von Mises stress in PDL were distributed on the mesial side of distal root of the second molars' PDL. The initial displacement of mesially tipping second molar was mesial part of root and crown were buccal tipped, distal part of crown was distal tipped and intruded, and mesial part of crown was distal tipped and extruded.

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Finite Element Analysis of Stress Distribution on lower incisor intrusion with clear aligner

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Abstract

This study aimed to evaluate the biomechanical behavior of clear aligners during the intrusion of mandibular anterior teeth, focusing on stress distribution within the periodontal ligament (PDL) using finite element analysis (FEA). A three-dimensional finite element model of the mandible, mandibular dentition, PDL, attachments, and a clear aligner was developed. The aligner was programmed to achieve 0.2 mm of intrusion in all four lower incisors, with the canines serving as anchorage teeth and horizontal rectangular attachments placed on their labial surfaces. Von Mises stress distribution in the PDL was analyzed to assess the biomechanical effects of the applied forces. The results showed that stress distribution was not uniform among the mandibular incisors, despite symmetrical aligner design and bilateral force application. The highest stress concentrations were observed at the distal aspect of the apical root in the lateral incisors (teeth 32 and 42), with values of 2.85 MPa and 3.67 MPa, respectively, while the central incisors (teeth 31 and 41) exhibited significantly lower stress levels. These findings indicate that clear aligners generate uneven stress during lower incisor intrusion, with lateral incisors experiencing greater apical stress, highlighting the importance of precise biomechanical planning to reduce the risk of root resorption.

Keywords: Clear aligners, Finite element analysis, lower incisor intrusion

1. Introduction

A deep overbite is frequently present in various types of malocclusions, regardless of whether the patient's growth pattern is vertical or horizontal. Correcting a deep overbite is a key goal in orthodontics, as excessive overbite can damage teeth and their supporting structures over time [1]. The Curve of Spee in orthodontics refers to the natural, upward curvature of the mandibular arch when viewed from the side (sagittal view). This curve begins at the incisal edges of the lower anterior teeth and extends posteriorly, following the buccal cusp tips of premolars and molars [2]. An exaggerated Curve of Spee is often linked to deep overbite cases and is most prominent in individuals

with Class II malocclusion [3]. Correction of a deep Curve of Spee often involves orthodontic leveling techniques, which may include intrusion of the anterior teeth, extrusion of the posterior teeth, or a combination of both approaches to establish proper occlusal harmony and function [4]. Clear aligners have gained popularity, especially among adults, because they are discreet, comfortable, and make oral hygiene easier to maintain [5]. However, achieving predictable lower incisor intrusion remains one of the more challenging tooth movements with aligners [6]. In previous studies, the mandibular incisors in the models were all upright, and different types of attachments were used on the anchorage teeth [7]. Despite

this, the detailed biomechanics and potential side effects of intruding lower anterior teeth with clear aligners are not yet fully understood. Therefore, this study uses finite element analysis to examine how stress is distributed in the lower incisor region during intrusion with clear aligners.

2. Materials and methods

This experimental study involves the creation of a three-dimensional model of the mandible, periodontal ligament (PDL), lower teeth, attachments, and a clear aligner using CAD software. Finite element analysis (FEA) was performed on the model to simulate intrusive forces generated by the aligner, which is designed to achieve 0.2 mm of intrusion in the lower incisors. Following the simulation, the resulting stress distribution on the lower incisors was analyzed.

2.1 Modeling of the mandible and teeth

The 3D image (DICOM file) of mandible bone and lower teeth was converted to 3D models via imaging. The 3D of mandible bone and lower teeth will be modified by engineering. Then, CAD software will be used to create, arrange, modify and finalize the 3D model.

2.2 Modeling of the attachments, PDL and clear aligner

CAD software was creating the 3D model of attachments, PDL and clear aligner. The PDL is set to extend uniformly on the root by 0.3 mm. Horizontal rectangular attachments (2 mm in height, 4 mm in width, and 1 mm in thickness) were designed for the lower canine. The aligners had a thickness of 0.6 mm and incorporated an external offset device for all crowns and attachments. They were designed to achieve a final incisor intrusion of 0.2 mm.

2.3 Finite element analysis and mechanical properties of materials

All components were employed for meshing and imported for FE analysis by Marc Mentat (MSC Software Corp., USA). The properties of material will be used as specify in table below [7].

Table 1 Mechanical Properties of Materials

	Young's modulus (MPa)	Poisson's ratio
Teeth	19613.3	0.15
PDL	0.6668	0.49
Plastic Aligner	528	0.36
Attachment	12,500	0.36
Cortical bone	13700	0.26
Cancellous bone	1370	0.3

The number of elements for the cancellous, cortex, dentition, PDL, attachment and the aligner was identically applied as 231,663, 204,607, 990,957, 453,893, 2,610 and 173,563 respectively. The model consists of 2,057,293 total elements and 500,625 nodes.

2.3.1 Intrusion design and parameter measurement

The finite element models were constructed with a Curve of Spee depth of 3.0 mm and a 0.2 mm spacing between the mandibular incisors. The horizontal rectangular attachments were placed on the labial surfaces of the canines and lateral incisors. Clear aligners programmed for 0.2 mm of intrusion were applied to all four lower incisors [8]. Subsequently, the stress distribution within the periodontal ligament (PDL) of the lower incisors was analyzed to evaluate the biomechanical response to the applied intrusion force.

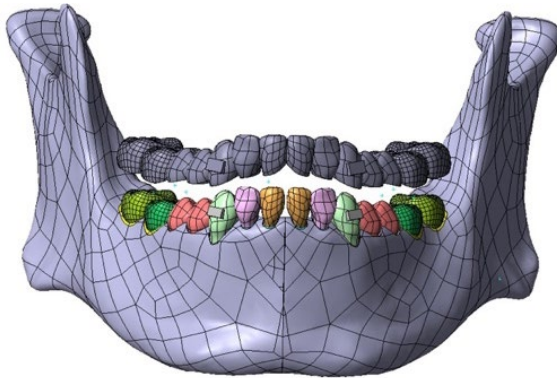


Figure 1: Finite models. (a) Models of the mandible, periodontal ligament, dentition, and attachment. (b) Model of the clear aligner.

3. Results

Finite element analysis revealed that the maximum Von Mises stress in the PDL occurred at the distal aspect of the apical root region. Despite symmetrical aligner design and bilateral force application, stress distribution was not uniform among the mandibular incisors (Table1). The highest stress values were observed in the lateral incisors (teeth 32 and 42), suggesting better load dissipation characteristics than the central incisors, but also higher susceptibility to apical stress accumulation.

Table 1: Maximum Von Mises stress (MPa) and location on lower incisor

Teeth No.	Maximum Von Mises stress (MPa) on PDL	Location of root
32	2.85401	Distal surface
31	0.0405088	Distal surface
41	0.049997	Distal surface
42	3.67269	Distal surface

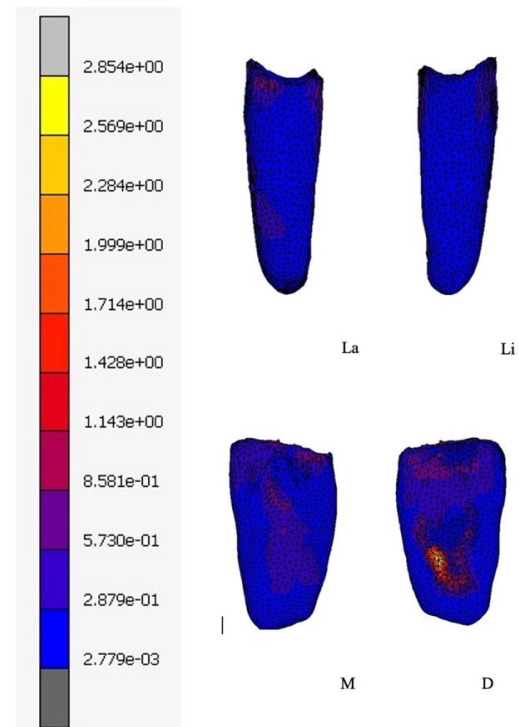


Figure 2 Von Mises stress distributions (MPa) in PDL tooth 32 (La)Labial, (Li)Lingual, (M)Mesial, (D)Distal

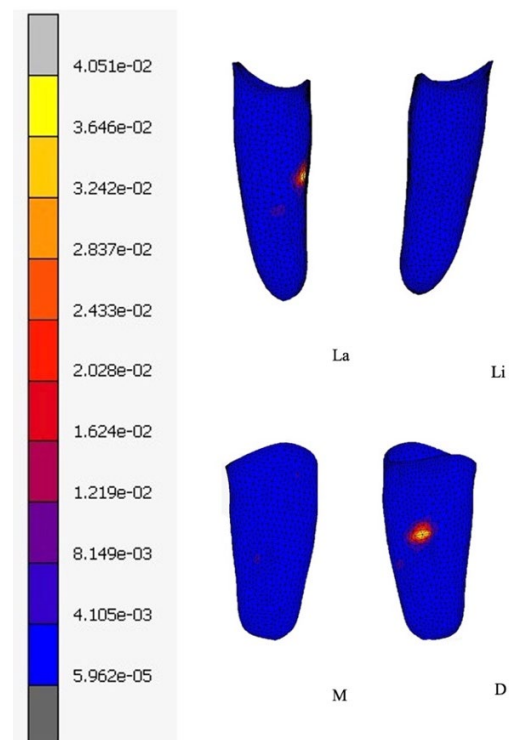


Figure 3 Von Mises stress distributions (MPa) in PDL tooth 31

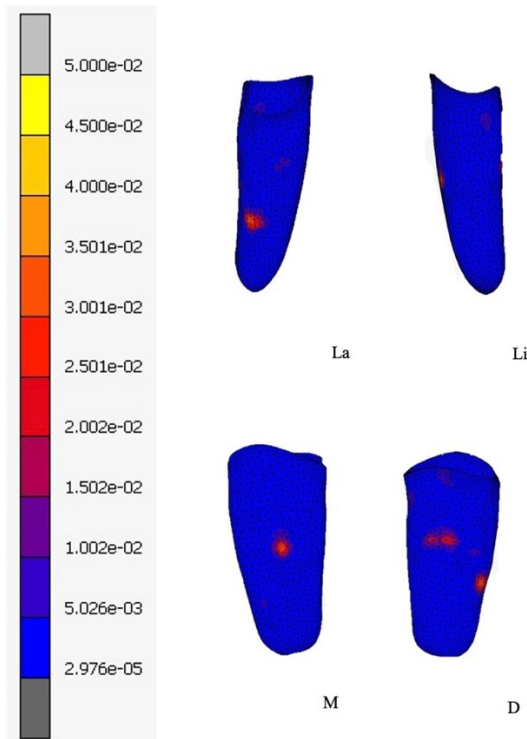


Figure 4 Von Mises stress distributions (MPa) in PDL tooth 41

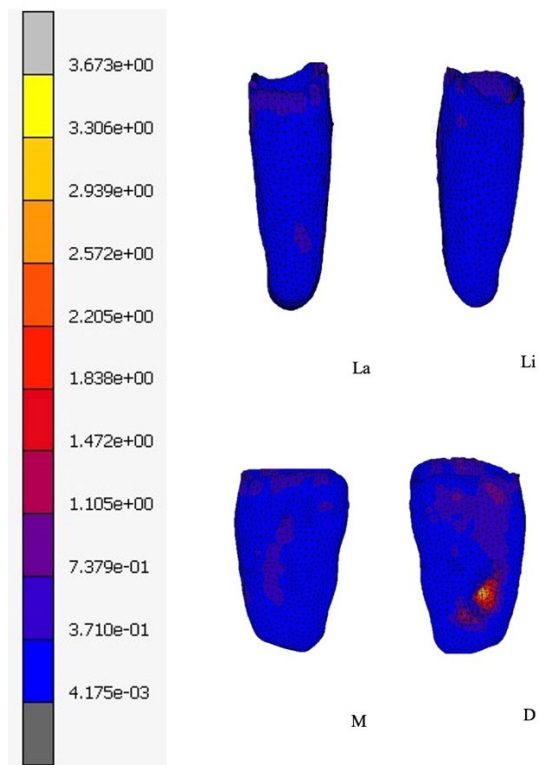


Figure 5 Von Mises stress distributions (MPa) in PDL tooth 42

4. Discussion

Flattening the Curve of Spee is one of the first objectives in comprehensive orthodontic treatment. This process helps open the bite and create a balanced occlusal plane by reducing the depth of an excessive curve, which is commonly seen in deep-bite cases. A key aspect of this leveling is the controlled intrusion of the lower incisors. Even with advancements in clear aligner technology, managing deep bites with aligners remains challenging, and lower incisor intrusion is still considered one of the least predictable tooth movements [6]. This study investigated the biomechanical behavior of clear aligners during the intrusion of mandibular anterior teeth, focusing on stress distribution within the periodontal ligament (PDL) using finite element analysis (FEA). The results revealed that Von Mises stress was not uniformly distributed among the lower incisors, despite symmetrical aligner design and bilateral force application. Our findings showed that the lower lateral incisors demonstrated a more favorable stress distribution compared to the lower central incisors. However, stress concentration at the apical region is a concern, as excessive stress in this area has been associated with root resorption and unfavorable alveolar bone remodeling [9]. Lateral incisors may be particularly vulnerable due to their narrower root morphology and lower root surface area for force dissipation. The magnitude and direction of the forces applied to the lower incisors during intrusion must be carefully controlled. The study also found that stress was consistently localized at the distal apical region of all mandibular incisors. This area of PDL compression, created by intrusive movement, increases the risk of root resorption [10].

5. Conclusion

Clear aligners generate stress distribution during lower incisor intrusion, with lateral incisors experiencing greater apical stress. Careful control of force magnitude and

direction is essential to minimize the risk of root resorption.

6. Acknowledgement

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Switching Analysis and Stability Assessment of the 500 kV Pakbeng-Tha Wang Pha Transmission Line for Cross-Border Interconnection

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Abstract

This study investigates switching overvoltage phenomena and reactive power compensation in a 500 kV transmission line connecting Pakbeng (PKB) and Tha Wang Pha (TWP), planned for cross-border interconnection between Laos and Thailand. Load flow and short-circuit analyses were performed to define steady-state conditions and post-interconnection fault levels. Switching overvoltages (SOVs) during line energization and reclosing were simulated using PSCAD/EMTDC under various protective configurations. Statistical switching with 200 operations was conducted to assess maximum overvoltages, revealing that single-end energization without surge arrestors can cause SOVs up to 1.974 p.u. Installing 444 kV arresters and 110 MVAR shunt reactors at both ends reduced peak voltages to acceptable levels (<1.7 p.u.). The results support insulation coordination and switching strategy planning. Future work will investigate temporary overvoltage (TOV) risks under varied fault scenarios.

Keywords: Power system interconnection, transient stability, reactive power compensation, surge arrester optimization, PSCAD simulation

1. Introduction

The expansion of the Lao PDR power grid and its planned interconnection with Thailand via a 500 kV transmission line between Pakbeng (PKB) and Tha Wang Pha (TWP) is a key milestone toward regional energy security and export-oriented development. This interconnection introduces operational challenges related to reactive power balance, overvoltage risk, and system stability, especially during switching events such as line energization and fault clearance.

High-voltage transmission lines experience significant switching overvoltages (SOVs) under light- or no-load conditions, particularly during single-end energization or reclosing operations. These transients may exceed equipment insulation levels and must be mitigated through coordinated application of surge arresters, shunt reactors, and

optimized switching sequences. Statistical switching analysis is necessary to evaluate the range of possible overvoltage peaks caused by asynchronous breaker pole closures.

Previous studies such as [3], [4], and [14] have analyzed the impact of protective devices and switching timing on transient overvoltages in extra high-voltage (EHV) systems. This study extends those methods to the Northern Laos power system using detailed PSCAD/EMTDC simulations. The scope includes load flow analysis, short-circuit assessment, and switching transient evaluation under multiple operating conditions. Key contributions include recommendations for shunt reactor sizing, arrester coordination, and insulation design.

2. Description Of the Studied Transmission System

Laos, known as the “Battery of Southeast Asia,” generated approximately 57,000 GWh in 2023 from its installed capacity of 11,652 MW, with 83% sourced from hydropower and the remainder from coal-fired and renewable sources [7]. To support both domestic demand and export growth, Laos has prioritized EHV transmission expansion, including the 500kV Pakbeng-Tha Wang Pha interconnection, a dedicated 120 km line connecting the Pakbeng hydropower switch across the Thai-Lao border to Tha Wang Pha in Thailand [8]. The system under study comprises a double-circuit 500 kV transmission line of approximately 64 km from Pakbeng switchyard to the Lao-Thai delivery point, followed by 13 km to the Tha Wang Pha substation [9]. Each circuit utilizes quad-bundle ACSR conductors, designed for high power flow and minimal corona effects. Reactive compensation is provided via shunt reactors (e.g., 110 MVAR units) at both ends to stabilize voltage under varying load conditions and counteract line charging currents. A parallel 230 kV line (150 km) also connects Pakbeng with the broader Laos grid, using four-conductor per phase 630 MCM ACSR, enabling flexible interconnection with domestic and export grids. Figure 1 illustrates a simplified single-line diagram of the system, highlighting major components including generation sources, line circuits, transformers, reactors, and surge arresters.

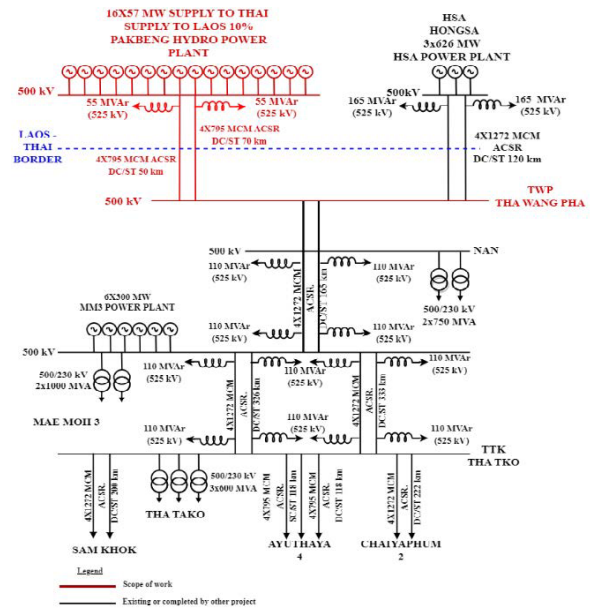


Figure 1 Single diagram of the PakBeng HPP

3. System Specifications and Modeling

In this study, a detailed electromagnetic transient (EMT) model of the 500 kV Pakbeng–Tha Wang Pha transmission system was developed in PSCAD/EMTDC. The system components include transformers, transmission lines, circuit breakers, surge arresters, shunt reactors, and network equivalents. Each component was modeled using parameter values and configurations derived from technical specifications, feasibility studies, and comparable international projects.

3.1 Transformer

The 500/242/22 kV three-winding autotransformers (750 MVA) were modeled using the Saturable transformer component in PSCAD, including magnetization characteristics based on knee-point voltage in per unit and air-core unsaturated inductance. Tap changer settings, winding configurations, and leakage reactance between windings were also incorporated. Saturation characteristics were implemented at the internal node of the high-voltage (H.T.) winding, and leakage impedance was lumped within the model. Equivalent single transformers were used per substation based on manufacturer design data [10], [11].

3.2 Transmission Line

The 500 kV transmission line from Pakbeng to Tha Wang Pha (total length 120km) was divided into twelve segments of 10km each to capture distributed parameter effects. Each phase used a quad-bundle 795 MCM ACSR conductor. Frequency-dependent phase models were developed using line constants (resistance, inductance, capacitance) calculated from conductor geometry, bundle spacing, midspan sag, and ground resistivity. The PSCAD transmission line model incorporated full phase transposition and propagation delay based on characteristic impedance [10], [11], [12].

3.3 Circuit Breaker

Circuit breakers were modeled using statistical switching logic to reflect real-world conditions of mechanical pole closing. Key parameters include transient recovery voltage (TRV), capacitive switching limits, pole closing delays, and use of pre-insertion resistors. The random pole-closing times followed a Gaussian distribution with specified mean and standard deviation, consistent with IEC and IEEE standards. The simulation considered both fault-clearing and line-energization scenarios [10], [13], [14].

3.4 Surge Arresters

Metal oxide surge arresters (MOSAs) rated at 444 kV were installed at both terminals of the 500 kV line. Their nonlinear voltage-current (V-I) characteristics were implemented in PSCAD using manufacturer-specified energy absorption ratings and protection curves. These arresters are essential for limiting switching overvoltages and ensuring insulation coordination [12],[16].

3.5 Shunt Reactors

To mitigate Ferranti effects under light or no-load conditions, 110 MVAR shunt reactors were installed at both Pakbeng and Tha Wang Pha substations. The reactors were modeled as nonlinear lumped inductors with two-slope saturation characteristics. Neutral reactors were added at the neutral point of the star-connected shunt reactors to control zero-

sequence resonance [13],[16].

3.6 Loads and Network Equivalent

The external Thai grid connected at Tha Wang Pha 500/230 kV substation was modeled as a Thevenin equivalent source with an impedance matrix for positive, negative, and zero sequences. Voltage magnitudes and phase angles were derived from DigSILENT load flow studies under heavy-load conditions. This equivalencing approach allowed accurate representation of boundary conditions during transient simulations [15].

4. Results and Discussion

This study presents an analysis of the 500 kV transmission system linking Pakbeng and Tha Wang Pha substations, utilizing DigSILENT PowerFactory and PSCAD/EMTDC. The simulation results emphasize steady-state load flow, short-circuit capacity after interconnection, and transient overvoltage phenomena under different switching conditions.

4.1 Load Flow Analysis

To establish steady-state operating conditions before switching simulations, a load flow analysis was conducted under minimum load assumptions for the year 2030. This scenario is considered the worst case for switching overvoltage studies, especially in no-load or light-load conditions commonly encountered during daytime energization. The results show that both the Pakbeng (PKB) and Tha Wang Pha (TWP) substations operate independently with no active power exchange, and voltages at both terminals remain above 1.0 p.u., indicating a balanced system with the potential for voltage rise due to reactive power charging. Shunt reactors were identified as necessary components to mitigate the Ferranti effect, particularly during single-end energization. These load flow conditions provide the foundation for

fault and switching studies

4.1.1 Split System Before Interconnection

Figure 2 shows that before interconnection, the system exhibits voltage magnitudes of approximately 631.1 kV at Pakbeng and 600 kV at Tha Wang Pha due to capacitive charging of the open-ended lines.

The lack of load causes elevated voltages due to charging currents, confirming the necessity of voltage control equipment before system synchronization.

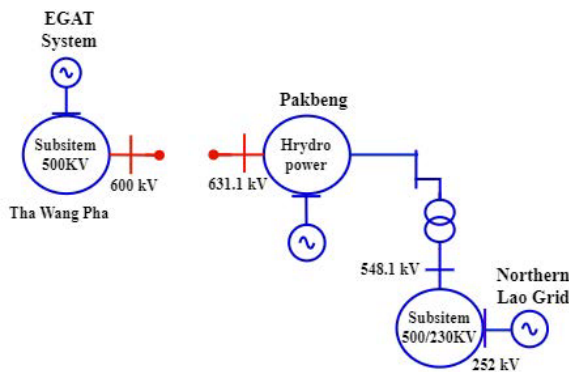


Figure 2 Load flow results of the Pakbeng-Tha Wang Pha 500 kV substations under no-load condition before interconnection

4.1.2 Single-End Energization of 500 kV Line

a) From Pakbeng Substation:

When energized from Pakbeng, the receiving-end voltage at TWP rises to 667 kV, while the sending-end remains at 619 kV. The reactive power injection reaches 284.5 Mvar due to capacitive effects.

Figure 3 shows the load flow simulation result when only one circuit of the 500 kV transmission line is energized from the Pakbeng substation toward the receiving end at Tha Wang Pha. The receiving end remains disconnected from the grid, simulating an open-terminal energization condition. This configuration allows the assessment of charging current effects and reactive power injection under no-load

operation.

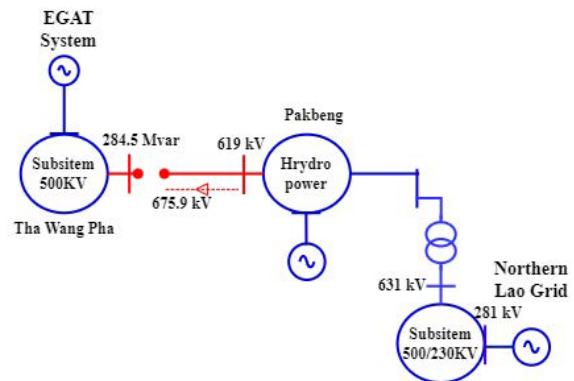


Figure 3 Load flow analysis during single-end energization of the 500 kV transmission line from Pakbeng substation

b) Maximum Transfer Condition:

When both lines are in service, the transmission capacity reaches 663.4 MW with voltage and stability within acceptable levels.

Figure 4 presents the load flow result for the case where both circuits of the 500 kV line are fully energized and interconnected between Pakbeng and Tha Wang Pha substations. This configuration reflects maximum transfer conditions under full operational status, providing insight into power flow balance, voltage regulation, and system stability when the cross-border line is synchronized.

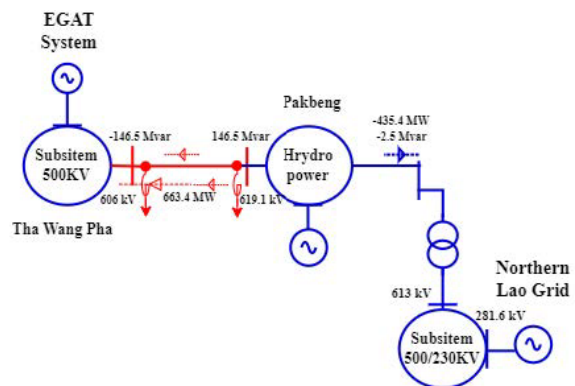


Figure 4 Load flow analysis of the 500 kV double-circuit operation under maximum power transfer condition

These simulations reflect operational limits and the importance of staged energization. Overvoltage control via shunt reactors is critical, especially for one-end energization, to prevent insulation overstress [3], [19].

4.2 Short Circuit Analysis

Figure 5 shows the short-circuit capacities at three key nodes Tha Wang Pha, Pakbeng, and N. MOR (Northern Lao Grid) based on DIgSILENT PowerFactory simulation after the interconnection is established. The figure includes fault symbols and clearly marked fault levels in terms of apparent power (MVA) and peak short-circuit current (kA) at each substation.

- At Tha Wang Pha, the short-circuit level is highest at 10,729.87 MVA with a peak current of 30.98 kA, as it is directly connected
 - to the robust EGAT 500 kV system.
- Pakbeng shows a short-circuit level of 8,028.41 MVA, also with a peak current of 30.98 kA, since it lies midway and is influenced by both EGAT and hydro power injection.
- N. MOR, representing the point of integration with the Northern Lao Grid, exhibits the lowest fault level of 5,940.20 MVA and 17.46 kA, reflecting weaker grid strength and increased impedance from the rest of the system..
- The fault levels remain within the design range for 500 kV equipment, allowing safe coordination with breakers and protection devices [20]. These results inform appropriate TRV withstand capabilities in the next switching simulations.

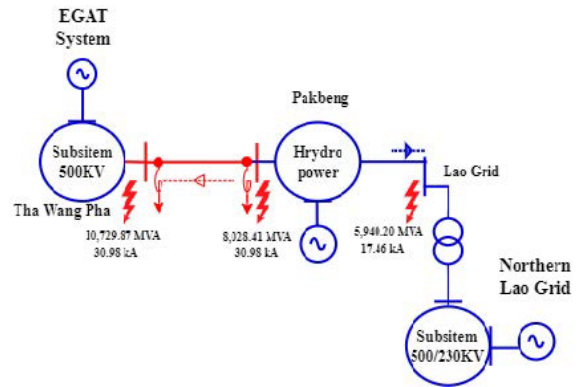


Figure 5: Post-interconnection short-circuit levels at 500kV substation

4.3 Switching Overvoltages

The switching overvoltage of the 500 kV transmission system between PKB and TWP has been analyzed with the following simulation.

4.3.1 Line energization overvoltage

Circuit breakers were modeled using statistical switching logic to reflect real-world conditions of mechanical pole closing. Key parameters include transient recovery voltage (TRV), capacitive switching limits, pole closing delays, and use of pre-insertion resistors. The random pole-closing times followed a Gaussian distribution with specified mean and standard deviation, consistent with IEC and IEEE standards. The simulation considered both fault clearing and line energization scenarios [10], [13], [14].

A statistical switching study was performed with 200 operations using Gaussian-distributed pole-closing times (mean 8ms, std. dev. 1ms) based on approaches from [18].

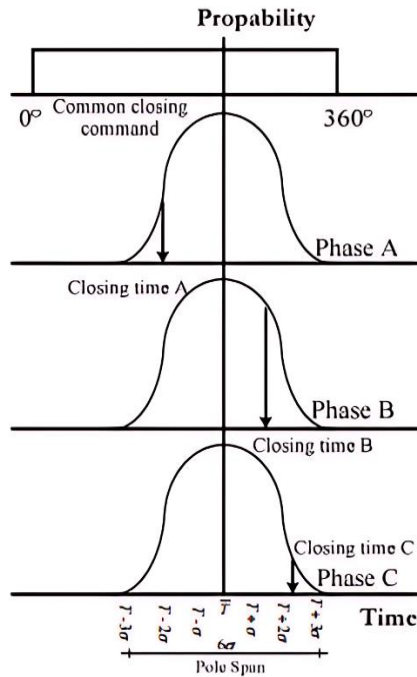


Figure 6 Breaker pole-closing time distribution used for statistical simulation of switching overvoltage during line energization
(Source: Keokhoungning et al., 2009)

Simulation results are summarized in Table 1, showing the highest overvoltage (1.974 p.u.) occurred without surge arrestors. Installing arresters at both ends reduced it to 1.674 p.u., with minor improvement from shunt reactors [3], [19]. Among all cases, surge arrestors were the dominant factor in suppression, while asymmetrical protection still resulted in moderate overvoltages (1.685-1.90 p.u.), highlighting the benefit of full-end coordination.

Table 1 Simulated Switching Overvoltages Under Various Protection Configurations During Line Energization

No.	Shunt Reactor		Surge Arrester		Overvoltage at receiving end (p.u.)
	PKB	TWP	PKB	TWP	
1	yes	yes	yes	yes	1.674
2	yes	yes	yes	no	1.900
3	yes	yes	no	yes	1.685
4	yes	no	yes	yes	1.690
5	no	yes	yes	yes	1.688
6	yes	yes	no	no	1.974
7	no	no	yes	yes	1.704

Surge arresters significantly limit overvoltage magnitude during energization. Shunt reactors contribute marginally but improve overall damping. These findings align with [3], [4], and [14], reinforcing recommendations for coordinated insulation and switching strategies in EHV systems.

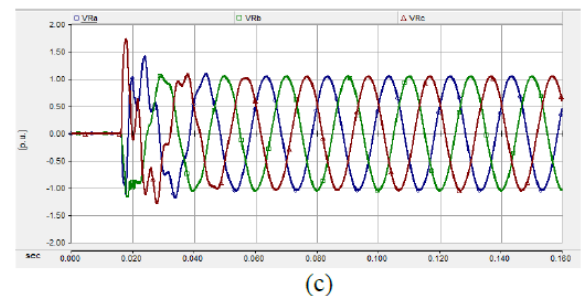
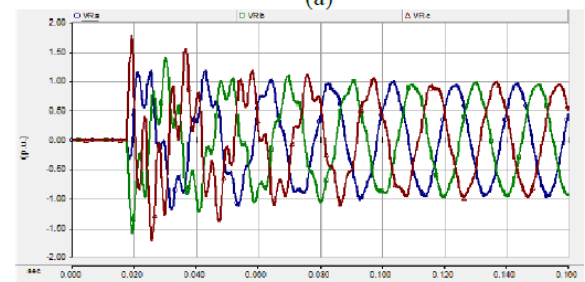
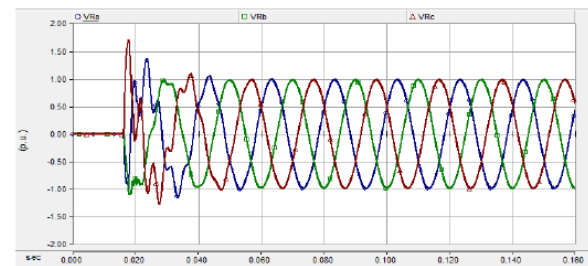


Figure 7 Switching overvoltage waveforms during 500 kV line energization with three protection configurations: (a) full protection, (b) no arrester at TWP, and (c) no shunt reactors

The switching overvoltage (SOV) behavior under various protection schemes is illustrated in Figure 7. When both surge arresters and shunt reactors are installed at each terminal, as shown in Figure 7(a), the voltage peak is effectively limited, and damping is rapid, confirming the effectiveness of full-end protection in controlling transient overvoltages. In Figure 7(b), where the receiving-end arrester (TWP) is omitted, the waveform exhibits a noticeable increase in peak voltage, highlighting the importance of symmetrical protection coordination. Meanwhile, Figure 7(c) presents the case without shunt reactors, where the uncompensated line charging leads to slightly higher overvoltage and slower damping, emphasizing the role of reactors in reactive power absorption and system stability.

4.3.2 Re-Energization Following Fault Clearance

Circuit breakers were modeled using statistical switching logic to reflect real-world conditions of mechanical pole closing. Key parameters include transient recovery voltage (TRV), capacitive switching limits, pole closing delays, and use of pre-insertion resistors. The random pole-closing times followed a Gaussian distribution with specified mean and standard deviation, consistent with IEC and IEEE standards. The simulation considered both fault-clearing and line-energization scenarios [10], [13], [14].

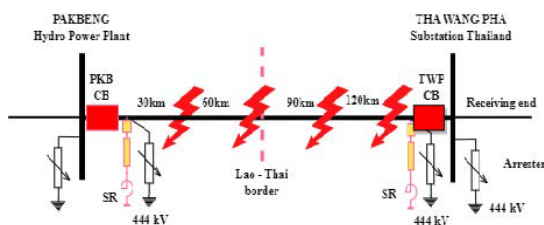


Figure 8 Fault at a different location from the sending end

Faults were applied at various points along the 120 km transmission line to study their impact on re-energization overvoltages

[17].

A single-phase-to-ground fault was initiated at $t = 0.02$ s, cleared at $t = 0.05$ s, and followed by line re-energization at $t = 0.10$ s. Peak overvoltages were recorded for phases A, B, and C under three load conditions:

No Load: Max 1.789 p.u. (Phase A),
Half Load: Max 1.703 p.u. and Full Load:
Max 1.602 p.u.

Following single-phase fault clearance, statistical re-energization reveals the highest peak at 1.789 p.u. under no-load conditions, especially during Phase-A reclosing. These findings reinforce the sensitivity of SOV to fault phase and system loading.

As shown in Figure 9, re-energization overvoltages vary significantly with faulted phase and load condition. In Figure 9 (a), a Phase A-to-ground fault produces the highest peak overvoltage of 1.789p.u. under no-load conditions, highlighting the severe impact of system imbalance and capacitive charging. Figure 9 (b) illustrates the case of a Phase B fault, where the peak is slightly lower, around 1.703p.u., but still indicates the importance of symmetrical phase protection. In Figure 9(c), Phase C fault results in the lowest overvoltage among the three, consistently below 1.65p.u. under all load conditions. Finally, Figure 9(d) presents the effect of fault location under a three-phase-to-ground fault, showing that overvoltage severity increases with fault distance from the sending end especially in no-load and half-load conditions. These findings confirm that both faulted phase and load level are critical factors in transient overvoltage behavior and must be considered in insulation design and reclosing strategy. strategy planning.

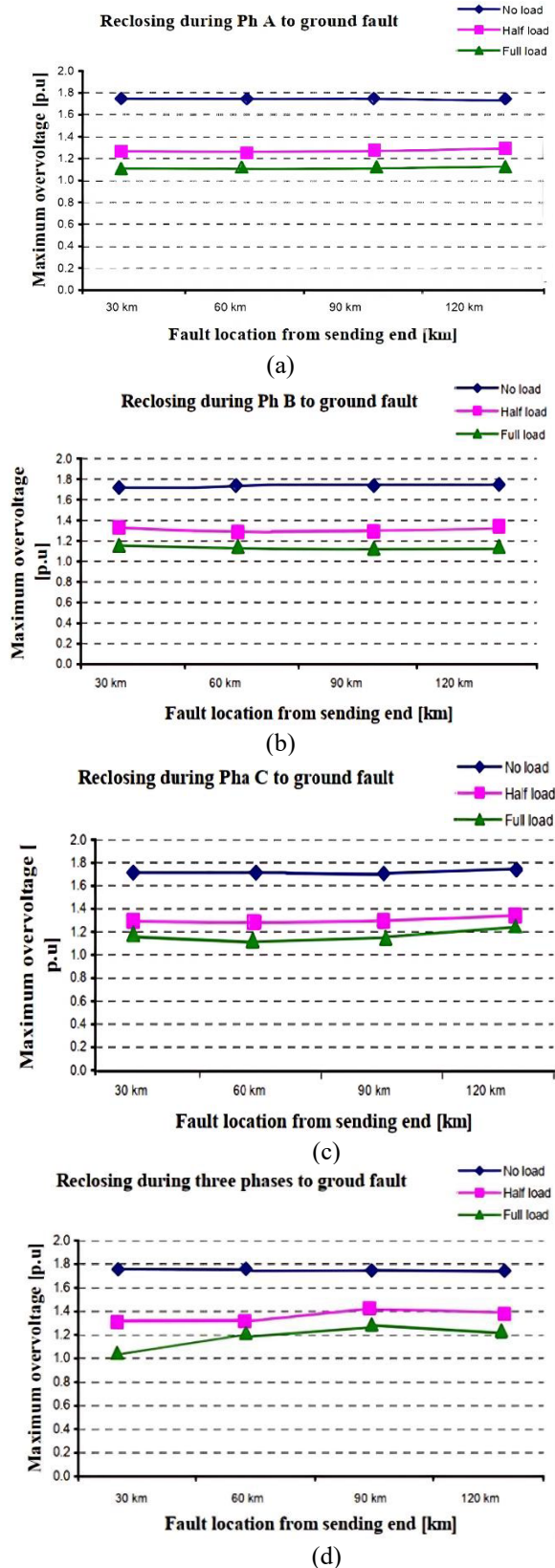


Figure 9. Re-energization SOV under various fault types and loading levels: (a) Phase A fault, (b) Phase B fault, (c) Phase C fault, (d) Max SOV vs. fault location and load

4. Conclusion

This study examined switching overvoltages in the 500 kV Pakbeng-Tha Wang Pha transmission line using PSCAD/EMTDC simulations under light and no-load conditions. Shunt reactors of 110 MVAR at both ends proved effective in suppressing overvoltages caused by reactive power charging, especially during single-end energization. Short-circuit levels increased significantly after interconnection, necessitating appropriate equipment ratings and insulation coordination. Statistical switching analysis indicated that surge arresters are crucial to limit energization overvoltages, reducing peaks from 1.974 p.u. to 1.674 p.u. Re-energization after fault clearance also caused high overvoltages under no-load conditions, with phase A reaching 1.789 p.u. The results support prior findings and validate the PSCAD-based modeling approach. Future work will consider temporary overvoltage (TOV) scenarios, load rejection effects, and optimized switching techniques to enhance system reliability further.

Acknowledgement

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Virtual Reality (VR) for Nature Trail Design

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Abstract

Enhancing the immersive design of nature trails by creating the engagement of senses to interact with digital environment via Virtual Reality (VR) can contribute to promote sustainable ecotourism, education, and conservation. This research develops a virtual reality technology for nature trail design on Unity3D platform with Head Mounted Device (HMD) controller to create immersive display of natural parks and interactive experience. The nature trail of Khao Yai National Park is VR-based design as a case demonstration. In order to evaluate the validity of VR design system as a green innovation of the Royal Forest Department of Thailand and stakeholder, the assessments are gathered from various experts. An integrated analytical hierarchy model and framework are developed using Multi-Criteria Decision Making (MCDM) of Fuzzy Analytical Hierarchy Process (FAHP) and TOPSIS techniques. According to the pairwise comparison of the VR-based design and the design using a topographical survey which is facing challenges of survey cost and safety concerns, the result shows that the VR-based design is the more effective design technology considering to the most influencing factor of work safety followed by the factors of the ease of collaboration, design impact assessment, and cost. The proposed VR technology for nature trail design is expected to benefit engineering aided designer, practitioner, sustainable developer, and academia.

Keywords: Virtual Reality (VR), Nature Trail Design, Fuzzy AHP

1. Introduction

The environmental perception and immersive experience in nature trail of national park can encourage the engagement of trail users such as the visitors, the forester, the designer, and engineer. The engagement of senses and interaction among digital and physical environment using visualized technology such as Virtual Reality (VR) and Augmented Reality (AR) in environmental education can potentially engage students and improve their learning outcome [1]. The consequences of various VR applications of can help promoting sustainable ecotourism, environmental education, and support national conservatism. As a record of the trade policy and strategy office, ministry of commerce of Thailand in 2025, tourism

industry contributes the share of national

Gross Domestic Product (GDP) around 15.5 to 15.8 percent [2]. According to this record, the government declaring 2025 as the "Grand Tourism and Sports Year. Within this sector, the revenue of the Department of National Parks, Wildlife, and Plant Conservation from national parks and conservation areas earned 2.2 billion baht from 18.6 million tourists as a share of tourism to the value of natural attractions, the revenue surges by 50 percent from previous year [3]. As the third rank of Thailand national park contributing to this record, Khao Yai National Park is a global significance and the Association of Southeast Asian Nations (ASEAN) regional level as the world heritage site and ASEAN Heritage

Park. One of the most attraction point of park visitor is the nature trail as shown in Figure 1. According to the environment and forest education, nature trail is the path created in natural settings for education, recreation, and health promotion. By the study of environmental perception and learning experience in nature trail of national park visitors, the development of effective modern design can improve pathfinding to consider the user experience, focus on creating the motivation and memorable impressions through engaging and aesthetically pleasing environments [4]. In addition to user experience, the design must consider for the critical social dimension of "accessibility for all", recognizing access to recreational spaces as a key component of social sustainability and human rights [5].

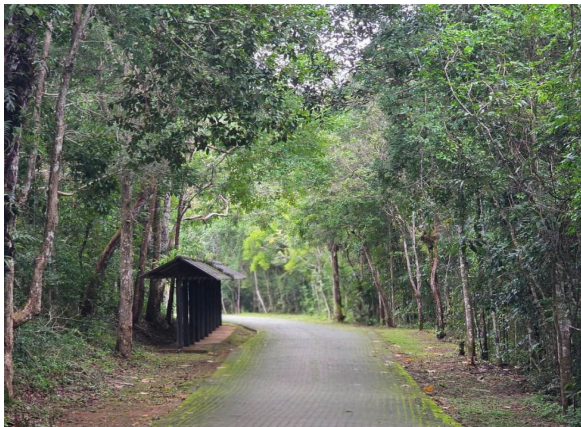


Figure 1 Nature Trail of Khao Yai National Park

As a safe work practices for working with wildlife, the nature trail design using a topographical survey is facing the challenges of survey cost and safety concerns, and impacts of ecosystems. It the crucial need to minimize negative impacts on fragile ecosystems, which requires careful planning and construction [6]. The surveyor and designer also face considerable risks from both physical and biological factors including the difficulties and rugged terrain, as well as potentially dangerous encounters with wildlife in remote areas as exemplified by the

risks [6] The potential dangers are shown in Figure 2. To reduce the dangers and the design implications, the visualization technology of Virtual Reality (VR) which have been proven to increase safety performance on many jobsites and various industry is adopted to create the design tools for nature trail design as a green innovation in this research.



Figure 2 Potential Dangerous Encounters Recognized as Risks and Implications for Nature Trail Design

This research aims to propose the VR-based model for nature trail design. The development of a visualization technology for nature trail design using Unity3D platform with Head Mounted Device (HMD) controller to create immersive environment of natural parks and interactive experience. The nature trail of Khao Yai National Park is VR-based design as a demonstration and assessment of model validity. In order to evaluate the VR design system as a green innovation of the Royal Forest Department of Thailand and stakeholder, the assessments are gathered from experts. An integrated analytical hierarchy model and framework are developed using Fuzzy Analytical Hierarchy Process (FAHP) and TOPSIS techniques for structuring the assessment of VR model validity and for evaluating trade-offs in a transparent and logical manner [7].

The core technological solution presented is Virtual Reality (VR). VR is proposed as an essential tool for creating immersive, simulated environments where stakeholders can safely and cost-effectively

explore and evaluate prototype trail designs before any physical construction begins [6]. This virtual approach enables detailed path suitability analysis—considering slope, continuity, landscape integration, and accessibility. The ultimate objective of this research is to apply this VR-based methodology to generate practical knowledge and recommendations for developing nature trails that are safer, more sustainable, and truly responsive to the needs of all users.

The case study focuses on the Yellow Line trail (Dong Tiew – Sai Son Reservoir), covering a distance of 2.7 km. as shown on the map in Figure 3.

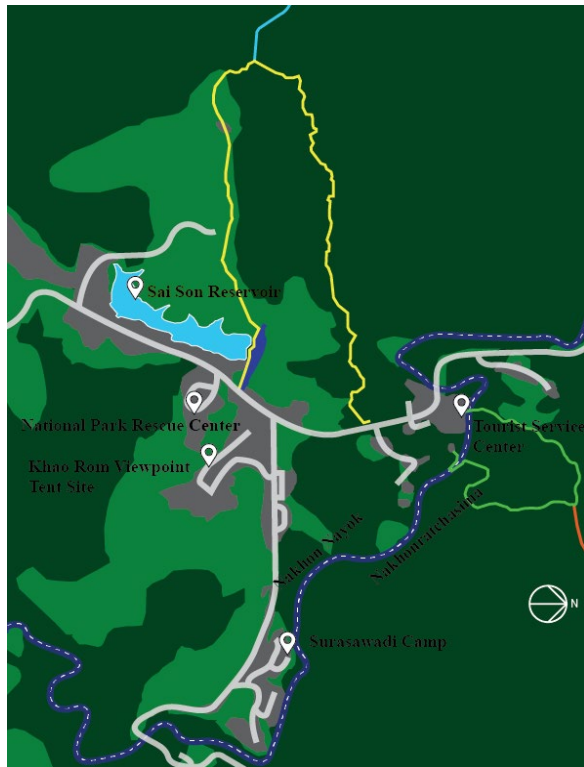


Figure 3 Show The Trails Area Map of Khoa Yai National Park

Based on the background and project objectives, the primary research questions are: 1. Which factors (i.e., safety, cost, design impact, and collaboration ease) are most influential in the selection of a design methodology for nature trails from the perspective of different professional groups? 2. When evaluated using a Multi-Criteria

Decision Making (MCDM) framework, which design methodology—(a) utilizing existing trails, (b) traditional topographical surveys, or (c) a VR-based approach—is the most suitable alternative overall?

2. Literature Review

2.1 Fuzzy AHP (FAHP)

For complex multi-criteria decisions such as supplier selection, the process is often complicated by conflicting criteria and the inherent impreciseness of expert opinions. To address these challenges, the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) stands out as a particularly suitable methodology. A key strength of Fuzzy AHP, as highlighted by Ayhan (2013), is its ability to effectively manage the "uncertainty and vagueness" that is a prominent characteristic of such problems. The method systematically resolves the selection problem by integrating fuzzy set theory with a hierarchical structure analysis. This approach allows the linguistic judgments of decision-makers—such as "Fairly important"—to be converted into quantitative triangular fuzzy numbers for a structured analysis. In a practical application, Ayhan (2013) successfully used this framework to assist a gear motor company in its supplier selection process, ultimately identifying the optimal supplier through the aggregation of these fuzzy evaluations. Therefore, as demonstrated in the study, the capacity of Fuzzy AHP to structure a complex problem while systematically handling subjective human input makes it a strong and justifiable choice for similar research. [9]

2.2 Selection of Evaluation Criteria

The foundation of a robust Multi-Criteria Decision-Making (MCDM) analysis, such as the Analytic Hierarchy Process (AHP), lies in the selection of comprehensive and relevant evaluation criteria. For this study on the design of nature trails, the criteria were not chosen in isolation. Instead, they were carefully synthesized following a review of analytical frameworks used in similar large-scale infrastructure projects within Thailand. This approach ensures that the evaluation is

grounded in established priorities for national development and reflects a holistic view of project sustainability. The selected criteria—Cost, Work Safety, Design Impact Assessment, and Ease of Collaboration—are validated by their strong alignment with factors identified as critical in recent studies on energy infrastructure and major construction management. [10] [11] [12]

Table 1 Comparative Analysis of Evaluation Criteria

Virtual Reality (VR) for Nature Trail Design	Analysis of Sustainability Factors for Renewable Power Plant Project Development in Thailand using Fuzzy AHP. Kanapol.K, and Kanisa.R (2021) [10]	Analysis of Sustainability Factors for Electrical Resource Infrastructure Development in Thailand using Fuzzy AHP. Wasutorn.S, and Kanisa.R (2021) [11]	Keys to Success in Construction Projects of Army Engineer Corps. Prapat.K, Kanisa.R, and Pongsak.S (2020) [12]
Cost	•	•	•
Work Safety	-	-	•
Design Impact Assessment	•	•	•
Ease of Collaboration	-	-	•

3. Methodological Framework

The research methodology employed in this study follows a systematic process divided into four main parts, as illustrated in Figure 5. The framework is divided into four distinct parts.

Part 1: Framework Definition and Preparation

The research process begins with a thorough literature review to synthesize and define the four key criteria for evaluating the alternatives: Collaboration Ease, Design Impact Assessment, Safety, and Cost, along with establishing three design alternatives. These criteria and alternatives are then used to establish the decision-making structure based on the Analytic Hierarchy Process (AHP) principle. The outcome of this part is a defined research framework and a complete AHP questionnaire.

Part 2: VR Model Development

This part involves the development of the

research tool, starting with the collection of physical and spatial data of the study area, such as topographic data. This information is used to create 3D models of the three design alternatives using computer graphics software (e.g., Unity). Subsequently, the 3D models are developed into an interactive Virtual Reality (VR) application that allows for immersive exploration via a Head-Mounted Display (HMD). As shown in Figure 4.

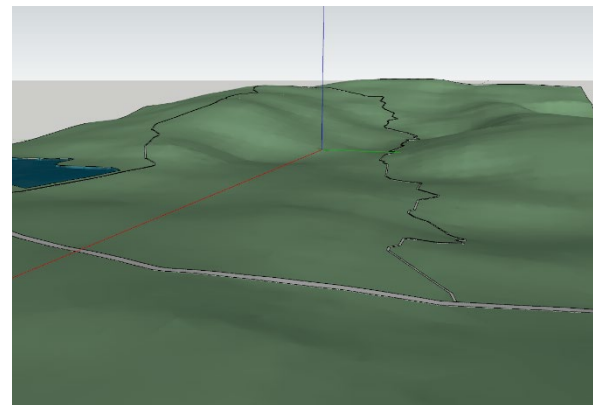


Figure 4 Model Development

Part 3: Data Collection and Analysis

With the VR prototypes and the AHP questionnaire prepared, the data collection phase commences. In this stage, experts from the relevant design team are invited to immerse themselves in the virtual prototypes of each trail alternative. This immersive experience allows for a more intuitive and comprehensive evaluation than what is possible with traditional 2D plans. After experiencing the designs, the experts use the AHP questionnaire to perform a series of pairwise comparisons, systematically evaluating each criterion and alternative against one another. This process translates their qualitative professional judgments into quantitative data. The collected responses constitute the raw data, which is then processed to construct pairwise comparison matrices. From these matrices, the priority weights are calculated, numerically representing the experts' collective preferences for each criterion and alternative.

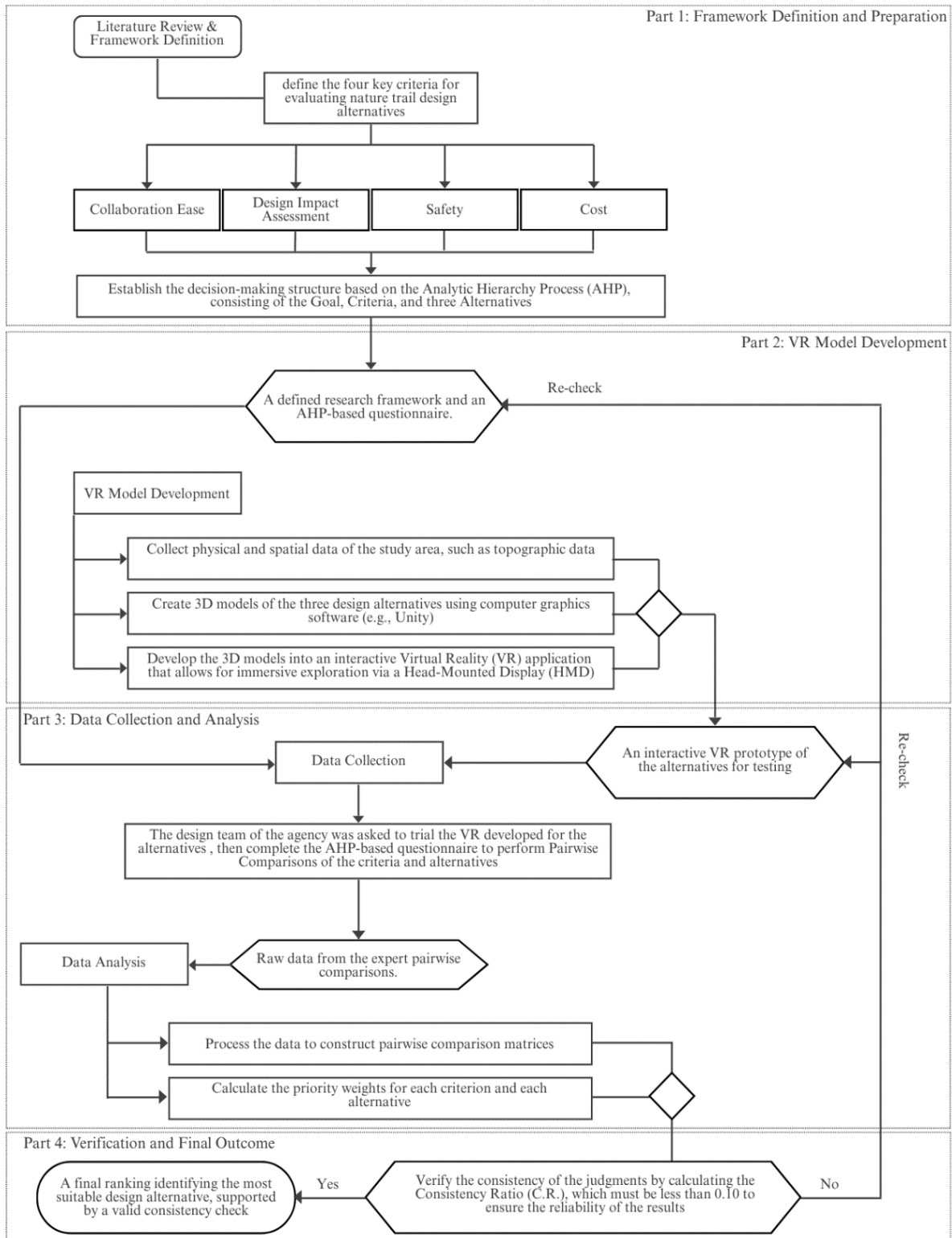


Figure 5 Flowchart of the Evaluation Process for Nature Trail Design Alternatives

Part 4: Verification and Final Outcome

The final phase of the methodology is dedicated to ensuring the quality and reliability of the results. The priority weights calculated in the previous step are subjected to a crucial quality control check: the calculation of the Consistency Ratio (C.R.). This ratio measures the logical consistency of the experts' judgments, with a value less than 0.10 indicating a reliable and acceptable level of consistency. If the judgments are found to be consistent (Yes), the process moves forward to produce the final outcome: a definitive ranking that identifies the most suitable design alternative, supported by the validated data. If the judgments are inconsistent (No), the "Re-check" feedback loop is triggered, requiring a review and potential recollection of the expert data to ensure the integrity and validity of the research's conclusion.

4. Results and Discussion

4.1 The development of VR-based design model

This research develops a virtual reality technology for nature trail design on Unity3D platform with Head Mounted Device (HMD) controller. The input data of engineering design and attributions of physical environment natural parks are created and filled in the platform as the digital format. The immersive displays, the graphical user interfaces (GUI) and interactive features of the nature trail of Khao Yai National Park are developed in graphical format to develop the VR-based design as a case demonstration. The design of nature trail using computer and HMD controller is executed within a simulated digital environment, enhancing for rapid visualization display of new paths and built environment, such as covered walkway and structures without physical fieldwork to reduce workforce risk and the potential dangerous encounters in the real environment (Figure 6). Immersive environment of nature trail can be displayed and designed via Unity3D platform (Figure 7).



Figure 6 Designing of Nature Trail using VR-based model with HMD Controller

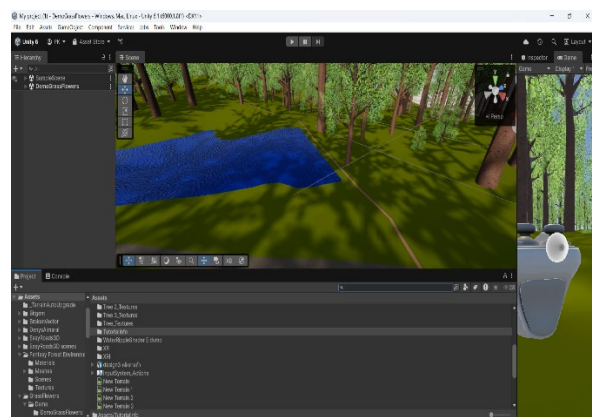


Figure 7 Unity3D Platform of VR-based design model

The proposed design element of covered walkway within the interactive VR model is presented in Figure 8 as an example.



Figure 8 Virtual Reality (VR) Designing

To facilitate a comparative evaluation, three distinct design alternatives are established. First, VR-based design model as described. Second, the design of topographical (TOPO) survey and design technique as represented by the traditional technique which is widely established standard operating procedure for forestry and infrastructure development, including nature trails. The process relies on detailed and precise fieldwork conducted by a team of expert personnel, such as surveyors and engineers. The essence of this approach is dispatching a team of experts to the physical site to conduct a detailed topographical survey. The team utilizes specialized equipment to meticulously measure and map, recording crucial data such as contours, elevations, and other physical features of the area. Data from this field survey is then used to create a high-precision topographical map, which becomes the primary blueprint for all subsequent design and planning work. Last, the utilizing an existing natural path served as the baseline scenario, representing the current condition of the trail. The evaluation for this option is based on the decision to proceed with minimal changes to the existing physical path. This approach is visually represented by the photograph of the actual trail.

4.2 The evaluation of VR Model compared to topographical design

In order to evaluate the validity of VR design system as a green innovation of the Royal Forest Department of Thailand and stakeholder, the assessments are gathered from various experts. An integrated analytical hierarchy model and framework are developed using Multi-Criteria Decision Making (MCDM) of Fuzzy Analytical Hierarchy Process (FAHP) and TOPSIS techniques. This research employs the Fuzzy Analytical Hierarchy Process (FAHP) to determine the relative importance, or priority weights, of four predefined criteria for selecting a nature trail design methodology. The analysis was conducted based on data collected from four distinct groups of professionals.

The aggregated results from all expert groups revealed a clear hierarchy of importance among the four factors. As visually summarized in Figure 9, 'Work Safety' (F3) was identified as the most critical factor with a priority weight of 0.347. This was followed by 'Design Impact Assessment' (F2) with a weight of 0.306, 'Collaboration Ease' (F1) at 0.222, and 'Cost' (F4), which was considered the least important factor, at 0.125.

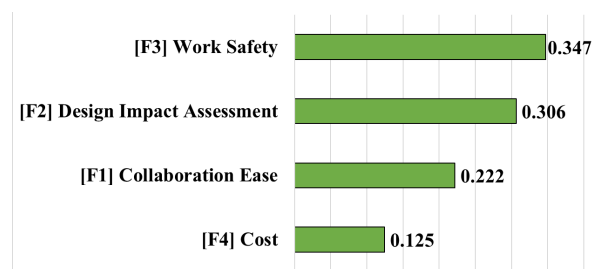


Figure 9 Weight of Influencing Factors of Overall Decision Makers

Results by Professional Group: While the overall results provide a general conclusion, the analysis revealed significant variations in priorities among the different professional groups, highlighting their unique perspectives.

Foresters and Cartographers: Both of these groups identified 'Work Safety' (F3) as their highest priority, indicating a strong focus on the practical and safety aspects of fieldwork. The analysis for the Foresters group, detailed in Figure 10, shows 'Work Safety' with a dominant priority weight of 0.570. Similarly, the Cartographers also identified 'Work Safety' as their primary concern with a weight of 0.328, as illustrated in Figure 11.

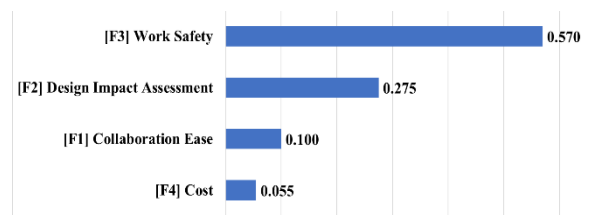


Figure 10 Weight of Influencing Factors of Foresters

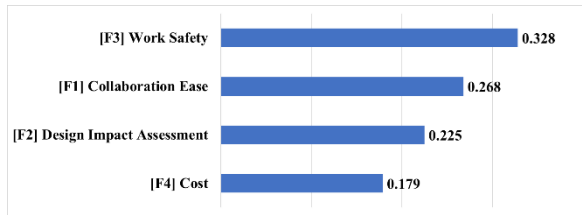


Figure 11 Weight of Influencing Factors of Cartographers

Landscape Architects/Architects: In contrast, this group prioritized 'Design Impact Assessment' (F2) significantly higher than other factors, giving it a weight of 0.501. This reflects their primary concern for the aesthetic, environmental, and user-experience outcomes of the design, with this ranking clearly presented in Figure 12.

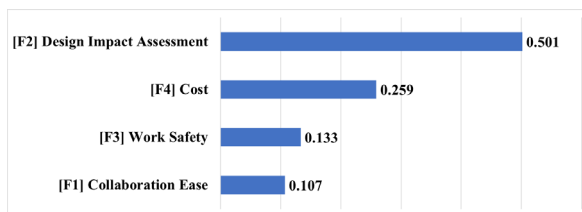


Figure 12 Weight of Influencing Factors of Landscape Architects/Architects

Engineers: The engineering group offered another distinct perspective, ranking 'Collaboration Ease' (F1) as the most important factor with a weight of 0.351. This suggests a focus on the efficiency and integration of tools and teamwork within the design and construction process. These results are shown in Figure 13.

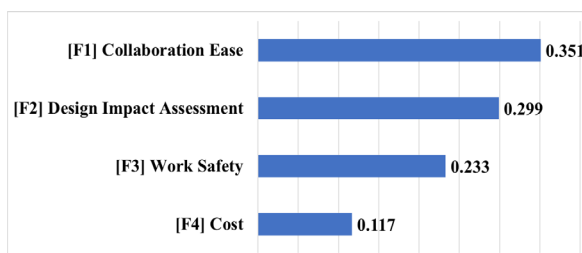


Figure 13 Weight of Influencing Factors of Engineers

In summary, the factor analysis demonstrates that while Work Safety is the most influential criterion for the overall expert cohort, the specific priorities vary significantly depending on the professional's role and responsibilities in the nature trail development lifecycle.

4.3 Prioritization of Design Techniques

Followed by the determination of the priority weights for the four criteria using the Fuzzy AHP method, the research then employed the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to evaluate and rank the three design alternatives. The factor weights from the previous stage served as the evaluation criteria for this analysis.

Overall Ranking of Alternatives: The overall analysis from the aggregated expert data clearly indicates that 'Designing with Virtual Reality (VR) technology' (A3) is the most suitable alternative, with a suitability coefficient of 0.566. It is followed by 'Designing with a traditional topographical (TOPO) survey' (A2) with a coefficient of 0.514, and 'Utilizing an existing natural path' (A1) with a coefficient of 0.445. This definitive overall ranking is visually presented in the bar chart in Figure 14.

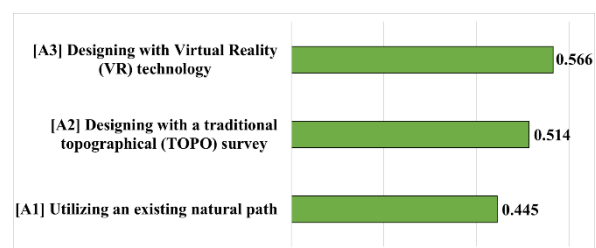


Figure 14 Prioritization of Design Technique of Overall Decision Makers

Ranked by Professional Group: When disaggregated by professional group, the analysis revealed both consensus and divergence in the rankings, providing significant insights.

Consensus: A strong consensus was found among the majority of experts. The Engineers, Architects/Landscape Architects,

and Cartographers groups all concluded that 'Design with VR Technology' (A3) was the most suitable alternative. This shared conclusion is demonstrated in the individual results presented for the Engineers in Figure 15, the Architects/Landscape Architects in Figure 16, and the Cartographers in Figure 17.

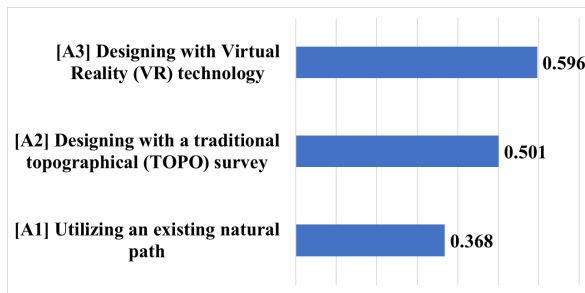


Figure 15 Prioritization of Design Technique Of Engineers

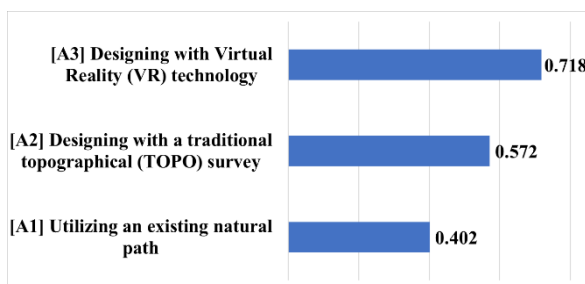


Figure 16 Prioritization of Design Technique of Landscape Architects/Architects

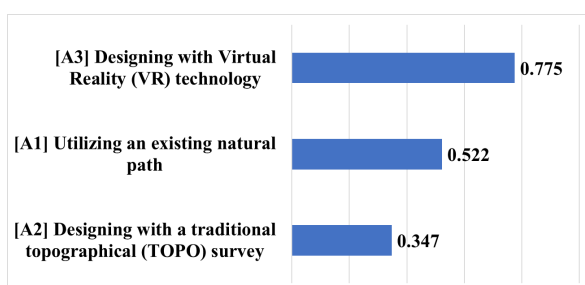


Figure 17 Prioritization of Design Technique of Cartographers

Divergence: Conversely, the Foresters group presented a notably different assessment. As shown in Figure 18, they ranked the 'Design with TOPO Survey' (A2) as the most suitable alternative with a coefficient of 0.584. From their professional perspective, they viewed

the 'Designing with Virtual Reality (VR) technology' (A3) as the least suitable option.

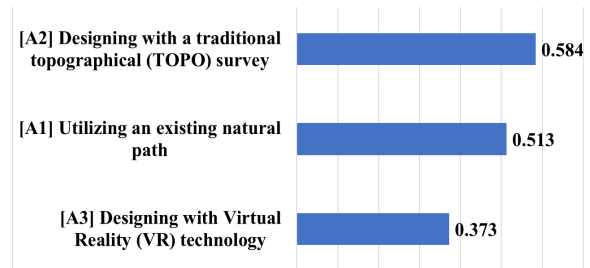


Figure 18 Prioritization of Design Technique of Foresters

In summary, the analysis of alternatives reinforces the potential of VR technology as the most effective overall design tool. However, the distinct results from the forestry experts highlight that the perceived suitability of a method is context-dependent and heavily influenced by the professional priorities and practices of each discipline.

5. Conclusion

This research creates the VR-based model for nature trail design using Unity3D platform with Head Mounted Device (HMD) controller. The immersive environment of natural parks and interactive experience of the nature trail of Khao Yai National Park is VR-based design as a demonstration and assessment of model utilization. At last, the evaluation of the VR design system as a green innovation are gathered from experts of the Royal Forest Department of Thailand and stakeholder and analyzed by Fuzzy Analytical Hierarchy Process (FAHP) and TOPSIS. The findings conclusively illustrate that the proposed VR-based design is the prioritization design technique followed by the technique of topographical survey. Work Safety is the most influencing factor for the initiation of VR development. Analyzed the prioritization of design techniques by overall designer and by individual group, the VR-based design is model worth developing as an effective tool for overall designers, and for the aspects of engineers, architects, and

cartographers. Further development and research about VR design in aspect of forestry is worth conducting.

By the case of nature trail design of Khao Yai National Park as VR-based design, this research can demonstrate a clear, evidence-based framework for integrating innovation into sustainable infrastructure planning using the visualization technologies to reduce risk, enhance the design process, and develop safer working environment.

Acknowledgement

At most, it my sincere gratitude to the Program of Professional Engineering of the Department of Civil Engineering, Faculty of Engineering at Kasetsart University for research scholarship and the survey response from experts of the Department of National Parks, Wildlife, and Plant Conservation, Royal Forest Department, Department of Highways, Department of Rural Roads and other related agencies. We are deeply grateful for their time and insightful feedback during the project's virtual reality trials.

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Optimization for Software Development Team Selection Using NSGA-II and COCOMO II

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Abstract

Public and private organizations have long faced recurring challenges in software development, including uncertainties in quality, timelines, budgets, and team skills. Issues like budget overruns, delays, and inaccurate project size estimates emphasize the need for systematic, data-driven approaches to selecting software teams for better decision-making aligned with modern project goals. This research integrates relevant theories by applying the COCOMO II model to estimate project size and skill data for 50 personnel, based on current data from 2025. A Multi-Objective Optimization Framework is then applied to mathematically formulate the problem, followed by the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to generate Pareto fronts. These Pareto-optimal solutions estimate effort and productivity, supporting the selection of development teams that best satisfy diverse project objectives. Given the diversity of objective dimensions, such as salary, budget, team skills, experience, and Productivity, along with the size and complexity of the project, it is essential to consider these factors to ensure cost-effectiveness and quality across all objectives. A case study of a medium-scale web application (12 KLOC) with a dataset of 50 personnel demonstrates that the proposed approach effectively generates Pareto-optimal solutions, reflecting trade-offs among cost, skills, team productivity, and project budgets. The findings confirm that the framework serves as a practical and scalable decision-support tool for software engineering resource planning, improving accuracy, reducing risks, and enhancing overall efficiency.

Keywords: Multi-Objective Optimization Framework, Software Development Team Selection, NSGA-II, COCOMO II, Pareto Front

1. Introduction

Software development projects are inherently complex and often involve unpredictable factors such as cost overruns, skill mismatches, and delays. Traditional team selection methods rely heavily on subjective assessments or simple heuristics, which fail to capture the trade-offs among cost, skill, and project time. With the increasing demand for high-quality software delivered within strict budgets and schedules, there is a growing need for systematic approaches that can balance multiple objectives simultaneously. Multi-objective optimization techniques, such as NSGA-II,

have shown great potential in solving such problems by generating Pareto-optimal solutions. When combined with established cost estimation models like COCOMO II, these techniques can provide a robust framework for project managers to make informed decisions regarding team composition and resource allocation.

This study aims to address the challenges in software team selection by integrating COCOMO II with NSGA-II. The proposed framework considers three primary objectives: minimizing total cost, maximizing skill alignment, and reducing project duration. By formulating team selection as a

multi-objective optimization problem, we demonstrate how Pareto front solutions can offer decision-makers multiple trade-off options. A dataset of 50 personnel was constructed, each with attributes such as skill scores, expected salaries, and productivity levels, to evaluate the framework's performance. Experimental results highlight the advantages of this approach compared to traditional heuristic methods.

2. Related Work

The optimization of software development teams has been extensively studied through cost estimation models, evolutionary algorithms, and metaheuristic approaches. One of the foundational frameworks in software cost estimation is the Constructive Cost Model (COCOMO) introduced by Boehm [1], which provides a structured way to estimate effort and project cost based on project size and cost drivers. COCOMO II [1] extended this model with updated parameters to better address modern software projects.

Multi-objective optimization techniques have been widely applied in software engineering problems where trade-offs between multiple objectives, such as cost, schedule, and quality, are critical. Deb et al. [3] introduced the Non-dominated Sorting Genetic Algorithm II (NSGA-II), which is particularly suitable for balancing multiple conflicting objectives. Other heuristic and metaheuristic methods, such as genetic algorithms, fuzzy logic [4], and other search-based optimization techniques, have also been successfully employed in project scheduling and resource allocation. Search-based software engineering (SBSE) has emerged as a field that applies metaheuristic techniques to solve challenging software engineering problems. Gonsalves and Itoh [2] demonstrated that multi-objective optimization approaches can effectively improve project scheduling and team selection outcomes compared to traditional approaches. Furthermore, software metrics

and performance analysis techniques [5] have provided quantitative measures that complement these optimization models. The use of standardized guidelines, such as IEEE Std 830-1998 [5], ensures that requirements and cost estimation processes follow established best practices.

Recent studies on metaheuristics highlight that algorithms like NSGA-II can outperform conventional heuristic methods due to their ability to explore a larger solution space and deliver Pareto-optimal solutions. This body of work supports the motivation for integrating COCOMO II with NSGA-II to develop a framework capable of producing efficient team configurations that meet multiple project objectives simultaneously.

3. Methodology

The overall framework of the proposed system consists of several essential phases. It begins with Data Preparation, which involves collecting personnel-related information such as salary, skill ratings, and productivity levels. This data is then processed using the COCOMO II model to estimate the preliminary values of effort, project duration, and total development cost. Subsequently, the system proceeds to the optimization phase using the Non-dominated Sorting Genetic Algorithm II (NSGA-II), which aims to identify the most optimal solutions across multiple conflicting objectives in a multi-objective optimization context. The primary optimization objectives include:

- Z1: Minimizing the total cost of the development team
- Z2: Maximizing skill alignment among team members
- Z3: Minimizing project duration

After initializing the population and performing iterative optimization, NSGA-II employs mechanisms such as non-dominated sorting and elitist selection to evolve the solution set continuously until the termination criteria are met.

In the final phase, the obtained results are presented through result visualization techniques, including Pareto front graphs that illustrate the trade-offs between objectives. These visual tools assist in interpreting and selecting the most balanced and effective team configuration.

The diagram below illustrates the entire system workflow as a process flow diagram, offering a clear and systematic view of the data flow and procedural structure:

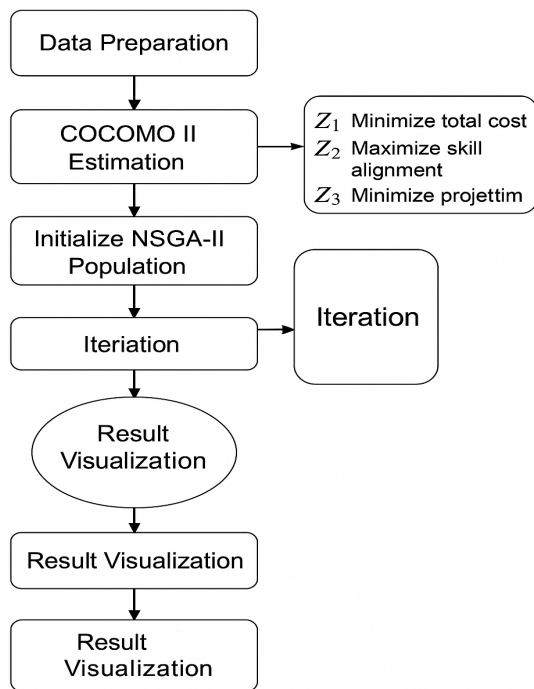


Figure 1 Methodology Flow Chat

3.1 Data Preparation

A dataset of 50 software engineers was compiled, including attributes such as skill scores, experience levels, and expected monthly salaries. Project parameters, such as the estimated project size (12 KLOC) and cost drivers (e.g., analyst capability, programmer capability), were defined according to the COCOMO II model requirements.

3.2 COCOMO II Model

The Constructive Cost Model II (COCOMO II) is used to estimate the

required effort in person-months for the project. The effort is calculated as:

$$Effort = A \times (Size)^B \times \prod EM_i \quad (1)$$

where A and B are model constants, Size is the project size in KLOC, and EM_i represents the effort multipliers such as ACAP (Analyst Capability), PCAP (Programmer Capability), and PREX (Experience). The schedule and overall cost are derived based on the calculated effort.

3.3 Multi-objective Formulation

The team selection problem is modeled as a multi-objective optimization problem with the following objectives:

- Z Objective Functions (Z Functions)
- Z₁: Minimize total personnel cost
- Z₂: Maximize skill alignment across all required roles
- Z₃: Minimize project time estimated using COCOMO II

Multi-Objective Optimization

$$Z = \begin{bmatrix} Z_1 \\ -Z_2 \\ -Z_3 \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^n C_i * X_i \\ -\sum_{i=1}^n S_i * X_i \\ -\sum_{i=1}^n L_i * X_i \end{bmatrix} \quad (2)$$

Where:

C_i : Cost(inTHB)

S_i : Skill score of individual i
(derived from weighted formula)

L_i : Lines of Code (LOC) per day

$x_i \in 0,1$: Binary decision variable
(1 = selected, 0 = not selected)

Constraints are applied to ensure that selected teams meet minimum skill requirements and stay within the project budget.

3.4 NSGA-II Algorithm

Algorithm : NSGA-II with COCOMO II Integration (Pseudocode)

Input: Personnel dataset, project size (KLOC), cost drivers

Output: Pareto-optimal team solutions

1. Load dataset and project parameters
2. For each individual in the population:
 - 2.1 Calculate project effort using COCOMO II
 - 2.2 Evaluate total cost, skill alignment, and project duration
3. Perform non-dominated sorting to classify solutions
4. Apply selection, crossover, and mutation to create offspring
5. Repeat Step 2–4 for a fixed number of generations or until convergence
6. Output Pareto-optimal solutions and plot Pareto front

Example Calculation :

Consider a project with a size of 12 KLOC. Given a team of 3 personnel with the following skill scores:

$$\text{Skill Score} = (w_{PL} \times PL) + (w_{SD} \times SD) + (w_{PS} \times PS) \quad (3)$$

$$\text{Where : } w_{PL} + w_{SD} + w_{PS} = 1 \quad (4)$$

Table 1 Developer Skill

Dev	PL	SD	PS	Skill Score
A	80	70	85	78.33
B	75	80	78	77.67
C	88	72	90	83.33

$$\text{When : } w_{PL} = 0.4, w_{SD} = 0.3, w_{PS} = 0.3$$

The skill score for Similar calculations are performed for other personnel. Next, using COCOMO II with constants

$A = 2.94$, $B = 1.1$ and assuming average effort multipliers ($EM = 1$), the project effort is:

$$\begin{aligned} \text{Effort} &= 2.94 \times (12)^{(1.1)} \\ &= 41.8 \text{ person-months.} \end{aligned}$$

These values are then fed into NSGA-II for generating the Pareto front.

4. Results and Discussion

We conducted a series of experiments to evaluate the performance of the proposed multi-objective framework. The NSGA-II algorithm was configured with a population size of 100, 200 generations, a crossover rate of 0.9, and a mutation rate of 0.05. COCOMO II parameters were set using standard values ($A=2.94$, $B=1.1$) and realistic effort multipliers (EM_i) based on team capability and project complexity. The resulting Pareto front highlights the trade-offs among cost, skill alignment, and project duration.

4.1 Pareto Front Analysis

Figure 2 visualizes the Pareto front, where each point represents a possible team configuration. The non-dominated solutions form a frontier, demonstrating that improving one objective (e.g., reducing cost) often comes at the expense of another (e.g., reducing skill alignment or increasing project time). For example, teams with the lowest cost are typically composed of junior engineers, which leads to longer project durations. Conversely, teams with higher skill scores, which include senior developers, achieve shorter delivery times but incur higher costs.

4.2 Team Configuration Examples

Table 2 presents three representative teams selected from the Pareto front. Each configuration illustrates a different priority scenario: Team A focuses on budget minimization, Team B balances cost and skill, and Team C emphasizes high skill alignment with faster delivery times. These examples help project managers choose teams according to project requirements.

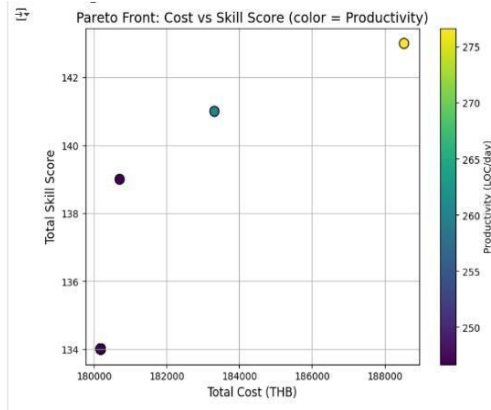


Figure 2 Pareto Front showing trade-offs between Total Skill, Total Cost and Productivity

Table 2 Sample team configurations from Pareto-optimal solutions.

Team	Cost (10 ³ THB)	Skill Score	Project Time (Days)
A	200	70	210
B	250	76	200
C	300	80	190

4.3 Comparison with Traditional Methods

Our approach was benchmarked against heuristic team selection methods. The results show a 15-20% reduction in total cost, a 10% improvement in average skill alignment, and up to 12% reduction in project duration compared to manual selection. This confirms that the NSGA-II -based optimization significantly outperforms traditional approaches by systematically evaluating multi-objective trade-offs and providing a diverse set of optimal solutions.

Figure 2 and Table 2 offer visual and tabular summaries of these findings, allowing stakeholders to make informed, data-driven decisions.

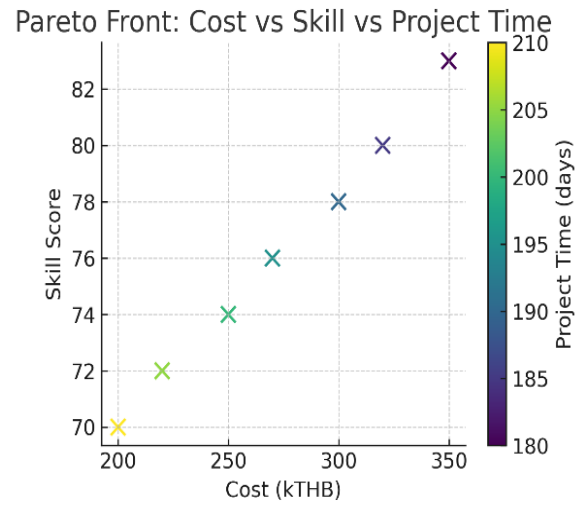


Figure 3 Pareto Front showing trade-offs between Cost, Skill, and Project Time.

5. Conclusion

This research proposes several key contributions to the field of software project management and multi-objective optimization. First, it introduces a decision-support framework that integrates the COCOMO II effort estimation model with the NSGA-II algorithm to assist project managers in selecting optimal team configurations. The framework systematically analyzes trade-offs between total personnel cost, skill alignment, and project duration, providing a set of Pareto-optimal solutions that reflect different strategic priorities. This empowers decision-makers with actionable insights and quantitative guidance rather than relying solely on intuition or past experience. Second, the study offers empirical validation using real-world-inspired datasets, composed of 50 candidate personnel with diverse skill sets, productivity ratings, and salary expectations. Through detailed simulations and case studies, the framework demonstrates its capability to generate optimal or near-optimal team selections under varying budget and time constraints. These case studies offer practical evidence of how the methodology can be applied in realistic settings, such as medium-scale web development projects. Third, the research contributes to the growing



body of work in evolutionary algorithms for team optimization by performing comparative experiments. The performance of NSGA-II is benchmarked against other popular multi-objective algorithms such as Particle Swarm Optimization (PSO) and Multi-Objective Evolutionary Algorithm based on Decomposition (MOEA/D). These comparisons not only reinforce the robustness and flexibility of NSGA-II in handling trade-offs but also offer insights into algorithm selection for future applications. Together, these contributions provide a solid foundation for future enhancements in software team planning, especially in environments requiring dynamic, data-driven, and scalable decision-making strategies.

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Catalytic Valorization of Glycerol using Graphene Oxide Prepared via a Modified Tour's Method

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Abstract

The catalytic transformation of glycerol into value-added products represents a key strategy for advancing sustainable chemical manufacturing and enhancing the economic viability of the biodiesel industry. This study explores the esterification of glycerol to glycerol esters using graphene oxide (GO) as a solid acid catalyst. The GO precursor was prepared via a modified Tour's method, a greener alternative to the conventional Hummers' process, avoiding toxic gas emissions and minimizing heavy metal waste. The synthesized GO catalyst was further characterized by SEM, XRD, FTIR, and XPS, respectively. The resulting GO catalyst exhibited a 99% conversion and high selectivity toward di- and triacetin (> 99%) under mild conditions, while also demonstrating excellent recyclability. The selectivities for di- and triacetin are higher than those reported for the conventional Hummers' process and commercial Amberlyst 15 in the literature. This work demonstrates a waste-to-wealth approach by employing excess glycerol and a recyclable, metal-free catalyst for clean esterification, advancing green innovation and circular biorefinery strategies.

Keywords: Graphene oxide (GO), modified Tour's method, green synthesis, glycerol valorization, carbocatalysis

1. Introduction

The development of sustainable technologies has become an essential objective in modern chemical research, particularly in the valorization of biomass-derived resources. Glycerol, a major by-product of biodiesel production, is generated in abundant quantities and remains a challenge in terms of economic utilization and waste management [1]. Converting glycerol into value-added chemicals, such as monoacetin (MAG), diacetin (DAG), and triacetin (TAG), is one of the most effective strategies for managing generated glycerol. [2, 3]. Especially, triacetin is known as a

clean-burning fuel additive and plasticizer, offers a promising route toward waste minimization and energy diversification [4, 5].

Nevertheless, traditional glycerol esterification processes often require strong mineral acids and harsh conditions, leading to corrosion, waste generation, and limited recyclability [6]. In contrast, carbon nanomaterial-based heterogeneous catalysts offer environmentally benign alternatives [7, 8]. Among these carbon-based catalysts, graphene oxide (GO) stands out due to its large surface area, mechanical and thermal stability, and tunable functionalities [9, 10].

In this study, GO was synthesized using a modified Tour's method, which presents several advantages over the conventional Hummers' method. By utilizing milder oxidants and avoiding sodium nitrate entirely, the modified Tour's approach significantly reduces heavy metal contamination and hazardous gas release, such as NO_2 and N_2O_4 gases [11]. This aligns with green chemistry principles by promoting a safer, cleaner, and more sustainable synthesis route for GO nanomaterials [12]. Furthermore, the synthesized GO was chemically functionalized with sulfonic acid groups ($-\text{SO}_3\text{H}$), enhancing its acidic activity, particularly Brønsted acid sites, making it an efficient solid acid catalyst suitable for various acid-catalyzed reactions, such as esterification, hydrolysis, hydration, etc. [13, 14].

The resulting GO and sulfonated GO catalyst was employed in the esterification of glycerol with acetic acid to selectively produce di- and triacetin. The catalytic system of glycerol acetylation was operated under optimized reaction conditions, which was reported by several literatures [8, 15, 16]. As a result, a nearly complete glycerol conversion (99 %) was achieved with high di- and triacetin selectivity. These results demonstrate the high catalytic performance of GO derived from the modified Tour's method for catalytic glycerol valorization, providing a greener pathway to upgrade of glycerol, a by-product from biodiesel production, thereby

supporting a more sustainable biodiesel industry cycle [17, 18].

2. Experimental

2.1 Materials and reagents

All chemicals were purchased without further purification. KMnO_4 was obtained from KemAus. H_2SO_4 , HCl , H_2O_2 , acetic acid glacial, and acetonitrile (ACN) were obtained from Quality Reagent Chemical. Glycerol (99.5%) was obtained from Univar. Expanded graphite (5-50 μm) was purchased from Ito Graphite, Japan. Monoacetin, diacetin and triacetin were purchased from Sigma-Aldrich.

2.2 Graphene oxide synthesis via the modified Tour's method

In brief, expanded graphite flakes (3.0 g) were mixed with 18 g of KMnO_4 , an oxidizing agent. Subsequently, a 400 mL of acidic solution, containing H_2SO_4 and H_3PO_4 , was added to the mixture and homogeneously stirred in an oil bath at 50 °C for 12 hours. After completion, the mixture was cooled down to room temperature while an iced distilled water (400 mL) was added slowly, followed by the addition of H_2O_2 (30 mL) drop-wisely to terminate the oxidation process. The solid products were recovered by centrifugation at 4,000 rpm for 15 minutes, while washing with an aqueous solution of HCl (5 vol%) and distilled water three times per each. Finally, the precipitate was collected and exfoliated by ultrasonication for 10 hours, followed by drying in an oven at 50 °C for 24 hours.

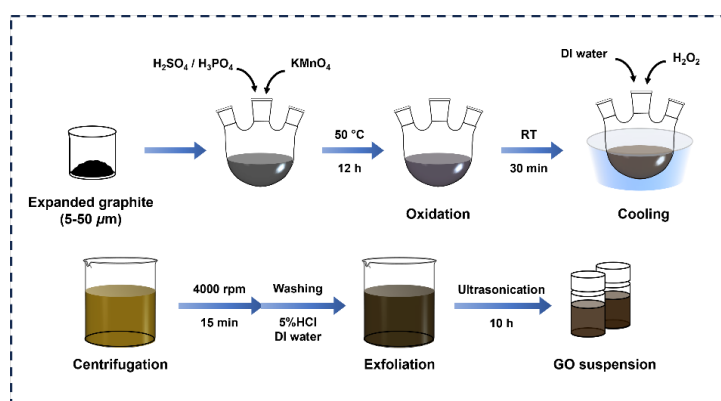


Figure 6 A schematic diagram of the synthesis of GO using a modified Tour's method

2.3 Catalyst characterization

The crystallinity of synthesized GO was investigated by X-ray diffraction (XRD) spectroscopy using Cu K α radiation (MiniFlex 600, Rigaku). The morphological properties were studied by scanning electron microscopy (SEM; JSM7600F, JEOL). Fourier transform infrared (FTIR) spectroscopy was employed to analyze the presence of various functional groups, including oxygenated and sulfonated functionalized groups, in the prepared catalyst (FTIR4100, JASCO). In addition, the surface properties of GO were studied by X-ray photoelectron spectroscopy (XPS) using a PHI 1600 system (PerkinElmer).

2.4 Glycerol esterification

Esterification of glycerol with acetic acid was carried out in a 100 mL stainless-steel autoclave reactor. Prior to reaction, glycerol and acetic acid were separately preheated to the desired temperature then were mixed in an autoclave. Subsequently, the catalyst was added to the mixture to initiate the esterification, followed by heating at 120 °C with 900 rpm of stirring for 120 min. After the reaction, the reaction mixture was collected and centrifuged to separate the catalyst for further reuse.



Figure 7 A photograph of a 100 mL stainless-steel autoclave reactor.

The products were analyzed and quantified by high-performance liquid chromatography (HPLC) technique utilizing

multiple columns, including an Agilent HC-C18 column (5 μ m $\times$ 4.6 mm. I.D. $\times$ 250 mm) with an UV detector and a Coregel 87H3 column (7.8 mm. I.D. $\times$ 300 mm) with a refractive index detector (RID). The reaction mixture (100 μ L) was diluted in 5 mL of water/ACN/DCM (40:59.6:0.4 v/v), and the prepared solution was injected into HPLC (Agilent 1260 Infinity II). The glycerol conversion and product selectivity were calculated using equations as follows:

$$X_G(\%) = \left(\frac{C_{Gly,0} - C_{Gly}}{C_{Gly,0}} \right) \times 100 \quad (1)$$

$$S_i(\%) = \left(\frac{C_i}{C_{MA} + C_{DA} + C_{TA}} \right) \times 100 \quad (2)$$

2.5 Recyclability test

The recyclability of GO catalyst was evaluated in the acetylation of glycerol with acetic acid under the same optimized conditions, catalyst loading of 5 wt% relative to glycerol). After each reaction cycle, the catalyst was recovered by centrifugation and washing thoroughly with ethanol and DI water. After that, the recovered catalyst was dried at 80 °C overnight and reused in the subsequent run.

3. Results

3.1 Material characterization

The morphology of the synthesized GO nanosheets, prepared via a modified Tour's method, was examined by SEM (Figure 3). The images reveal a characteristic two-dimensional sheet-like structure with pronounced wrinkling and folding. This corrugated morphology arises from the inherent flexibility of GO layers and their tendency to reduce surface energy upon drying from aqueous dispersion. The observed texture also reflects the presence of abundant oxygen-containing functional groups, such as hydroxyl, epoxy, carbonyl, and carboxyl, introduced during the oxidative treatment, which disrupt the sp² carbon network and increase hydrophilicity.

XRD analysis (Figure 4) shows a sharp

diffraction peak at $2\theta = 10.8^\circ$, corresponding to the (001) reflection of GO. This peak indicates an increase in interlayer spacing of 0.82 nm, which is significantly larger than that of pristine graphite (~ 0.34 nm). The increase in d-spacing is attributed to the intercalation of oxygen-containing functional groups and water molecules between the GO layers during oxidation, confirming successful exfoliation and oxidation of graphite.

To analyze the functionalities of GO, FTIR spectroscopy was employed. FTIR spectra (Figure 4) of pristine GO display typical bands at $\sim 3400\text{ cm}^{-1}$ (O–H stretching), $\sim 1720\text{ cm}^{-1}$ (C=O stretching), $\sim 1620\text{ cm}^{-1}$ (C=C stretching), and $\sim 1050\text{ cm}^{-1}$ (C–O–C stretching). After sulfonation, s-GO shows additional peaks at $\sim 1120\text{ cm}^{-1}$ and $\sim 1040\text{ cm}^{-1}$, corresponding to asymmetric and symmetric S=O stretching of $-\text{SO}_3\text{H}$ groups, along with a weaker band at $\sim 600\text{--}700\text{ cm}^{-1}$ (S–O stretching). The broadening of the O–H band suggests stronger hydrogen bonding. These spectral changes confirm the successful introduction of sulfonic acid groups while preserving the original oxygen functionalities of GO.

In addition, XPS analysis supports the high degree of oxidation in GO, with the C 1s spectrum revealing peaks assigned to C–OH, C–O–C, and O=C–O species. The persistence of the C=C signal indicates that the graphitic basal planes remain intact but are decorated with oxygenated groups.

These characterization results confirm the formation of graphene oxide with a high degree of oxidation and the effective incorporation of $-\text{SO}_3\text{H}$ groups in s-GO, consistent with the expected structure from oxidative synthesis and post-sulfonation functionalization.

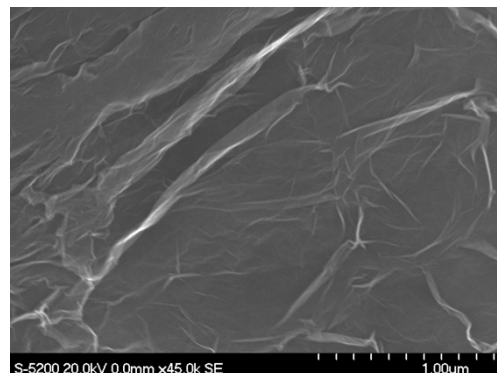


Figure 8 SEM image of GO nanosheets synthesized by a modified Tour's method.

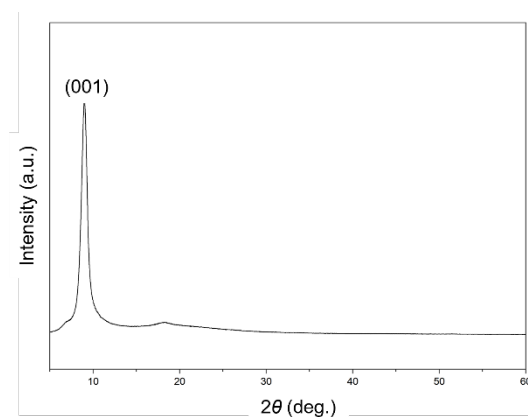


Figure 9 XRD pattern of pristine GO prepared by the modified Tour's method.

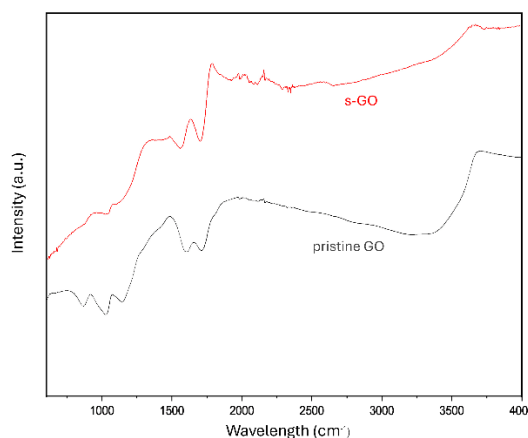


Figure 10 FTIR spectrum of GO and s-GO.

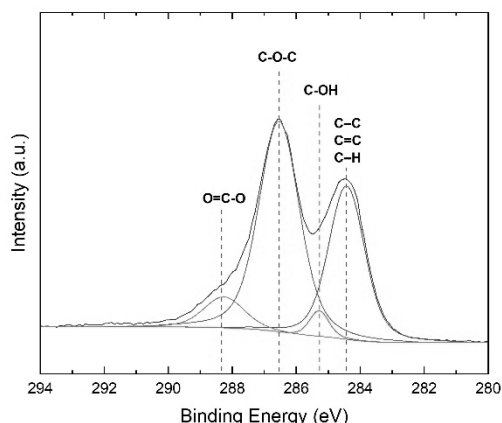


Figure 11 XPS C1s spectrum of the synthesized s-GO.

3.2 Catalytic performance on glycerol acetylation

The catalytic activity of GO and s-GO was examined in the acetylation of glycerol. The acetylation of glycerol with acetic acid was performed at 1:9 molar ratio, the reaction temperature of 120 °C, and the amount of catalyst of 5 wt.% (relative to glycerol mass). In the absence of a catalyst, glycerol was converted to glycerol esters at 70% conversion, indicating that glycerol esterification is a self-catalytic reaction under elevated temperature and excess acetic acid conditions. Compared to the blank esterification, GO (Tours) showed a significant increase in conversion to 97%, which is comparable to conventional prepared GO (Hummers), as shown in Table 1. This

performance attributed to the presence of oxygen-containing functional groups that act as abundant acidic sites, enhancing the rate of esterification. Surprisingly, the DAG and TAG selectivity for GO were achieved at 69.3% and 30.2% respectively. Additionally, the catalytic activity of s-GO was demonstrated in glycerol acetylation, achieving a slightly higher conversion (99.6%) than pristine GO catalyst.

These findings confirm that GO catalyst is a highly effective catalyst for achieving near-complete conversion and favorable selectivity toward higher-value di- and triacetin.

3.3 Recyclability of catalyst

The glycerol acetylation over GO catalyst was obtained with a conversion of 98.6%, which only slightly decreased to 98.5% in the second run and 98.2% in the third run. This minimal change indicates that GO retains most of its Brønsted acid sites and structural integrity during reuse. These results confirm that GO exhibits excellent short-term stability, maintaining nearly complete glycerol conversion for at least three consecutive reaction cycles. However, for extended reuse beyond three cycles, regeneration strategies such as oxidative washing and calcination may be necessary to restore its catalytic performance.

Table 1 Comparison of acetylation of glycerol over carbon-based and commercial catalysts.

Catalyst	Reaction conditions	X _G (%)	S _{DAG+TAG} (%)	Ref.
GO (Hummers)	1:9 MR, 110 °C, and 120 min	94	N/A	[19]
	1:10 MR, 120 °C, and 120 min	98.5	94.5	[7]
GO (Tours)	1:9 MR, 120 °C, and 120 min	98.6	99.5	This work
Amberlyst-15	1:9 MR, 110 °C, and 240 min	97.1	92.2	[16]

X_G = glycerol conversion, S_{DAG+TAG} = selectivity of di- and triacetin, MR = molar ratio

These results confirm that GO exhibits excellent short-term stability, maintaining nearly complete glycerol conversion for at least three consecutive reaction cycles. However, for extended reuse beyond three cycles, regeneration strategies such as oxidative washing and calcination may be necessary to restore its catalytic performance.

4. Conclusion

In summary, GO was successfully synthesized via the modified Tour's method using expanded graphite as the carbon precursor. Structural and chemical characterizations confirmed the presence of abundant oxygen-containing functional groups, which provide active sites for esterification. Under optimized reaction conditions (5 wt.% catalyst, 120 °C, 120 min), the prepared GO catalyst achieved 98.6% glycerol conversion with a high selectivity of 99.5% toward diacetin and triacetin. These results demonstrate that GO is an effective and sustainable solid acid catalyst for glycerol upgrading, offering a green pathway for converting biodiesel byproduct glycerol into valuable fuel additives.

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Carbon footprint comparison between Rammed earth houses and conventional residential Buildings using Building Information Modeling (BIM)

A case study two-story Rammed earth house by La Terre Co., Ltd

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Abstract

Residential construction significantly contributes to CO₂ emissions, with wall systems being the primary source. This study explores a two-story house (720 m²) developed by La Terre Co., Ltd., using rammed earth walls. A BIM model via Autodesk Revit 2025 Carbon Insight was used to compare its environmental impact with conventional designs.

A Life Cycle Assessment (LCA), based on a Cradle-to-Gate approach, revealed

The results indicate. Ramed Earth Wall (Two-Story, 300 mm thick): Total embodied carbon of approximately 45 kg Co₂e/m². Conventional Wall (Approx. 25 mm thick) Total embodied carbon ranging from 60 to 90 kg Co₂e/m².

Whole Life Carbon (WLC) and Life Cycle Cost (LCC) analyses further support sustainable housing design. The findings aid in creating low-carbon material databases and design frameworks for future eco-friendly architecture. Establish a material database for calculating the carbon footprint of alternative construction materials to support environmentally friendly residential design in the future

Keywords: Building Information Modeling, Embodied carbon, Whole Life Carbon, Life Cycle Assessment, Life Cycle Cost

1. Introduction

Global warming and climate change have emerged as critical global challenges, prompting international commitments to reduce greenhouse gas emissions by the year 2030 and to limit the global temperature increase to no more than 2°C above pre-industrial levels. Among the major contributors to greenhouse gas emissions is the construction industry, particularly through wall systems such as prefabricated walls, which account for a substantial share of CO₂ emissions. In response to these environmental concerns, low-carbon construction strategies have been developed, emphasizing sustainable architectural design, the use of locally sourced

materials, and the integration of green spaces into the built environment. Rammed earth construction, which utilizes native soil as its primary material, presents significant environmental and cultural benefits. It reduces emissions associated with material transportation and contributes to lower construction costs. This study investigates a two-storey rammed earth residential building designed by La Terre Co., Ltd., which has been in operation for two years. The research employs a Life Cycle Assessment (LCA) based on the Cradle to Grave approach, encompassing all phases from raw material extraction to end-of-life disposal.

Building Information Modeling (BIM),

implemented through Autodesk Revit 2025, is utilized to simulate material quantities, energy consumption, and embodied carbon (EC) throughout the construction process. The study integrates both Whole Life Assessment (WLA) and LCA methodologies. Experimental data were used to determine the emission factor (EF) of rammed earth walls, which were then incorporated into Revit 2025 via a custom analytical platform. BIM serves as the central framework for data integration and visualization. The findings underscore the environmental viability of rammed earth construction, positioning it as a promising and sustainable alternative for future architectural development

1.2 Research Objectives

1.2.1 Analyze rammed earth housing using BIM tools (Autodesk Revit 2025, Carbon Insight, and All-in CarboLife to calculate Operational Carbon (OC) and Embodied Carbon (EC).

1.2.2 Apply Life Cycle Assessment (LCA) to determine Carbon Emission Factors (EF) and assess the carbon footprint of rammed earth wall construction.

1.2.3 Evaluate the environmental sustainability of rammed earth housing through LCA and Whole Life Carbon (WLC), comparing it with conventional wall systems

1.3 Scope of the Study

This study focuses on a two-storey rammed earth house with a total usable floor area of 375 square meters, designed by La Terre Co., Ltd. and completed in 2023. Autodesk Revit 2025 was employed to develop a detailed Building Information Modeling (BIM) model, enabling precise quantification of construction materials such as concrete, steel, wood, glass, and rammed earth the primary material of the project.

1.3.1 The research emphasizes the analysis of Embodied Carbon (EC) and Operational Carbon (OC), applying specific Carbon Emission Factors (EF) for rammed earth walls in conjunction with the Life Cycle Assessment

(LCA) methodology.

1.3.2 Whole Life Carbon (WLC) analysis was conducted using Carbon Insight and All-in CarboLife tools, covering all stages from material extraction, transportation, and construction to end-of-life management.

1.3.3 The study evaluates the environmental sustainability of the building and proposes recommendations

2. Literature Review and Related Theories

2.1 Rammed earth is a sustainable construction method that creates strong, load-bearing walls by compacting layers of soil—typically sand, clay, silt, and gravel into formwork. It offers excellent thermal performance, durability, and natural aesthetics. The use of stabilizers like lime or cement enhances strength and water resistance, while reinforcement with steel or fibers improves structural integrity.

Environmentally, rammed earth uses local materials, generates minimal waste, and has a low carbon footprint. Its high thermal mass reduces energy consumption, and its natural appearance supports biophilic design. Safe, non-toxic, and long-lasting, rammed earth blends traditional techniques with modern for resilient and eco-friendly engineering architecture.



Figure 1. Rammed earth by La Terre Co., Ltd.,

2.2 Life Cycle Assessment (LCA) is a comprehensive analytical framework that evaluates the environmental, economic, and social attributes of energy systems throughout

their entire life cycle from raw material extraction to the functional use of energy carriers. This approach integrates principles from life cycle costing, environmental impact assessment, and other methodologies to provide a holistic view of a product or system's sustainability.

Key Stages of LCA in Construction.

2.2.1 Material Stage (Embodied Carbon)

This stage involves identifying all materials required for construction, tracing their origins, and analyzing how they are produced. It includes tracking resources from forests or mines to delivery at the construction site.

2.2.2 Construction Stage (Embodied Carbon) This phase assesses the environmental impact of the construction process, including energy consumption, waste generation, and emissions produced during building activities.

2.2.3 Use Stage (Operational Carbon) Once construction is complete, the focus shifts to how the building is operated. For example, in commercial buildings, the configuration of HVAC systems is analyzed to estimate energy consumption over the building's lifespan.

2.2.4 End-of-Life Stage

2.3 Whole Life Carbon (WLC) refers to the total amount of carbon dioxide emissions associated with a built asset throughout its entire life cycle. This includes emissions from material production, construction, operation, maintenance, demolition, and potential reuse or recycling. The key components of WLC are as follows Components of Whole Life Carbon

Embodied Carbon is Emissions resulting from material extraction, manufacturing, transportation, and construction activities. Operational Carbon is Emissions generated from energy consumption during the building's operational phase. User Carbon is Emissions arising from occupant activities, such as appliance usage and commuting.- End-of-Life Carbon is Emissions from

demolition, waste processing, and material recycling or disposal .WLC Assessment Standards

The assessment of Whole Life Carbon typically follows standards such as the RICS Whole Life Carbon Assessment Standard, which categorizes emissions into four modules A, B, C, and D covering all stages of the building life cycle.

Module A Pre-construction and Construction Phase Covers emissions from material production and construction processes.

Module B Use Phase Covers emissions during the operational life of the building.

Module C End-of-Life Phase Covers emissions at the end of the building's life.

Module D Benefits Beyond the Building Life Cycle

Module D is reported separately from Modules A–C to avoid double-counting. It accounts for the net benefits of recovered materials and energy beyond the building's life cycle.



Figure 2. Whole Life Carbon (WLC)

2.4 Greenhouse Gas (GHG) Emission Calculations.

In most cases, greenhouse gas (GHG) emissions cannot be directly measured. Instead, they are estimated by converting activity data into emission values using standardized emission factors. The general formula for calculating GHG emissions is as follow.

$$\text{GHG} = \text{Activity Data} \times \text{Emission Factor} \quad (1)$$

$$\text{kgCO}_2\text{eq} = \text{Unit} \times \text{Emission Factor} \quad (2)$$

Activity Data refers to quantitative information related to energy use, fuel consumption, or raw materials involved in a specific activity.

Emission Factor is a coefficient that represents the amount of GHG emitted per unit of activity

Table 1. Emission Factor is a coefficient.

Material / Activity	Emission Factor (EF)	Unit
Cement (Portland)	0.85–0.95	kg CO ₂ e/kg
Steel (Rebar)	1.5–2.0	kg CO ₂ e/kg
Ready-mixed Concrete	0.1–0.15	kg CO ₂ e/kg
Brick	0.25–0.35	kg CO ₂ e/kg
Glass	1.0–1.2	kg CO ₂ e/kg
Aluminum	9.0–11.0	kg CO ₂ e/kg
Diesel (for machinery)	2.68	kg CO ₂ e/liter
Electricity (Thailand grid)	~0.55	kg CO ₂ e/kWh
Transport (by truck)	0.2–0.3	kg CO ₂ e/ton-km

2.5 Life Cycle Cost (LCC) analysis is a crucial tool for efficient resource management. It provides a comprehensive overview of all expenses associated with an asset or project throughout its entire lifespan. This approach serves as a fundamental basis for strategic decision-making in an era where cost-effectiveness and sustainability are key goals of development

2.6 Building Information Modeling (BIM)

Building Information Modeling (BIM) plays a crucial role in integrating Life Cycle Assessment (LCA) into building design and management. Show in figure 3 and Table 2. By embedding Environmental Product Declarations (EPDs) into 3D models, BIM enables accurate calculation of Embodied Carbon (Stages A1–A3) and supports Whole Life Carbon (WLC) analysis from early design stages.

BIM also connects with energy simulation tools like Autodesk Revit Insight to evaluate Operational Carbon (Stages B6–B7) using real-world performance data. It aids post-occupancy assessments and end-of-life planning (Stages C1–C4), including resource tracking and material recovery. Advanced BIM-based Decision Support Systems, using methods like IDEF3, further enhance data accuracy and

reduce fragmentation, improving the reliability of WLC evaluations.



Figure 3. Building Information Modeling (BIM)

Table 2. Tool Whole Life Carbon (WLC) with (BIM)

Tool	CapEx	OpEx	LCA	BIM	Location
Causeway GATO	Advanced	Basic	N/A	Advanced	UK
One Click LCA	Basic	Basic	Advanced	Advanced	Finland
BRE IMPACT	Basic	Basic	Advanced	Basic	UK
BLP Butterfly	Basic	Basic	Basic		UK
Beck Tech Destini	Advanced	N/A	N/A	Advanced	Texas
Exactal CostX	Advanced	N/A	N/A	Advanced	UK
RICS BCIS	N/A	Advanced	N/A	N/A	UK
Tocoman	Advanced	N/A	N/A	Advanced	Finland
Trimble VICO	Advanced	N/A	N/A	Advanced	USA
eTool LCD	Basic	Basic	Advanced	Basic	Australia

2.7 Quick-Action Carbon Calculation Tools for Embodied Carbon (LCA)

Carbo Life Calculator is a tool that automatically analyzes Revit-based models to assess Embodied Carbon and optimize design for lower emissions. It relies on Environmental Product Declarations (EPDs), which provide standardized LCA-based data on material impacts. Various LCA and carbon calculators use EPDs or custom material data to help stakeholders choose low-carbon materials. These tools streamline sustainable design by generating building-wide carbon metrics directly from BIM models.

2.8 Autodesk Revit 2025 and Carbon Insight Plugin Autodesk Revit 2025 introduces the powerful Carbon Insight plugin, which enhances early-stage design evaluation by providing detailed assessments of carbon

emissions associated with building materials. This plugin integrates environmental impact data directly into BIM components, allowing users to measure the carbon footprint of individual materials and optimize selections accordingly. The plugin supports both Embodied Carbon Analysis Evaluating carbon emissions embedded in materials and construction processes. Operational Carbon Analysis Assessing emissions from building operation, such as energy and resource consumption. Additionally, the integration of the EC3 Database (Embodied Carbon in Construction Calculator) provides average carbon values for commonly used materials. This database offers comprehensive carbon factors for construction products, enabling project teams to select more sustainable material alternatives based on verified environmental data.

3. Research Methodology

3.1 Literature Review A comprehensive review of relevant literature was conducted to explore concepts and theories related to the research, including theses and academic articles both domestically and internationally. The study focused on carbon footprint assessment, rammed earth wall systems, and construction techniques. Autodesk Revit 2025 was utilized in conjunction with the Carbo Life Calculator (All-in) to determine the total carbon emissions. The study also incorporated Building Information Modeling (BIM) using Autodesk Revit 2025 to analyze total carbon accumulation from rammed earth house construction, assessing environmental impacts within the framework of Life Cycle Assessment (LCA)

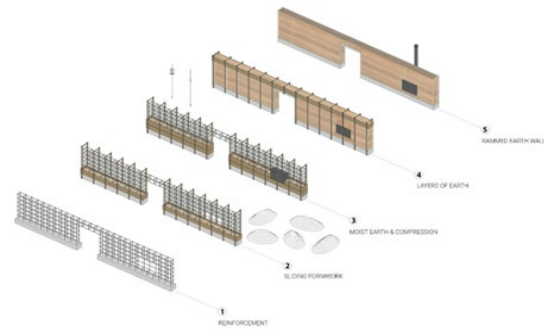


Figure 4. Building Rammed earth wall.

3.2 Case Study Selection A two-story rammed earth house was selected as the case study. The design and construction process were examined in detail, with emphasis on construction techniques employed by Later Co., Ltd. The study aimed to trace and quantify the embodied carbon within the building.

3.3 Carbon Footprint Assessment The carbon footprint of

the rammed earth wall construction process was evaluated using Life Cycle Assessment (LCA). A spreadsheet template was developed to calculate carbon emissions based on the Emission Factor (EF) specific to rammed earth walls.

3.4 3D Modeling A 3D architectural and structural model was created using Autodesk Revit 2025 to support the analysis.



Figure 5. 3D Modeling Rammed earth by revit.

3.5 Emission Factor Calculation The Emission Factor (EF) for rammed earth walls was calculated using the Carbo Life Calculator integrated with Autodesk Revit 2025, allowing comparison across different wall systems.

3.6 Carbon Analysis via Autodesk Revit 2025 was employed to perform Embodied Carbon Analysis and Operational Carbon Analysis, facilitating a comprehensive Whole Life Carbon (WLC) assessment.

3.7 Whole Life Carbon Assessment The total carbon emissions over the building's entire lifecycle (WLC) were evaluated using Autodesk Revit 2025.

3.8 Comparative Analysis A comparative analysis was conducted to evaluate the properties of rammed earth construction against other wall systems.

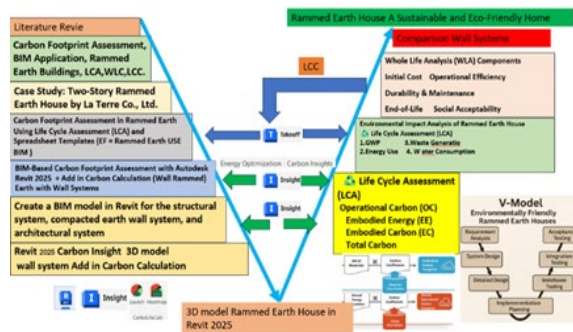


Figure 6. Research Procedure Flowchart V-Model

4. Results and Discussion

4.1 Experimental Procedure

4.1.1 Material Selection Locally available clay and lateritic soils were selected as the primary materials for rammed earth wall construction. To enhance structural integrity and reduce cracking, bio-based additives such as straw and rice husk were incorporated into the soil mixture.

4.1.2 Material Property Testing A series of laboratory tests were conducted to evaluate the physical and thermal characteristics of the selected soil mixtures Compaction Test.

Used to determine the optimum moisture content and maximum dry density of the soil, ensuring effective compaction during wall formation. Unconfined Compressive Strength (UCS) Performed to assess the compressive strength of the compacted earth samples, providing insight into load-bearing capacity. Thermal Conductivity Test Conducted to analyze the material's ability to transfer heat,

which is critical for evaluating its thermal insulation performance.

4.1.3 Wall Sample Construction Wall specimens were constructed with a standard thickness of 40 cm and a height of 3 meters. The construction process involved compacting the soil in successive layers, each adjusted to the optimal moisture content determined from the compaction test. This method ensured uniform density and minimized voids within the structure. 4 Carbon Emissions from Experimental Activities The total carbon footprint generated during the experimental phase including material preparation, testing, and sample construction was calculated to be 3,000.28 kg CO₂e.

4.2 Emissions from Construction Phases

This value serves as a baseline for evaluating the environmental impact of rammed earth construction under controlled conditions Emissions from Construction Phases A detailed carbon footprint assessment was conducted across four key phases of the rammed earth wall construction process. Each phase was analyzed to quantify its contribution to total greenhouse gas emissions, measured in kilograms of carbon dioxide equivalent (kg CO₂e). The results indicate that the Mixing and Forming phase (C102) is the most carbon-intensive, accounting for over 61% of total emissions. This is primarily due to the energy required for material preparation and the use of cement as a stabilizing agent. The Wall Construction phase (C103) also contributes significantly, followed by emissions from Waste Management (C104) and Material Sourcing (C101). These findings underscore the importance of optimizing material processing and exploring alternative binders to reduce the environmental impact of rammed earth show table 5 and figure 7.

Table 3. Carbon Footprint Assessment for Rammed Earth House Construction

Total Carbon Footprint Summary		
Phase	Carbon Footprint Assessment for Rammed Earth	CarbonFootprint (kg CO ₂ e)
	C101 – Material Sourcing	607.31
	C102 – Mixing & Forming	11076.86
	C103 – Wall Construction	5,769.06
	C104 – Waste Management	662.05
	Total	18,115.28

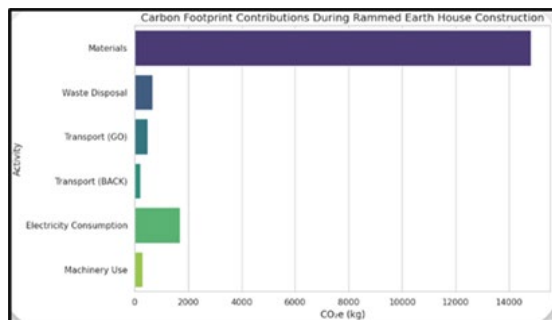


Figure 7. Carbon Footprint (LCA) Reammed Earth wall.

4.3 This study presents a comprehensive assessment of the carbon footprint associated with rammed earth wall construction. The methodology applies Life Cycle Assessment (LCA) in combination with spreadsheet-based modeling to evaluate greenhouse gas emissions across all stages of the construction process including raw material sourcing, transportation, mixing, wall formation, and waste management. Quantitative analysis indicates that the total carbon emissions amount to 18,115.28 kg CO₂e, with cement stabilization contributing 9,627 kg CO₂e, or approximately 53% of the total emissions. The carbon intensity was calculated at 0.10 kg CO₂e per kilogram of material and 62.47 kg CO₂e per square meter of wall surface. An emission factor (EF) of 0.10 kg CO₂e/kg was applied to analyze the environmental impact of walls across different building levels. The inclusion of steel reinforcement was found to significantly increase the emission factor. The analysis was conducted using Autodesk Revit 2025 in conjunction with the Carbon Calculation Add-in show figure 8 ,where rammed earth walls were

modeled using predefined wall systems. Environmental Product Declaration (EPD) data were integrated to assess the environmental impact of each wall configuration. The construction of upper floors (levels 2–3) introduced additional complexity in terms of structural design and material usage, further influencing the carbon footprint outcomes



Figure 8. Carbon Footprint Comparison Wall Systems by the Carbo Life Calculator (All-in)

4.4 The carbon footprint analysis of rammed earth wall construction across three building floors reveals distinct patterns in environmental impact. On the first floor, the total carbon footprint is the highest, reaching approximately 107.47 kg CO₂e/m². This is primarily due to the significant use of steel reinforcement, which contributes 45 kg CO₂e/m², despite the base material emissions being relatively low at 62.47 kg CO₂e/m². The second floor presents a more balanced profile. Although the carbon footprint from the wall materials increases to 68.72 kg CO₂e/m², the steel reinforcement drops to 25 kg CO₂e/m². This results in a total footprint of around 93.72 kg CO₂e/m². Interestingly, the third floor has the highest emissions from wall materials, at 74.96 kg CO₂e/m². However, it uses the least amount of steel reinforcement only 1 kg CO₂e/m² leading to the lowest overall carbon footprint among the three floors, at 84.96 kg CO₂e/m². This comparison underscores the significant role of steel reinforcement in shaping the total carbon footprint. While material emissions tend to increase with height, reducing reinforcement can effectively offset this rise, offering a strategic approach to sustainable multi-story construction show in figure 9.

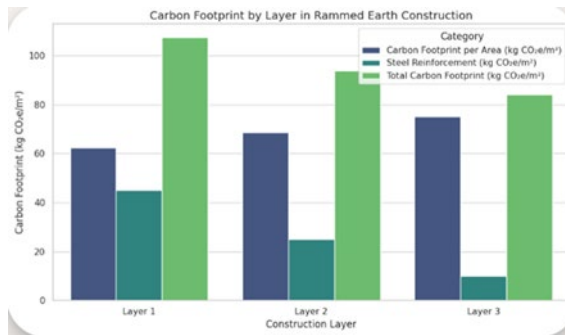


Figure 9. Comparison Layer in Rammed Earth Construction

4.5 This study focuses on the Whole Life Carbon Assessment (WLCA) and Life Cycle Cost (LCC) of a two-story rammed earth house, featuring a total wall area of 300 square meters and a usable floor area of 1,200 square meters over a 30-year lifespan. The assessment cover stages A–C, including Embodied Carbon (EC), Operational Carbon (OC), and End-of-Life Carbon (EOLC), while also considering energy and water usage within the building and its economic implications. The Whole Life Carbon Assessment (WLCA) and Life Cycle Cost (LCC) analysis was using Autodesk Revit 2025 in conjunction with the Carbon Calculation Add-in show figure 5.

4.5.1 In stages A1–A3 (Product Stage), the construction of rammed earth walls results in an average carbon footprint of 107.47 kg CO₂e/m² for the lower floor and 93.72 kg CO₂e/m² for the upper floor, totaling approximately 30.18 tons of CO₂e. This is significantly lower than conventional materials such as concrete or brick. In stages A4–A5 (Construction Stage), the use of steel reinforcement and energy-intensive compaction processes slightly increases the carbon emissions.

4.5.2 During stages B1–B7 (Use Stage), electricity consumption from household appliances such as air conditioners, refrigerators, and LED lighting is estimated at 11,212 kWh/year. If grid electricity is used exclusively, the OC would reach approximately 168.18 tons CO₂e over 30

years. However, installing an 8–10 kW solar photovoltaic system, capable of generating over 12,000 kWh/year, can reduce OC to just 16.8 tons CO₂e.

4.5.3 In stages C1–C4 (End-of-Life Stage), rammed earth materials can be reused or returned to the natural environment without energy-intensive recycling, resulting in a very low EOLC of approximately 1 ton CO₂e. Additionally, average water consumption of 20,000 liters/year contributes about 0.21 tons CO₂e over the building's lifespan.

When all carbon sources are combined, the total Whole Life Carbon (WLC) is approximately 48.19 tons CO₂e with solar integration, compared to 249.86 tons CO₂e without solar demonstrating that renewable energy can reduce total carbon emissions by more than 75%.



Figure 10. the Whole Life Carbon Assessment (WLCA) Ramme Earth by the Carbo Life Calculator (All-in)

Table 4. the Whole Life Carbon Assessment two-story rammed earth house,

Category	Floor 1	Floor 2	Two-Story House (30 Years)
Wall Area (m ²)	100	100	600
Wall Material Emissions (kgCO ₂ e/m ²)	62.47	68.72	
Steel Reinforcement Emissions (kgCO ₂ e/m ²)	45	25	
Total Carbon per Floor (kgCO ₂ e/m ²)	107.47	93.72	
Total Wall Construction Emissions (tons)	10.747	9.372	
Total Construction Emissions (tons)			30.18
Total Rammed Earth Construction Emissions			50.299
Operational Carbon – Grid Power (tons)			168.18
Operational Carbon – Solar Power (tons)			16.8
End-of-Life Carbon (tons)			1
Water Usage Emissions (tons)			0.21
Total WLC – Without Solar (tons)			249.869
Total WLC – With Solar (tons)			98.489

4.6. This study presents Revit 2025 enhances sustainable design by integrating both types of carbon analysis into a unified system Embodied Carbon (EC) And Operational Carbon (OC) show in Figure 10.

Using the Insight tool in combination with Revit's Energy Analytical Model, designers can accurately simulate and visualize the carbon impact of building designs



Figure 10. the Whole Life Carbon Assessment (WLCA)
Ramme Earth by Revit Carbon in sights.

5. Conclusion

This research highlights the environmental and economic potential of rammed earth wall construction, evaluated through Life Cycle Assessment (LCA), Life Cycle Cost (LCC), and Whole Life Carbon (WLC) frameworks. The study integrates Building Information Modeling (BIM) tools specifically Autodesk Revit 2025 with the Carbon Insight extension and Carbo Life Calculator add-in to simulate and analyze wall systems under varying material compositions and structural conditions.

Field experiments were conducted to determine the emission factor (EF) of locally sourced rammed earth, which was then applied in BIM modeling to compare wall configurations. The results revealed significant variations in carbon emissions and cost depending on material type, transport distance, local construction standards, and structural requirements. Notably, the first floor of a two-story building required additional steel reinforcement to support the upper level, resulting in higher embodied carbon than the second floor. Cement content was standardized at approximately 10% to ensure structural integrity while minimizing carbon intensity.

The BIM system was also used to estimate construction costs, focusing specifically on the rammed earth wall system. When compared

with conventional wall types such as brick masonry, in-situ concrete, and lightweight blocks rammed earth demonstrated lower long-term costs due to inexpensive materials and minimal maintenance needs, particularly in terms of repair and surface treatment, which avoids chemical based finishes. From a carbon perspective, the use of natural soil sourced locally significantly reduces embodied carbon. In some cases, soil was obtained from on-site excavation activities, such as pond or reservoir construction, further minimizing transport emissions. For single-story buildings, the absence of steel reinforcement and the use of minimal cement (less than 3%) further enhance environmental performance. The thermal mass of rammed earth also contributes to passive temperature regulation, reducing the need for mechanical cooling and eliminating the need for additional insulation. Moreover, the material's recyclability and negligible end-of-life impact reinforce its sustainability profile. The integration of solar energy systems further reduces operational carbon (OC), enhancing overall WLC performance show table 7.

Although skilled labor may increase initial construction costs, the projected service life of 30–50 years supports the long-term economic viability of rammed earth construction. The study concludes that rammed earth walls can reduce Whole Life Carbon by approximately 40–60% compared to conventional wall systems. This positions rammed earth as a low-cost, environmentally friendly solution for sustainable architecture, particularly in regions with access to suitable soil resources.

Table 5. Conclusion comparison Wall Systems

Wall Type	EC (t CO ₂ e)	OC (t CO ₂ e)	EOLC (t CO ₂ e)	Total WLC (t CO ₂ e)	LCC (THB)
Rammed Earth (with solar)	30.18	16.8	1	48.19	≈ 1.9 million
Rammed Earth (no solar)	30.18	168.18	1	199.57	≈ 2.7 million
Clay Brick (plastered)	~45.00	168.18	~3.00	216.18	≈ 2.8 million
In-situ Concrete Wall	~60.00	168.18	~5.00	233.18	≈ 3.0 million
Concrete Block (plastered)	~40.00	168.18	~3.00	211.18	≈ 2.6 million
Lightweight AAC Block	~30.00	168.18	~2.50	200.68	≈ 2.5 million



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How to apply 3D printing and direct printed clear aligner in daily dental practice

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Abstract

The integration of three-dimensional (3D) printing into dental practice is reshaping clinical workflows, especially using direct printed aligners. Unlike traditional thermoformed aligners that generate significant plastic waste and require multiple physical molds, direct printed aligners are manufactured directly from digital files, thereby reducing material usage and energy consumption. This study explores the daily clinical applications of 3D printing with a focus on the environmental benefits of new-generation biocompatible resins. The workflow involves digital intraoral scanning, computer-aided design (CAD) for orthodontic planning, and direct printing of aligners using eco-conscious, FDA-approved photopolymers. Clinical cases demonstrate that this approach not only improves treatment accuracy and efficiency but also significantly reduces the environmental footprint by eliminating physical models, reducing packaging, and enabling on-demand production. The materials used are designed for lower toxicity, minimized waste, and improved recyclability compared to conventional thermoplastics. This innovation supports the transition toward greener dentistry while maintaining high clinical standards.

Keywords: 3D printing; direct aligner; eco-friendly dentistry; digital orthodontics; sustainable materials



Mechanical Properties of 3D Printed Femur Model to be Used for *in vitro* Validation

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Abstract

Additive Manufacturing (AM) is increasingly vital in industries such as manufacturing and healthcare, primarily due to its ability to reduce design time, lower production costs, and create surgical models. In medicine, while cadaveric bones are traditionally used, they are insufficient to meet demand, leading to the use of artificial bones for surgical studies and replacements. However, artificial bones face limitations, including high costs and sizes designed for non-local populations. This study aims to develop customizable artificial bones using 3D printing with polylactic acid (PLA) filament. The research employs a four-point bending test to assess the mechanical properties, focusing on key 3D printing parameters such as build orientation (horizontal, edge, vertical) and material density. Strain gauges were used to measure stress during testing, and finite element analysis (FEA) was employed to validate the results. Findings reveal that horizontal and edge orientations perform better under compressive forces than vertical orientations, with FEA results showing less than a 20% deviation from mechanical tests. The study highlights that build orientation significantly affects the stiffness and strain of 3D-printed bones.

Keywords: 3D printing; femur model; artificial bone



Numerical Investigation of Baffle Angle Effects on Sound Pressure Level and Internal Gas Dynamics In a 9 mm Gun Suppressor

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Abstract

This study presents a computational investigation of how varying the baffle angle affects the acoustic and flow performance of a 9 mm gun suppressor. The analysis was conducted using transient three-dimensional computational fluid dynamics (CFD) simulations, focusing on five baffle angle configurations: 45°, 50°, 55°, 60°, and 65°. All designs utilized a fixed number of seven baffles and were developed to be compatible with compact firearm systems, such as 9 mm submachine guns (SMGs) with 7-inch barrels and semi-automatic pistols. The CFD model incorporated realistic internal ballistic boundary conditions, including a peak muzzle pressure of 24.1 MPa and gas temperature of 1800 K. Pressure-time data were captured at the suppressor exit to compute sound pressure levels (SPL) via Fast Fourier Transform (FFT). Results revealed a strong influence of baffle angle on shockwave behavior and gas expansion, with steeper angles achieving up to 17 dB SPL attenuation. A second-order polynomial model was developed to predict SPL as a function of baffle angle. These findings offer valuable guidance for optimizing suppressor performance under compact size constraints. In addition to acoustic performance optimization, this work contributes to the broader goals of sustainable innovation by promoting modular, reusable suppressor components and reducing reliance on iterative physical prototyping through CFD-driven design.

Keywords: 9 mm suppressor, baffle angle, CFD, sound pressure level, acoustic attenuation, gas dynamics

Productivity evaluation of marine rotifer *Brachionus rotundiformis* (S-type) fed with various microalgae species

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Abstract

This study aimed to investigate the productivity of marine rotifer, *Brachionus rotundiformis* (S-type) cultured fed with different microalgae species, i.e., *Chlorella* spp. (Ch), *Nannochloropsis oculata* (Nan), *Tetraselmis suecica* (Te), *Isochrysis galbana* (Iso) and *Chaetoceros calcitrans* (CC). Batch culture of rotifer in a 200-liter plastic tank at initial density of 10 rotifers/ml, they fed with microalgae at 10^5 cell/ml, for 3 days. Results showed that mean final density of rotifer fed with Te and Ch were 23.11 ± 6.14 and 21.22 ± 3.12 rotifers/ml, respectively, both higher ($P < 0.05$) than those fed with CC (10.97 ± 3.58 rotifers/ml), Iso (9.77 ± 3.77 rotifers/ml), and Nan (7.25 ± 1.77 rotifers/ml). In productivity, rotifer fed with Ch showed higher ($P < 0.05$) wet weight (15.80 ± 0.94 g/100 l) than those of CC (6.04 ± 2.02 g/100 l), Nan (4.63 ± 1.87 g/100 l), Te (12.63 ± 1.16 g/100 l), and Iso (12.20 ± 1.17 g/100 l). Meanwhile, rotifer fed with Te and Iso had a significantly higher wet weight than CC and Nan. For quantity of rotifer per g of weight, it was found that rotifer fed with Iso had a lowest quantity ($80,762.06 \pm 6,795.56$ rotifers/g) than other groups. This study demonstrated that cultivating S-type rotifers with various microalgae species significantly influences yield, specifically in terms of density and wet weight. Among the tested species, Te and Ch were identified as the most suitable for cultivation. This production method offers a practical and viable approach for farmers and individuals in aquaculture to improve their practices and advance their careers.

Keywords: Biomass productivity, Rotifer cultivation, S-type rotifer strain

Introduction

Rotifer (*Brachionus rotundiformis*) is a zooplankton that is very important in the nursery of coastal aquatic animals and is commonly used in major food sources for fishes and crustacean larvae in the aquaculture industry worldwide [1-5]. Currently, there are small, medium, and large hatcheries that have different production processes depending on the experience and expertise of the breeder, but the main goals were to produce juveniles with high survival rates, good health, disease-free, and good growth rates, which were desired by farmers and aquaculture operators [6]. Many factors affect the success of aquaculture, and rotifer production was one of the most important

factors, as rotifers play a key role in the initial stages of juvenile breeding, which affects the growth and health of juveniles in the later stages. Because rotifers have high nutritional value, they are very suitable for use as initial food for young aquatic animals. In addition, rotifers fast reproductive cycle allowing mass production, small size, slow swimmers, and the ability to be enriched with adequate nutritional supplements [6,7].

Production of rotifers mainly depends on the production of microalgae used as feed for them. The nutritional characteristics of the microalgae directly influence the growth, reproduction, and health of the rotifer population. Common microalgae used in rotifer production such as *Tetraselmis*,

Nannochloropsis, *Chaetoceros*, *Isochrysis* [5,6,8]. These microalgae species provide essential nutrients that not only improve rotifer production but also enrich their nutritional content, making them a high-quality food source for the early stages of aquatic animal larvae. Selective of the microalgae species is therefore crucial for the successful mass production of rotifers in aquaculture systems.

The current study aims were to investigated the productivity of marine rotifer, *Brachionus rotundiformis* (S-type) was cultured fed with different microalgae species, i.e., *Chlorella* spp. (Ch), *Nannochloropsis oculata* (Nan), *Tetraselmis suecica* (Te), *Isochrysis galbana* (Iso) and *Chaetoceros calcitrans* (CC) in terms of density and wet weight. The knowledge gained from this study may be offers a practical and viable approach for farmers and individuals in aquaculture to improve their practices and advance in live feed culture.

Materials and methods

Experimental Design

The experiment was designed as a completely randomized design (CRD) with 5 treatments of 9 replications to increase the precision and reliability of the results. Rotifer cultured fed with different microalgae species, i.e., *Chlorella* spp. (Ch), *Nannochloropsis oculata* (Nan), *Tetraselmis suecica* (Te), *Isochrysis galbana* (Iso) and *Chaetoceros calcitrans* (CC) (Figure 1[19]. This study hypothesizes that if rotifers are cultured with different microalgae species will have varying effects on rotifer production.

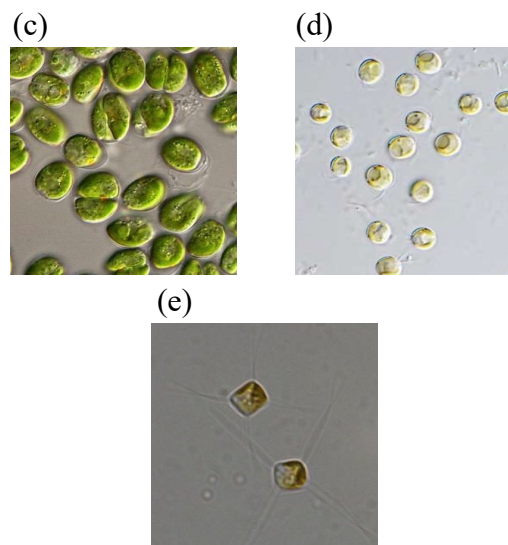
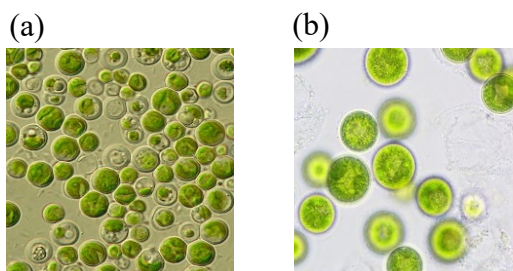


Figure 1 Biological characteristics of microalgae species, (a)*Chlorella* spp., (b)*Nannochloropsis oculata*, (c)*Tetraselmis suecica*, (d)*Isochrysis galbana* and (e)*Chaetoceros calcitrans*.

Each microalgae species represents a treatment group to test its effect on rotifer production in terms of population density and biomass (wet weight). Microalgae inoculum from the laboratory with a cell density of approximately 10^6 cells/ml or inoculum in the exponential stage was mass culture in 800-liter plastic tanks. Batch culture of rotifer in a 200-liter plastic tank at initial density of 10 rotifers/l, they were fed with microalgae at about 10^5 cell/l, for 3 days.

Harvesting Rotifers

During a 3-day rearing period, all rotifers with growth rates in the exponential phase were harvested after being cultivated in batches. Before harvesting, a random count of the rotifers was conducted. Afterward, two layers of plankton filter bags were used to harvest the rotifers, a bottom layer with a mesh size of 48 microns was used to harvest the rotifers, while an upper layer with a mesh size of 224 microns was used to capture sediment. The rotifers were collected and transferred to a 10-liter tank. They were then filtered again using 48-micron mesh plankton filter bags. Afterward, their wet weight was measured

over a five-minute period [9].

Data analyses

Initially, experimental data was tested for normality of distribution using Shapiro-Wilk's W-statistic. One-way analysis of variance (ANOVA) was used to compare significant differences between treatments. After getting significant differences of triplicate mean ($P < 0.05$), Duncan's multiple range test) was used to rank the groups on IBM SPSS statistics for windows (version 24.0; IBM Corp., Armonk, NY. USA) The results are presented as mean $\pm$ SD.

Results

The results of the density of marine rotifer cultured fed with different microalgae species showed that it cultured fed with Te and Ch had highest density ($P < 0.05$), at 23.11 ± 6.14 and 21.22 ± 3.12 rotifers/ml, respectively, while rotifers cultured fed with CC (10.97 ± 3.58 rotifers/ml), Iso (9.77 ± 3.77 rotifers/ml), and Nan (7.25 ± 1.77 rotifers/ml) had a lowest density ($P < 0.05$), as shown in Figure 2.

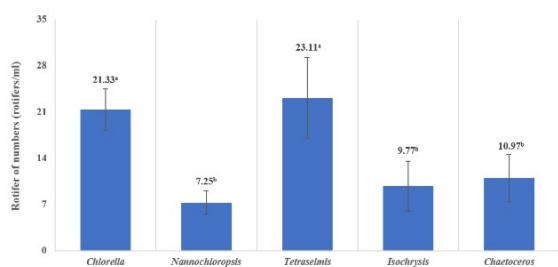


Figure 2 Density of marine rotifer, *Brachionus rotundiformis* (S-type) cultured fed with different microalgae species. Different lowercase letters indicate a significant ($P < 0.05$) difference.

For the wet weight yield of rotifers, it was found that those cultured fed with Ch produced the highest yield ($P < 0.05$), at 15.8 ± 0.94 g/100 l, while rotifers cultured with CC (6.04 ± 2.02 g/100 l) and Nan (4.63 ± 1.87 g/100 l) had the lowest wet weight yield ($P < 0.05$), as shown in Figure 3.

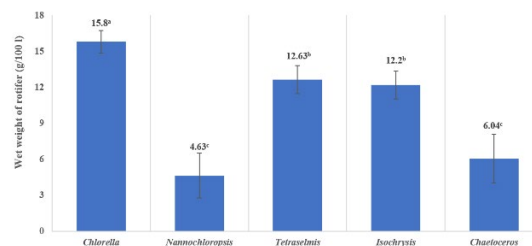


Figure 3 Wet weight of marine rotifer, *Brachionus rotundiformis* (S-type) cultured fed with different microalgae species. Different lowercase letters indicate a significant ($P < 0.05$) difference.

The number of rotifers per 1 g of wet weight showed that rotifer density of individuals cultured fed with Iso ($80,762.06 \pm 6,795.56$ rotifers/g) had a lowest ($P < 0.05$) than those fed with Nan, Te, Ch, and CC (Figure 4).

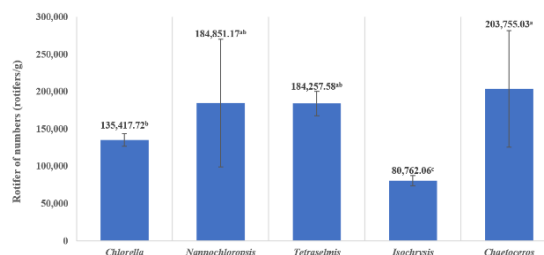


Figure 4 Number of marine rotifer, *Brachionus rotundiformis* (S-type) cultured fed with different microalgae species. Different lowercase letters indicate a significant ($P < 0.05$) difference.

Discussion

In the aquaculture industry, rotifers have been widely used as food source for first-feed aquatic animals [2-4]. Also, the relatively slow motility, rapid reproduction, tolerance to various environmental conditions, and nutritional value depending on food source (microalgae) of rotifers [10-12]. In this study, the farming of rotifers with different microalgae species of food affects the number of rotifers that are raised. The experiment revealed that the rotifer culture with Te and Ch which was significantly higher than that cultured with CC, Iso, and Nan. This result indicated that Te and Ch were better food

sources for the increase of rotifers compared to other plankton species in the tested groups, which might be due to the difference in nutritional value that supports the growth and reproduction of rotifers.

Batch [8,13,14], continuous [15], and semi-continuous [16] culture techniques, as well as the creation of a re-circulatory aquaculture system [14,17], have all been used in attempts to create effective rotifer production methods.[18] stated that it is necessary to culture rotifers at high density in order to produce more larvae. In Japan, high-density rotifers were cultured at a rate of 20,000–30,000 rotifers/ml. Later on, ultra-high-density rotifer culture (160,000 rotifers/ml) was effective in meeting the increasing demand for rotifers as feed for larvae.

According to [14], In batch rearing system, rotifers were cultivated with Ch over three days at an initial density of roughly 250 rotifers/ml, yielding a population of 366 ± 12 rotifers/ml. while in the recirculation system yielding a population of 790 ± 25 rotifers/ml. In addition, A recirculatory aquaculture system was used to cultivate and harvest rotifers, with an inoculation density of 10–12 rotifers/ml, according to [17]. The maximum number on the 8th day of rotifers (365.33 ± 2.18 rotifers/ml) was found in the food type Ch. While rotifers were fed CC, the maximum growth rate of 30.6 rotifers/ml was observed on the 10th day. The declining phase in this case began on the 12th day [8]. According to a study by [7], The rotifer is life span was significantly increased in the Iso-fed group than in the Te, Ch, Iso, CC, and Nan groups. The Te-fed group had the most cumulative offspring and daily reproduction, while the Ch-fed group had the lowest.

The wet weight of rotifers of cultured fed with different microalgae species. In the comparison between Te and Iso, both strains showed significantly higher wet weight than CC and Nan. This result indicated that Ch was the most efficient food source for increasing the wet weight of rotifers, while Te and Iso

were still better and more efficient than CC and Nan. Meanwhile, [1] found that rotifer culture with Ch produced an average of 9.78 ± 1.54 g/100 L, Nan produced 11.70 ± 1.74 g/100 L, and Te produced 9.76 ± 1.00 g/100 L after a three-day culture period. These results showed no difference ($P > 0.05$). [14], reported the cultivation of rotifers fed with Ch in a batch-rearing system over three days giving a rotifer yield of 2 g/100 L.

The culture of rotifers with different microalgae species of food affects the rotifer numbers (rotifers/g). According to the experimental results, CC had the highest potential to increase the rotifer numbers. In addition, cultures with Nan and Te gave similar results. Cultures with Ch gave significantly more rotifer numbers than cultures with Iso. In the report by [14], rotifers were cultivated using Ch in a batch-rearing system, producing 172,413 rotifers per gram.

Conclusion

This study showed that cultivating S-type rotifers with different microalgae species had a substantial impact on yield, specifically density and wet weight. Of the species investigated, Te and Ch received to be the most successful. This production approach offers aquaculture farmers and individuals an efficient and viable opportunity to improve their practices.

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Analysis of GPS Spoofing Attacks and Security Enhancement Strategies for Maritime Navigation Systems

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Abstract

The Global Navigation Satellite System (GNSS), particularly the Global Positioning System (GPS), serves as a fundamental navigational aid in modern maritime operations. However, GNSS signals are inherently vulnerable to external interference and susceptible to spoofing attacks—a technique in which counterfeit signals are transmitted to deceive GPS receivers into reporting false positions. Such spoofing attacks may go undetected by vessel operators, posing significant threats to navigational safety. Real-world incidents have been reported in various regions, including the Black Sea, the Strait of Hormuz, and certain coastal areas of China.

This study aims to investigate the patterns, methodologies, and impacts of GPS spoofing attacks on maritime navigation systems. Particular focus is given to positional errors that compromise autonomous navigation, collision avoidance systems, and vessel tracking via the Automatic Identification System (AIS). The research also proposes a framework to enhance GNSS security by integrating redundancy technologies and multi-source verification methods. These approaches are intended to address growing cyber threats specific to the maritime transportation sector and to support the development of resilient navigational infrastructure for future maritime safety.

Keywords: GNSS, GPS, GPS Spoofing, AIS, Maritime Navigation, Cyber Security



Advancing Shipboard Sustainability: Innovations in Green Technology for Emission Control and Energy Efficiency at Sea

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Abstract

Advancing shipboard sustainability is a crucial goal within the maritime industry, driven by strict international environmental regulations and increasing global awareness of climate change. This paper evaluates emerging green technologies designed to enhance emission control and energy efficiency onboard ships, in line with the International Maritime Organization's (IMO) sustainability directives. It examines significant innovations such as hybrid propulsion systems that utilize alternative fuels like LNG, biofuels, hydrogen, and ammonia, discussing their practicality and impact on reducing ship emissions. The study also highlights technological advancements in waste heat recovery systems, energy-efficient machinery, and advanced scrubber technologies aimed at effectively mitigating SO_x and NO_x emissions. Furthermore, the incorporation of intelligent ship management solutions such as AI-driven vessel routing optimization, IoT-enabled real-time monitoring systems, and predictive maintenance using digital twins, underscores the potential of digitalization to enhance sustainable vessel operations. Through a comprehensive analysis of selected case studies from industry-leading vessels, this paper illustrates measurable improvements in fuel consumption, reductions in greenhouse gas emissions, and overall cost efficiencies achieved by implementing these green technologies. The discussion identifies ongoing barriers and emerging opportunities, ultimately providing recommendations for policymakers, industry stakeholders, and ship operators to promote the widespread adoption of sustainable innovations onboard ships, thereby fostering a greener maritime future.

Keywords: Shipboard Sustainability, Emission Control, Energy Efficiency

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Anatomical and histological insights into the Digestive system of the Mangrove horseshoe crab *Carcinoscorpius rotundicauda* (Xiphosura: Limulidae)

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Abstract

The mangrove horseshoe crab (*Carcinoscorpius rotundicauda*) is an invertebrate with jointed appendages, belonging to the phylum Arthropoda. It is also known as a living fossil due to its morphological resemblance to its ancient ancestors. The digestive tract of *C. rotundicauda* has a U-shaped bend in the anterior region. Anatomical identification of the digestive tract requires close examination of the alimentary canal walls, which display distinct internal folds. For anatomical studies, *C. rotundicauda* specimens were immersed in Davidson's solution, which is a mixture of formalin, ethanol, and glacial acetic acid, to soften the prosoma and opisthosoma and facilitate dissection and structural analysis. Subsequently, samples were preserved in Bouin's fixative for histological processing. Tissue sections were stained with hematoxylin and eosin for microscopic examination. The results indicate that most epithelial tissues are covered by a cuticle layer, and that the majority of digestive organs lack glands or specialized structures for enzyme production. Therefore, the horseshoe crab relies primarily on enzymes produced by the hepatopancreas. These findings enhance our understanding of the digestive system in arthropods and support further research into anatomical and histological relationships within this group.

Keywords: Digestive system; Mangrove horseshoe crab; Hepatopancreas; Gizzard; Histology

1. Introduction

Horseshoe Crabs, also known as living fossils, have been around for more than 470 million years [1]. They can be categorized into four extant species, two of which are commonly found in Thailand: horseshoe crab and Mangrove horseshoe crab. Their eggs are often used to consume [2]. Moreover, their blood plays a significant role in the biomedical field [3].

The mangrove horseshoe crab is an invertebrate, classified in the phylum of Arthropoda characterized by jointed appendages. They belong to the subphylum Chelicerata consisting of spiders, sea spiders, scorpions, horseshoe crabs, and ticks. The

Chelicerates are characterized by the chelicerae, a pair of the most anterior appendages commonly used for grasping and tearing food. The term "chelicerae" originates from the Greek words "chele" (claw) and "keras" (horn) describing their pincer-like or fang-like morphology [4]. The Mangrove horseshoe crab is in the class of Merostomata. Their body can be divided into two distinct parts. Prosoma, which bears the mouth parts and walking legs, and opisthosoma includes pusher legs and telson. On the dorsal side of the prosoma, a pair of ocelli is presented at the center of the carapace, and a pair of compound eyes is located laterally. The hinge joint connects the prosoma to the

opisthosoma, used for contraction, shrinkage, and helps the horseshoe crabs turn themselves over. On the opisthosoma possess six pairs of spines, which are movable through joints, under the control of the nervous system. The center of its body revealed the keel, which is located in the middle of Carapace across the Prosoma to the Opisthosoma. The inhalant channel is found between the genal angle and the opisthosoma. These channels aid water respiration by facilitating the flow of water through the book gills and out to the exhalant channel [5].

Xiphosurans are the only four extant species in the class of Merostomata consisting of distinct species characterized by their telsons, the number of bulbous segments and claws, and the sulci of the carapace [9].

1. *Carcinoscorpius rotundicauda* (Mangrove horseshoe crab) possesses a round telson. The second and third male appendages are bulbous claws. They are often found in the Pacific Ocean, along the coasts of the Indian Ocean, Philippines, Indonesia, and Malaysia.

2. *Limulus polyphemus* (Atlantic horseshoe crab) has a triangular telson. Bulbus claws are only found in the male second appendage. This species is often found in the Northern American continents.

3. *Tachypleus gigas* (Horseshoe crab) has a triangular telson. The second and third male appendages are bulbous claws. They are often found in the Pacific Ocean, along the Indian Ocean coast (east coast of the Bay of Bengal), the region from Indonesia to Vietnam, Sarawak, Malaysia, Singapore, and Thailand.

4. *Tachypleus tridentatus* (Japanese horseshoe crab) has a triangular telson. The second and third male appendages are bulbus claws, and in the male Japanese horseshoe crab the sulci of the carapace was found. This species frequently found in the Pacific Ocean, specifically along the coasts of Japan, the East

China Sea, the South China Sea, Taiwan, and around northern Borneo [2].

The oral appendages are located on the prosoma consisting of six appendages. The first pair, the chelicera, are used for grasping food and bringing it into their mouth. Each chelicera is divided into three segments: protomerite, deutomerite and tritomerite which is movable. Following these are four pairs of walking legs. Each walking leg has six segments. The initial segment, the coxa, forms the base and connects to the gnathobase. The remaining segments are the trochanter, patella, tibia, tibiotarsus, and dactylopodite respectively. The dactylopodite, being the final segment, is movable. Additionally, the second appendage is also called the pedipalps, which can be used to distinguish male and female horseshoe crabs. Male pedipalps have a large bulbous claw used to hold female horseshoe crabs when mating firmly. The female's pedipalp appears to be like regular walking legs. The sixth pair of appendages is called a pusher leg or swimming leg. It is divided into nine segments: coxa, trochanter, femur, patella, tibia, pretarsus, processes, and apotele. Furthermore, the flabellum has a paddle-like structure, which is used to detect substances within the inhalant channel. Lastly, a small appendage called chilaria, located on the opisthosoma, prevents food from escaping behind pusher legs [5,6,7].

Digestive system anatomy [10]

The horseshoe crab's digestive system has a straight, tube-like structure. It can be divided into the luminal alimentary tract and the accessory organs. The alimentary tract is a straight tube consisting of multiple parts the entire length spans from the prosoma to the opisthosoma. It is connected to the hepatopancreas by hepatopancreatic collect tubules. The luminal alimentary tract is comprised of the oral cavity, oesophagus, proventriculus, intestines, and rectum, with a chitinous cuticle covering the mucosal lining

of each organ except the intestine. The alimentary tract begins at the mouth, located at the center of the prosoma. Oral appendages are found on the ventral side - starting with the chelicera, small fangs that have developed into pincers used to grasp food into the mouth. There are four pairs of walking legs that bear structures known as gnathobases, which help grind food before it enters the oesophagus and the crop for storage. The food is transferred to the gizzard, where grinding occurs by numerous small chitinous teeth. The ground food moves to the midgut to digest and is absorbed in the hindgut. The rectum collects the food waste and excretes it through the anus. The hepatopancreas is located around the prosoma, which connects to the midgut by hepatopancreatic duct and secretes enzymes to facilitate digestion within the midgut.

Digestive system histology

The oral cavity (mouth) is located between the third and fifth pairs of appendages. Numerous spiny gnathobases are found creating a rough surface [10].

The oesophagus has a layer of esophageal mucosa folded longitudinally and a cuticle overlying the mucosa. In the submucosa layer, a large number of small blood vessels, including arterioles, are present. There are also reserve cells, which regenerate damaged tissue. The muscle fibers are found within the muscularis externa layer.

The proventriculus consists of the crop and ventriculus (gizzard). The mucosa folds are similar to esophageal mucosa. In the ventriculus, the ventricular mucosa is present, and the tunica muscularis externa is relatively thick, reaching its maximum thickness in the ventriculus. The mucosal epithelium has a cuboidal shape while the submucosa contains few cells and is composed mainly of connective tissue and blood vessels.

The pyloric valve has a thinner layer of cuticle compared to the previous regions.

Inside, there are interlocking ridges, and small muscle fibers are in a circular pattern. The subepithelial space shows an irregular structure, which forms a vascular meshwork.

The midgut consists of intestinal epithelium which has numerous folds but lacks a cuticular layer. Basophilic cells can be found under the basal lamina. The submucosa and muscularis layers are thin, containing orderly and dispersed cells composed of hemocytes. Additionally, the midgut has branched structures called diverticula, which extend and connect to the hepatopancreas forming collecting tubules.

The rectum, the terminal part of the intestine, is characterized by internal folds. A cuticular layer is present on the mucosa including the muscularis, which is divided into longitudinal and circular muscle fibers.

The hepatopancreas is formed by interstitial cells interrupted regularly by hepatopancreatic duct which consists of epithelial cells and tubular epithelium. The hepatopancreatic duct are comprised of two primary cells. Dark cells, which contain secretory granules, release their contents via merocrine secretion and light cells, which are approximately four times more numerous than dark cells, function as phagocytic cells. Additionally, interstitial cells, also known as storage cells, may be found, which are storage cells. Numerous eosinophilic granules are also observed surrounding the heart, digestive tract, and central nervous system.

2. Materials and methods

2.1 Anatomical methods

Specimens of *Carcinoscorpius rotundicauda* were collected from Samut Songkhram. 70% ethanol combined with clove oil was used to anesthetize the specimens, causing the organisms to extend their bodies, enhancing the anatomical examination efficiency. Subsequently, the specimens were transferred to Davidson's

fixative to soften the carapace as the glacial acetic acid breaks down the chitin components. Before the dissection, the specimens were preserved in 70% ethanol for 24 hours to ensure the stability of the tissue [7].

The dissection began with a cut from the ventral side using a pair of fine-tipped scissors to remove the appendages at the coxal segments. The carapace of the opisthosoma was cut using a bone cutter and extended toward the prosoma. Special caution was taken to avoid damaging the hepatopancreas, which distributes around the digestive tract. The blunt side of the scalpel was used to gently clear the surrounding tissue to prevent tearing. After the carapace was entirely removed, the digestive tract was carefully separated from the heart to enhance the anatomical observation effectiveness.

2.2 Histological methods

Specimens of *Carcinoscorpius rotundicauda* were collected from Samut

Songkhram. 70% Ethanol combined with Clove oil was used to anesthetize the specimens, causing the organisms to extend their bodies, enhancing the anatomical examination efficiency. Then remove the section designated for studying and clean the sample with 4% Formalin, removing any food inside the alimentary tract. The Davidson fixative method was used to preserve the tissue for 24 hours. Dehydration was performed in an Alcohol series (50%–100%) and cleared the samples by using a butanal : xylene and xylene respectively. Subsequently, the samples were embedded in paraplast and sectioned using a rotary microtome at a thickness of 6–8 microns. Lastly, the sections were stained with haematoxylin and eosin, mounted on slides and sealed to prepare for imaging under compound light microscope [7, 8].

3. Result

3.1 Anatomical results

The mangrove horseshoe crab, considered a detritivore, possesses a complete

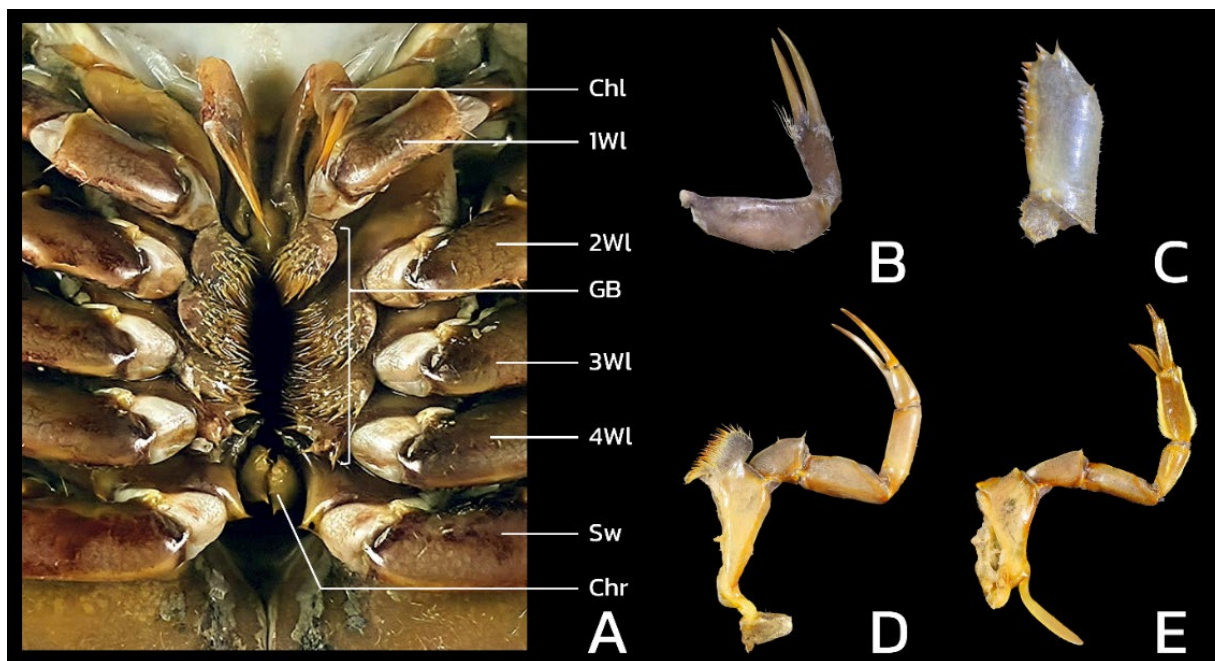


Figure 1 Gnathobase characteristic surrounding the mouth (A) Appendages located at the prosoma surrounding the mouth (B) Chelicerae (C) Chilaria (D) 1st – 4th Walking legs (E) Swimmer leg. Anatomical abbreviations: 1Wl, First walking leg; 2Wl, Second walking leg; 3Wl, Third walking leg; 4Wl, Fourth walking leg; Chl, Chelicerae; Chr, Chilaria; Sw, Swimmer leg

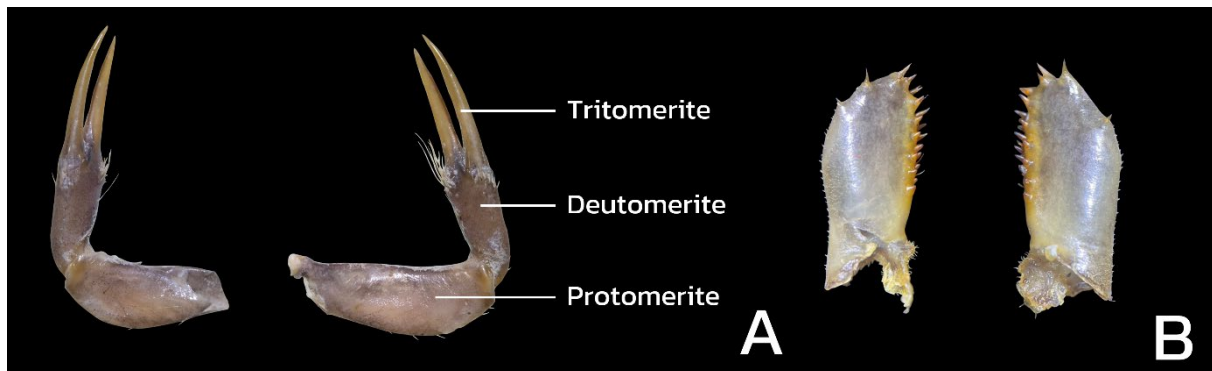


Figure 2 The small appendage of Mangrove horseshoe crab (A) Chelicerae the first pair of appendages (B) Chilaria the last pair of appendages.

digestive tract, featuring a U-shaped bend at the anterior part. The digestive tract begins with the mouth, where oral appendages are located, by utilizing the chelicerae, the first pair of appendages at the prosoma developed from small pinchers, for grasping food. Also, the first to fourth walking legs (1Wl, 2Wl, 3Wl, and 4Wl) possess a pincer at the terminal segment, enhancing their capability to capture food. At the gnathobase (Gb) the base segment was found, a structure which extends from its mouth, functioned as a food grinder; however, the swimmer's leg appendage lacks the gnathobase. Chilaria (Chr), the smallest appendage, is characterized by its small spine assisting its process of eating which is shown in Fig 1.

Chelicerae (Chl), the first pair of appendages, consists of three segments which is shown in Fig 2.

1. Coxa: The longest segment connected from the vault.

2. Tibia: An immovable segment next to the coxa.

3. Tarsus: The terminal segment with pointed end is a movable finger.

Walking legs (1Wl, 2Wl, 3Wl, and 4Wl) have a pincer-like structure and function in locomotion and prey capture. Each appendage consists of six segments which is shown in Fig 3 and 4.

1. Coxa: The first segment, connected to the vault.

2. Tronchanter: The second segment, a short segment located after the coxa.

3. Femur: The third segment which is the longest part of the leg.

4. Petella: The fourth segment, located after the femur.

5. Tibia: The fifth segment, having a pointed end and functioning as the immovable finger.

6. Tarsus: The sixth segment, ending in a pointed end functioning as the movable finger.

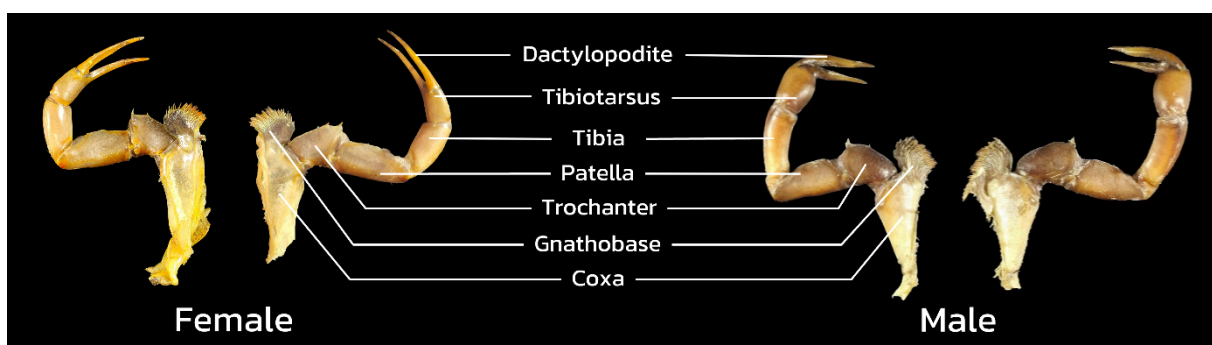


Figure 3 The First walking legs Used to determine the sex of Horseshoe crab

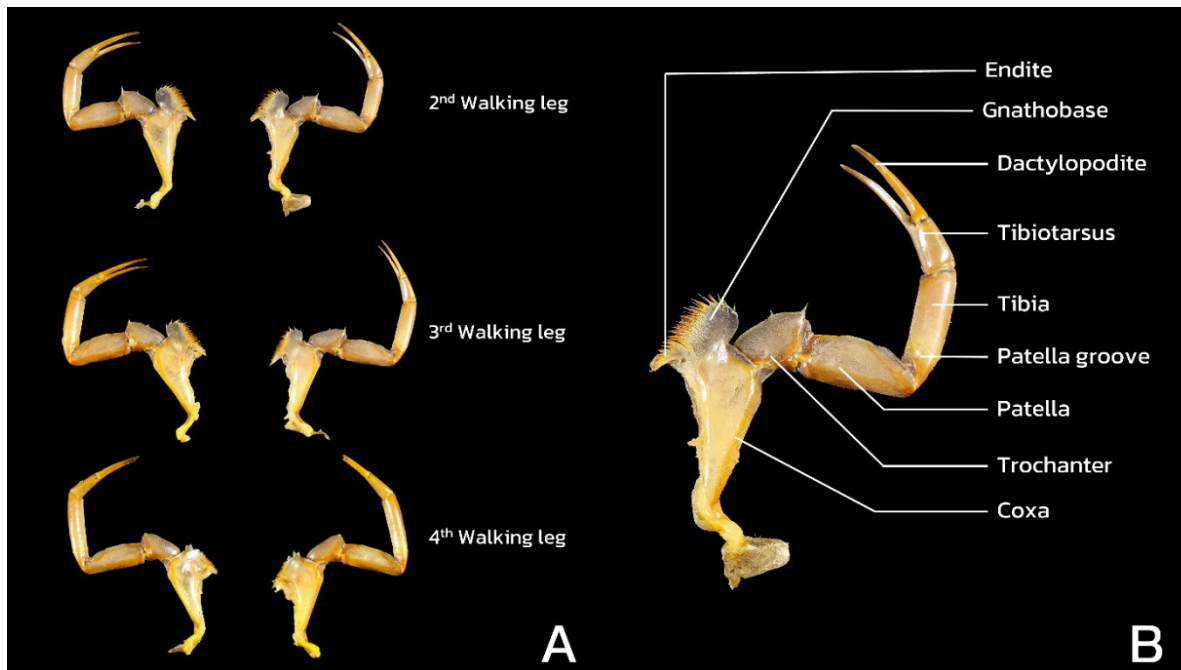


Figure 4 The Second, Third and Fourth walking legs function in locomotion and prey capture.
(A) Walking leg with spiny gnathobase (B) Walking leg segments

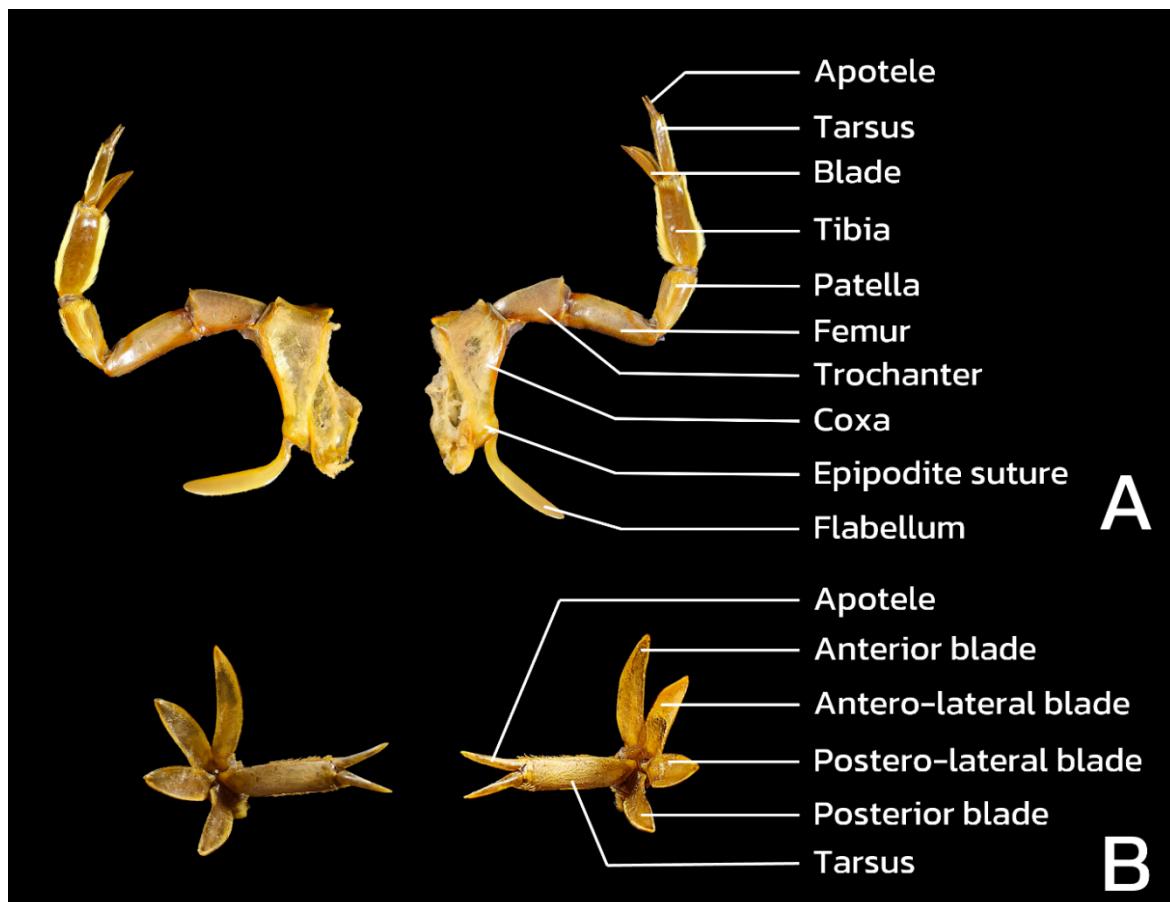


Figure 5 Swimmer legs (A) Ventral view of swimmer leg (B) 4 Blades found in the base of tarsus segment

In addition, the structures use to support the walking legs are Endite is terminal part of the for food processing. and patella groove is a gnathobase, extending into the gnathostome groove on the patella that supports the femur when the leg is retracted.

for food processing. and patella groove is a gnathobase, extending into the gnathostome groove on the patella that supports the femur when the leg is retracted.

Swimmer legs (Sw), the sixth appendage, are used for prey capturing, walking and swimming. They are similar to walking legs featuring a pincer-like characteristic and consisting of six segments, but possess four additional parts which is shown in Fig 5.

1. Pretarsus: 2 small pincers at the tip of the tarsus
2. Blade: A flat structure extending from the tibia, used for pushing and lifting the horseshoe crab. There are four blades: the anterior blade, antero-lateral blade, postero-lateral blade, and posterior blade.
3. Endopodite suture: groove on the coxa, located before the flabellum.
4. Flabellum: A flap-like structure extending from the coxa, used for swimming.

Chilaria (Chr), the seventh appendage, has a claw-like structure located at the lowermost part of the gnathostome which is shown in Fig. 2.

Food enters the first part of the digestive tract through the mouth (M), which has a circular shape and is located at the center of the ventral side of the prosoma, with numerous pairs of spiny gnathobases functioning in food grinding. Then, the food is gradually transferred to the oesophagus (Oes), which transports it to the crop (C) for temporary storage. After the crop, it enters the gizzard (Gz), where mechanical digestion takes place. In this section, there are small, tooth-like structures aiding the process. Next, the food passes through the pyloric valve (PV), which is a muscular structure that prevents backflow of the food. After that, the food enters the midgut (MG), which has thin, wave-like folded walls. Additionally, the hepatopancreatic ducts (Hpd) are connected to the midgut, delivering the digestive enzymes from the hepatopancreas. The remaining food enters the hindgut (HG), which has thicker walls. Lastly, food waste is collected in the Rectum (R) and excreted at the anus (A) which is shown in Fig: 6, 7 and Table 1.

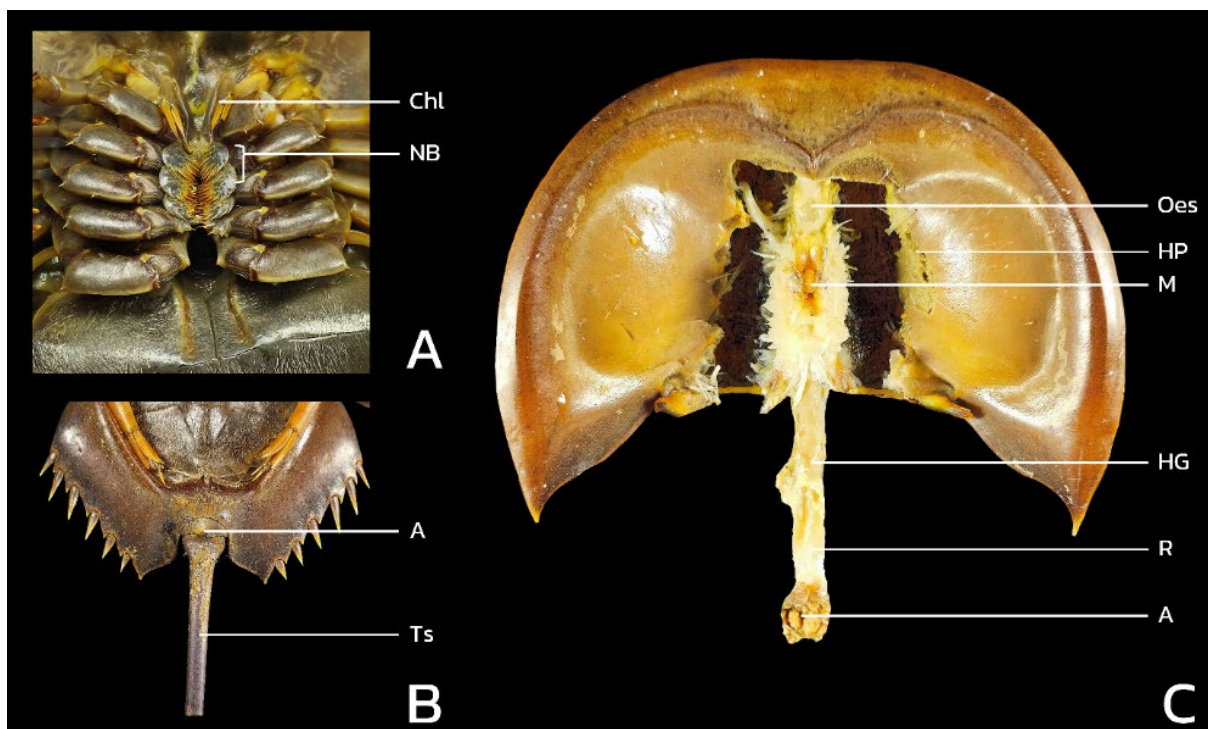


Figure 6 The digestive tract of horseshoe crab (A) Gnathobase characteristic surrounding the mouth (B) The anus near movable telson (C) Digestive system of Horseshoe crab. Anatomical abbreviations: A, Anus; C, Crop; Chl, Chilaria; Gz, Gizzard; HG, Hindgut; Hpd, Hepatopancreatic duct; M, Mouth; MG, Midgut; NB, Gnathobase; Oes, Oesophagus; PV, Pyloric valve; R, Rectum; Ts, Telson

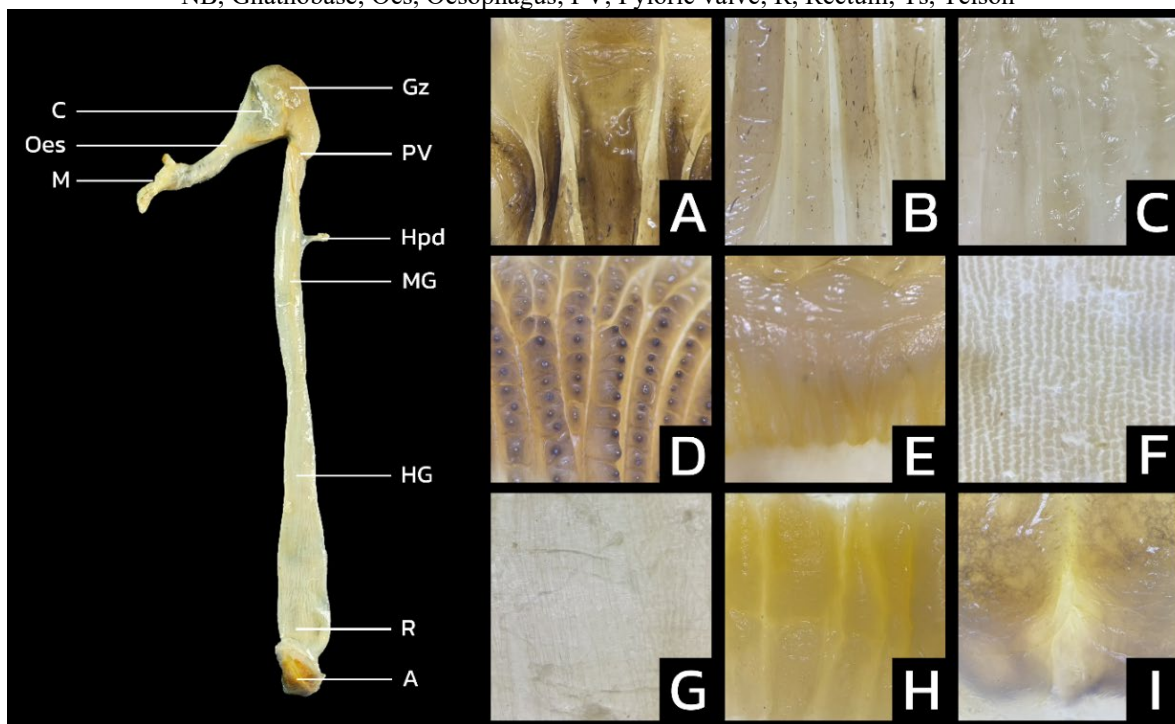


Figure 7 The dissection of alimentary tract without hepatopancreas (A) Mouth (B) Oesophagus (C) Crop (D) Gizzard (E) Pyloric valve (F) Midgut (G) Hindgut (H) Rectum (I) Anus

Table 1 Inner wall of alimentary tract character of mangrove horseshoe crab

Label	Structure	Characteristic
A	Mouth	There are folds with invaginations forming elevated ridges with a curved, semi-circular pattern resulting in varying coloration, with some areas appearing darker and others lighter. Additionally, small setae are present.
B	Oesophagus	Folds with invaginations are present. Longitudinally, there are minimal overlapping folds resulting in less color variations. Small satae are also present.
C	Crop	Folds with invaginations are present. White ridges occur longitudinally with minimal overlapping, without any mall satae.
D	Gizzard	Elevated tissue forms gizzard teeth, functioning in food grinding. Small satae are absent.
E	Pyloric valve	There are inverted triangular folds that function as a sphincter and prevent the backflow of food.
F	Midgut	The tissue has a distinct plica circularis folds, forming evenly spaced horizontal ridges
G	Hindgut	Folds and small satae are absent.
H	Rectum	Folds with longitudinally invaginations are observed. However, there is no overlapping leading to the absence of color varying.
I	Anus	A non-folding structure with a thick and relatively rigid wall of tissue, due to a high chitin content.

3.2 Histological results

3.2.1 Mouth

The mouth, the entry point of the food into the digestive system, possesses the oral cavity (OC) located in the central area of the mouth, and consists of three distinct tissue layers: epithelial tissue, connective tissue, and muscularis. In the epithelial tissue features a simple low columnar epithelium (Lo) with a thick cuticle (C) layer. The connective tissue layer (CT) has irregular elevations, which appear as ridges or branch into 2–3 lobes. The muscularis is composed of thick layers of circular muscle (M), which assist in moving food into the mouth which is shown in Fig 8.

3.2.2 Oesophagus

The oesophagus is a thin tubular structure consisting of three tissue layers: epithelium tissue, connective tissue, and muscularis. The epithelial tissue consists of simple low columnar epithelium (Lo), characterized by a thick cuticle (C) layer. The connective tissue

(CT) features irregular elevations, which appear as ridges or branch into 2–3 lobes. The muscularis presents thin layers of circular muscle (M) compared to the mouth which is shown in Fig 9.

3.2.3 Crop

The crop is a tubular structure connected to the oesophagus that serves as temporary food storage before entering the gizzard, consisting of three layers of tissues: stratified squamous epithelium, connective tissue, and muscularis. A stratified squamous epithelium (Sq) is presented in the epithelial tissue with a thick cuticle layer. The connective tissue (CT), classified as a loose connective tissue, represents the densest layer in this region. The external part known as muscularis contains thin longitudinal and circular muscles (M) that enable the crop to expand, allowing the crop to store a larger amount of food which is shown in Fig 10

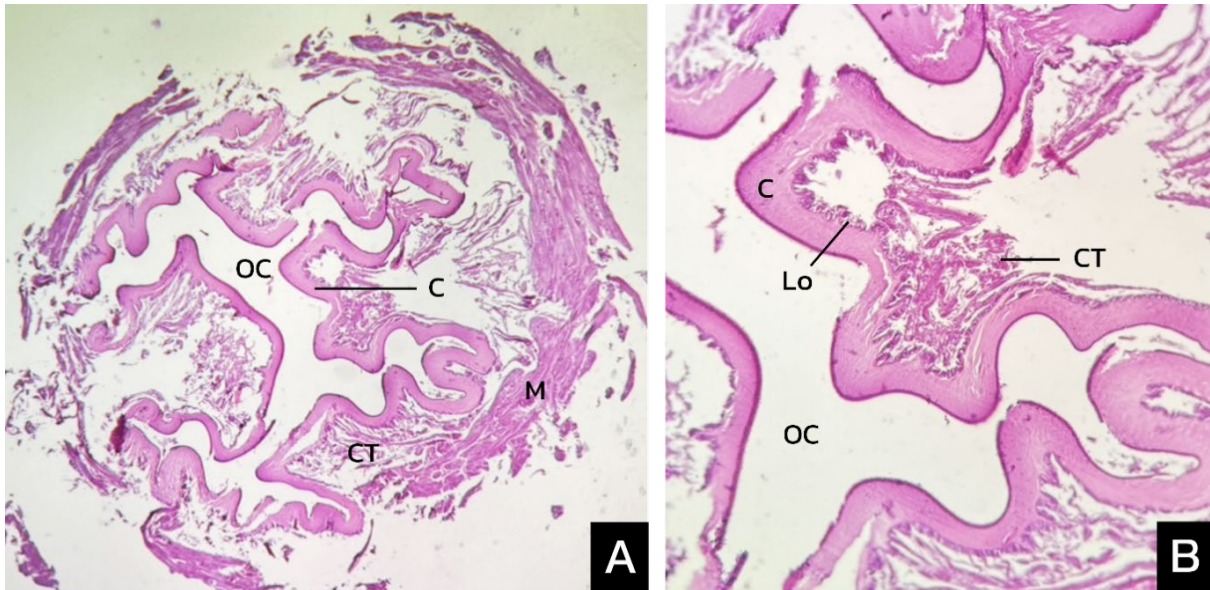


Figure 8 Mouth cross section (A) The central cavity called oral cavity surrounded with cuticle layer (40X)
(B) The simple low epithelium is found in mouth covered by cuticle layer (100X). Histological abbreviations:
C, Cuticle; CT, Connective tissue layer; Lo, low columnar; M, Circular muscle; OC, Oral cavity.

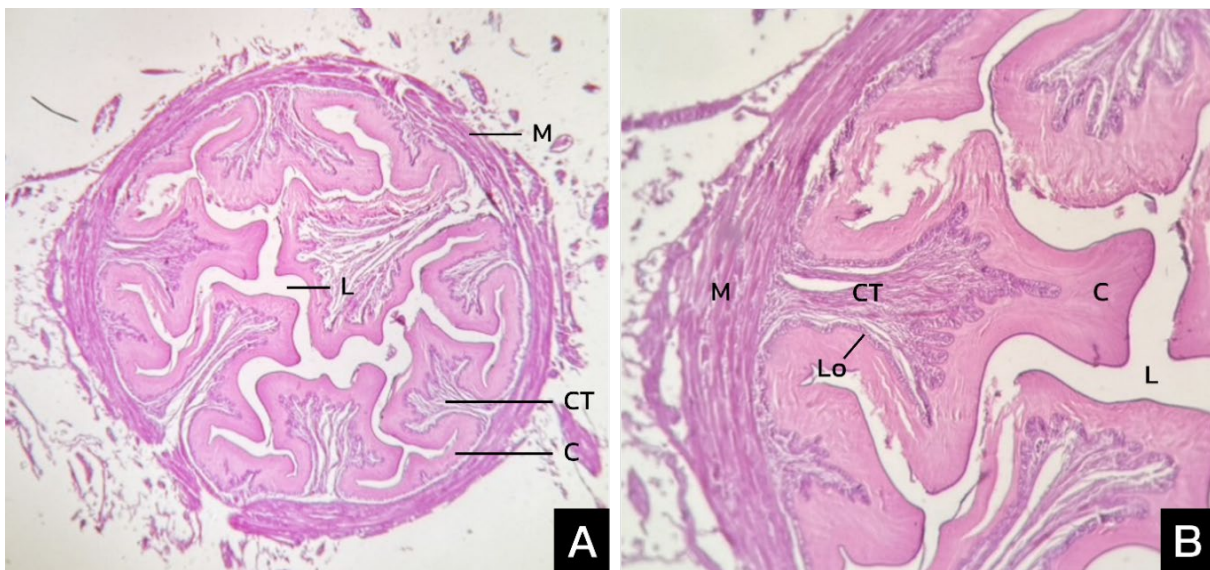


Figure 9 Oesophagus cross section (A) The narrow lumen of oesophagus by folding of connective tissue (40X)
(B) The tissue layer of oesophagus (100X). Histological abbreviation: C, Cuticle; CT, Connective tissue;
L, Lumen; Lo, Simple low columnar epithelium; M, Muscle

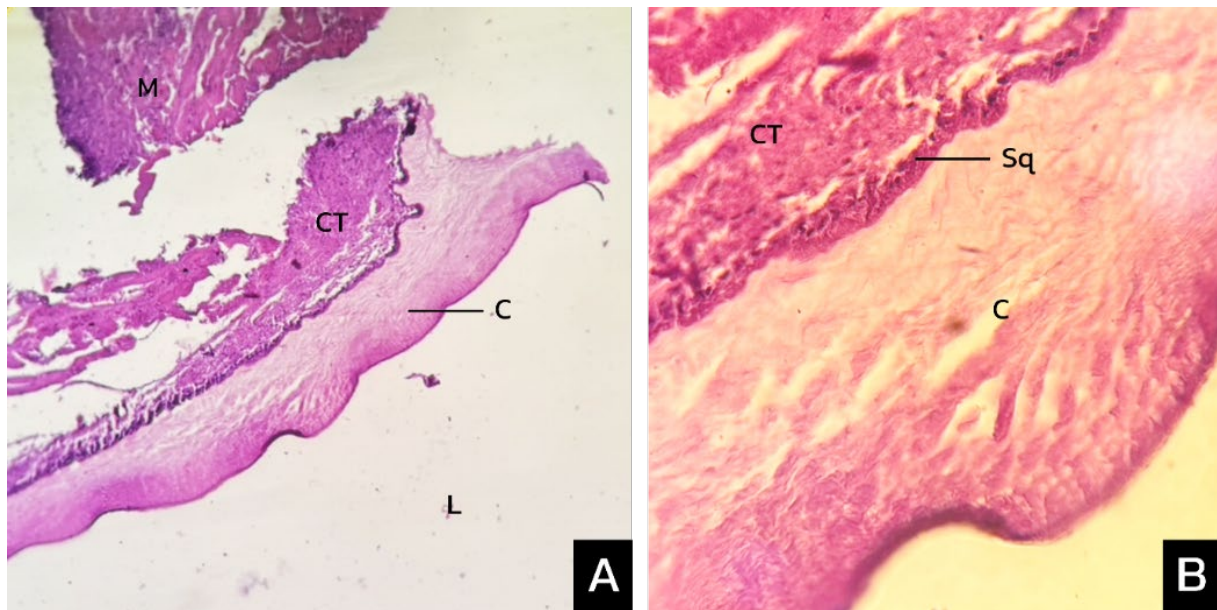


Figure 10 Crop cross section (A) The thin wall of crop (100X) (B) The three tissue layer of crop (400X).
Histological abbreviations: C, Cuticle; CT, Connective tissue; L, Lumen; M, Muscles; Sq, Stratified squamous epithelium;

3.2.4 Gizzard

The gizzard is a thick tubular structure characterized by a narrow lumen that connects to the midgut through the pyloric valve. Its epithelium is presented in a simple columnar epithelium (Co) form, which is coated with a thick cuticle (C) layer and an additional epicuticle layer (EC). Additionally,

the connective tissue features elevations form a tooth-like structure called gizzard teeth (GT). The collective tissue consists of loose connective tissue and a thick muscularis (M). When the circular muscles contract, the gizzard teeth allow them to grind food mechanically which is shown in Fig 11.

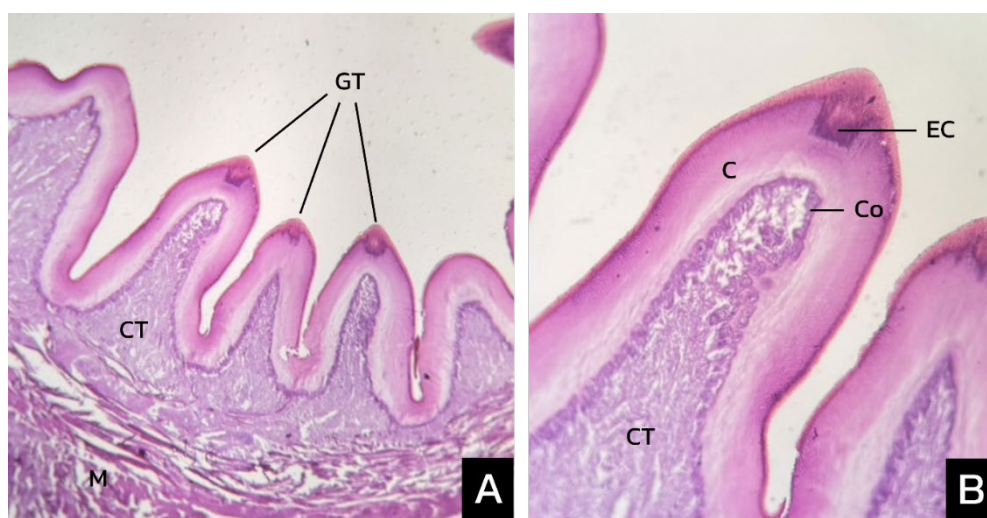


Figure 11 Gizzard cross section (A) The fingers like structure are found in gizzard called gizzard teeth (40X) (B) The top of gizzard teeth found epicuticle layer (400X). Histological abbreviations: C, Cuticle; Co, Simple columnar epithelium; CT, Connective tissue EC, Epicuticle layer; GT, Gizzard teeth; M, Muscularis

3.2.5 Pyloric valve

The pyloric valve is characterized by a short tubular structure with a narrow lumen that connects to the midgut serving to prevent the backflow of food, and it consists of three tissue layers: epithelium, connective tissue, and muscularis. The epithelium is presented in Stratified squamous epithelium (Sq) and is covered by a thick cuticle (C) layer. The

sphincter muscle (Spm) forms elevations that create a raised structure known as the Pyloric valve (Pyv). The connective tissue layer (CT) consists of a thin layer of loose connective tissue and a thick muscularis (M). Throughout the process of muscle contraction, the lumen narrows, preventing the backflow of food which is shown in Fig 12.

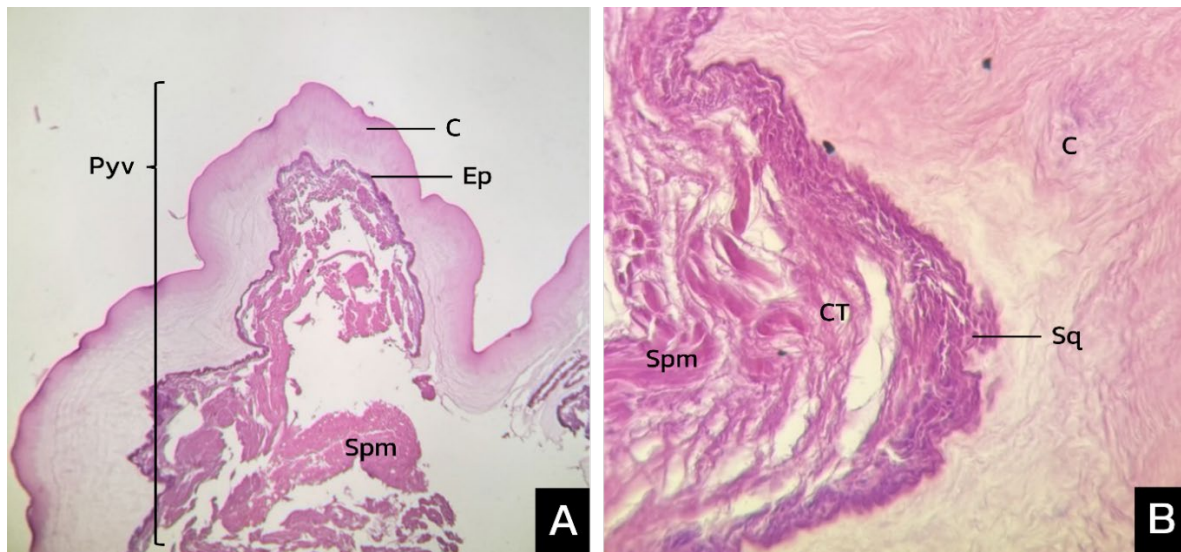


Figure 12 Pyloric valve cross section (A) The sphincter muscle in Pyloric valve (40X) (B) The 3 layers of pyloric valve 400X. Histological abbreviations: C, Cuticle; CT, Connective tissue layer; Ep, Epithelium; M, Muscularis; Pyv, Pyloric valve; Spm, Sphincter muscle; Sq, Stratified squamous epithelium.

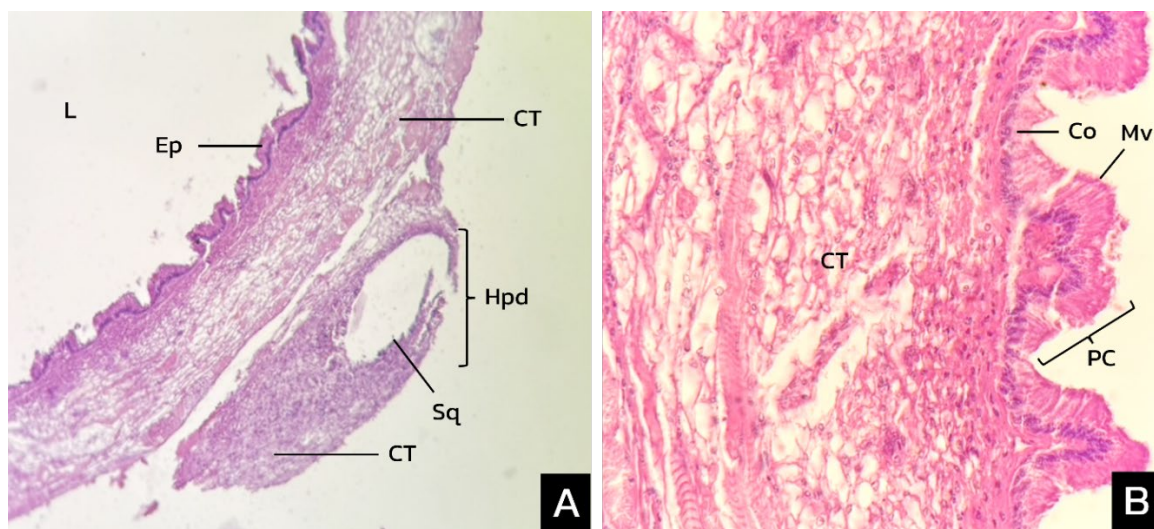


Figure 13 Midgut cross section (A) The large lumen of midgut (40X) (B) The plica circularis is found in midgut (400X). Histological abbreviations: Co, Simple Columnar epithelium; CT, Connective tissue; Ep, Epithelium; Hpd, Hepatopancreatic duct; L, Lumen; Mv, Microvilli; PC, Plica circularis; Sq, Simple squamous epithelium.

2.6 Midgut

The midgut is a thin tubular structure characterized by a large lumen (L) that is connected to the hindgut. Within the midgut, the epithelium (Ep) is found; it contains a simple columnar epithelium (Co). The cellular surface contains microvilli (Mv), enlarging the surface area and enhancing both digestion and nutrient absorption. The epithelium is encircled by connective tissue (CT) in the form of relatively thick loose connective tissue, which facilitates the midgut expansion and causes the formation of raised folds known as plica circularis (PC). Additionally, hepatopancreatic duct (Hpd) are connected to the midgut, delivering the digestive enzymes from the hepatopancreas. These ducts are composed of simple squamous epithelium (Sq), surrounded by loose connective tissue (CT) which is shown in Fig: 13.

3.2.7 Hindgut

The hindgut is characterized as the narrowest tubular structure within the digestive tract with the widest lumen (L); it connects to the rectum and consists of two main tissue layers: the epithelium and the connective tissue. The epithelium (Ep) is classified as simple columnar epithelium

(Co), characterized by the absence of microvilli and connective tissue folds such as plica circularis. The connective tissue itself is a relatively thin layer interspersed with 2–3 coatings of muscle (M) which is shown in Fig 14.

3.2.8 Rectum

The rectum is a thick tubular structure that serves as temporary storage for waste before it exits the body through the anus. The internal cavity is called the anal canal (AC), which transports waste directly to the anus. The rectal wall consists of three layers: the epithelium, connective tissue, and the muscular layer. The epithelial tissue contains stratified squamous epithelium (Sq) coated by a thick cuticle (C) layer, and chitinocyte (Ch), a cell which plays a significant role in the chitin production process, are also present, giving the rectum a darker appearance. Within the connective tissue layer, there are glandular structures known as the rectal glands (RG), which can be classified into two types: Serous acini (Se), groups of serous cells, and mucous acini (Mu), groups of mucous cells. The muscular layer contains both circular and longitudinal muscles that facilitate the movement of fecal matter toward the anus which is shown in Fig 15.

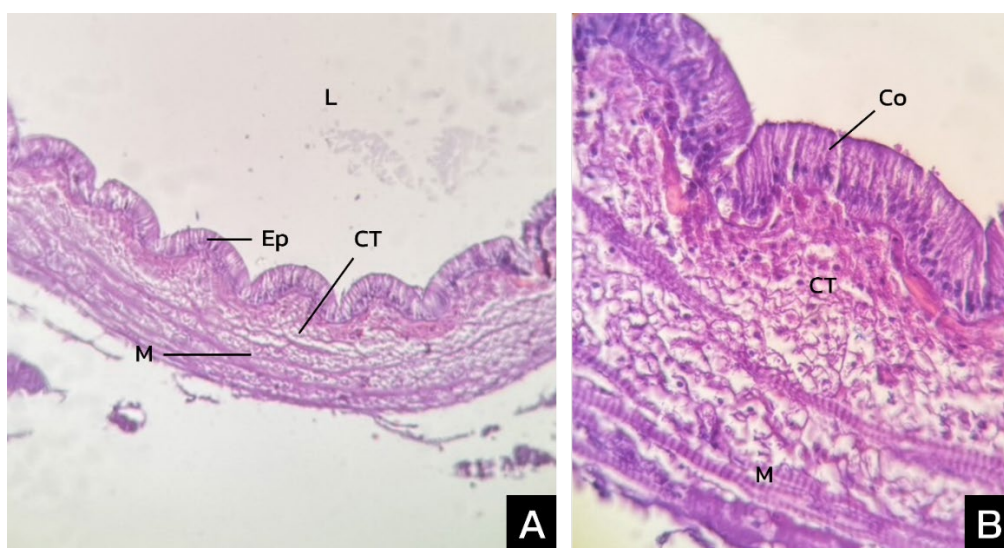


Figure 14 Hindgut cross section (A) The largest lumen in Alimentary tract is found in hindgut (40x) (B) The 3 layers of hindgut (400X). Histological abbreviations: Co, Simple columnar epithelium; CT, Connective tissue; Ep, Epithelium; L, Lumen; M, Muscle

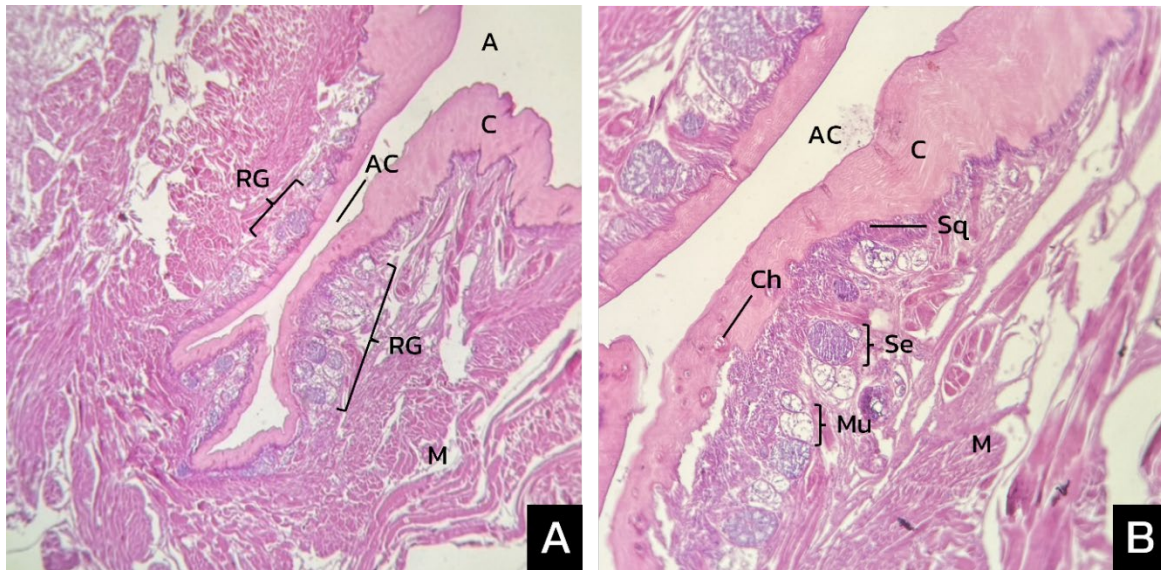


Figure 15 Rectum long section (A) The epithelium of rectum covered by thick cuticle layer (40X) (B) The Serous and mucous acini are found only rectum (400X). Histological abbreviations: AC, Anal canal; Sq, Stratified squamous epithelium; C, Cuticle; Ch, Chitinocyte; RG, rectal glands; Se, Serous acini; Mu, Mucous acini; M, Muscularis

3.2.9 Anus

The anus (A) is an external orifice that connects to the anal canal (AC). Its wall consists of three distinct layers: epithelium connective tissue (CT), and muscularis (M). The epithelial tissue features a simple low columnar epithelium (Lo) covered by a cuticle (C) that is narrower compared to the

rectum. The connective tissue (CT) layer is composed of loose connective tissue and contains the telson nerve (TN). The muscularis layer is characterized by circular muscles that enable the horseshoe crab to right itself when overturned which is shown in Fig 16.

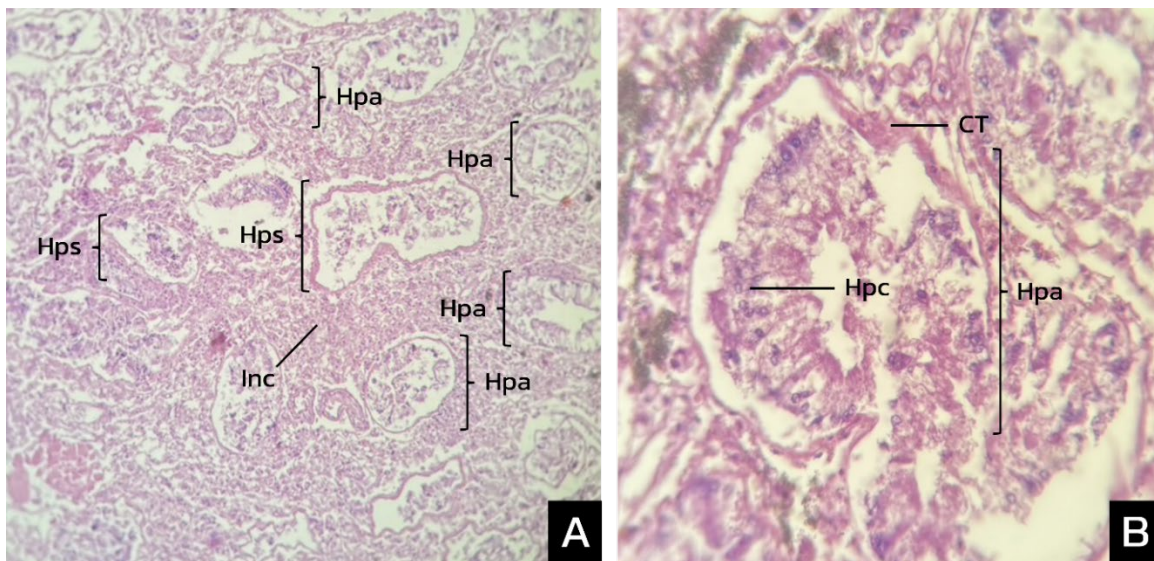


Figure 17 Hepatopancreas cross section (A) The hepatopancreas filled with Inner cell mass (40X) (B) The hepatopancreatic acini (100X) Histological Abbreviation: CT, Connective tissue; Hpa, Hepatopancreatic acini; Hpc, Hepatopancreatic cells; Hps, Hepatopancreatic sinusoids; Inc, Inner cell mass

3.2.10 Hepatopancreas

The hepatopancreas is a large organ located within the prosoma, distinguished by its convoluted tubular structure; the arrangement pattern of this structure is called the Hepatopancreatic acini (Hpa), which is encircled by connective tissue (CT). Hepatopancreatic cells (Hpc) play a crucial role in producing digestive enzymes. Furthermore, this organ also contains the hepatopancreatic sinusoids (Hps), the capillary-like vessels, which function as blood reservoirs. Surrounding the hepatopancreatic acini and sinusoids are the interstitial cells (Inc), which serve by providing support for the hepatopancreatic cells which is shown in Fig 17.

4. Conclusion

From this study, it was observed that *Carcinoscorpius rotundicauda* possesses a thick exoskeleton. Adding acid to soften the chitinous shell is recommended, facilitating dissection. Specimens were anesthetized using clove oil mixed with 70% ethanol for 30 minutes and fixed in Davidson's solution to preserve the internal structures for anatomical and histological examination.

Anatomically, the horseshoe crab's digestive tract is primarily a straight tube, with a U-shaped bend in the anterior part, which is a primitive characteristic found in the digestive systems of arthropods. One large digestive gland, the hepatopancreas, was identified functioning in enzyme production. Enzyme is delivered to the midgut by ducts, suggesting that the digestive system of the horseshoe crab is less developed compared to other arthropods such as insects and crustaceans.

Histologically, the digestive tract contains simple columnar epithelium or simple low columnar epithelium, which are mostly absorptive cells. There is no specialized enzyme-secreting glands or cellular structures found. A thick cuticle layer covers most of the epithelial surfaces. Variations in the morphology of the

epithelium, connective tissue, and muscle layers allow us to identify the digestive organs. For example, the foregut, including the mouth and oesophagus, has similar epithelial and connective tissue layers, but the muscle layer of the mouth is significantly thicker, suggesting a role in active food intake rather than passive transport. The crop contains stratified squamous epithelium, allowing the crop to expand for food storage. The gizzard can be easily distinguished because of the gizzard teeth, while the pyloric valve contains a thick sphincter muscle.

The midgut and hindgut show similar tissue characteristics and lack a cuticle layer. These regions can be classified by the presence and pattern of plica circularis formed by invaginations of the connective tissue. Lastly, the rectum is the only organ that contains both serous and mucous acini, which is how it can be classified.

Acknowledgement

The anatomical and histological study of the mangrove horseshoe crabs have received support from various sources. Our research team would like to express our sincere gratitude to Dr. Thanit Siriboon, a lecturer in the Biology department at Srinakharinwirot University, for providing the location and specialized equipment for histological studies, as well as for his guidance throughout the research process. We would like to convey our appreciation to Ms. Thanalawan Pealkha, a professor in the Global Health Innovation major at the Science department of Srinakharinwirot University and Prasarnmit Demonstration School (Secondary), for her assistance in facilitating communication between the school and the biology faculty, and for her ongoing support throughout the progression of our research.

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Anatomical and Histological of the Digestive Organs of the Japanese mantis shrimp *Oratosquilla oratoria* (Stomatopoda: Squillidae)

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Abstract

The Japanese mantis shrimp (*Oratosquilla oratoria*) is an economically important marine species. It possesses a straight, tubular digestive tract with a U-shaped curvature near the head, which is considered a primitive characteristic compared to the more developed raptorial claw appendages used for capturing prey. This study aims to expand histological knowledge to facilitate comparison and explanation of cellular mechanisms. The findings reveal that chemical digestion in the mantis shrimp occurs only in the intestine, supported by enzymes produced by the hepatopancreas, where cells are organized into hepatic acini. In contrast, the cardiac and pyloric stomachs are composed of rigid structures containing chitin, functioning in mechanical digestion through muscle contraction. No serous cells were observed, further affirming that only mechanical digestion occurs in these regions. The digestive tract tissues can be divided into three layers: the epithelium, connective tissue, and muscularis. The characteristics of each layer can serve as criteria for distinguishing different regions of the digestive system.

Keywords: Digestive system; Mantis shrimp; Hepatopancreas; Cardio-pyloric valve; Histology

1. Introduction

The Japanese mantis shrimp (*Oratosquilla oratoria*) is an invertebrate belonging to the phylum Arthropoda and class Malacostraca [2]. A key characteristic of this group is the presence of a hard exoskeleton made of chitin, which is shed through a process called ecdysis to allow for growth. A distinctive feature of the mantis shrimp includes triflagellate antennules, which are used for environmental sensing, and the second pair of thoracic appendages (maxillipeds) that have evolved into large raptorial claws for capturing prey [9]. These claws consist of three articulated segments: the meropodite, protopodite, and dactylopodite, forming a grasping structure similar to the forelegs of a praying mantis—hence the common name “mantis shrimp.”

The mantis shrimp is a marine animal belonging to the crustacean group, similar to crabs and shrimp. Its meat has a taste comparable to that of shrimp and crab, making it increasingly popular as a food source [3]. Additionally, the mantis shrimp holds significant economic value in Thailand and is in demand in both domestic and international markets, including Hong Kong, Singapore, Taiwan, and Japan. Mantis shrimps are found exclusively in marine and brackish waters, particularly in tropical regions. They typically inhabit burrows that they dig themselves or live among crevices in rocks or coral reefs. They can be found from intertidal zones to depths of up to 1,500 meters. Globally, around 450 species have been recorded, and in Thailand, at least 61 species have been reported. However, only 7

of these species are commonly consumed [9].

Digestive System

The digestive system of the mantis shrimp consists of seven main parts: mouth, esophagus, cardiac stomach, pyloric stomach, intestine, rectum, anus, and hepatopancreas [7]. Food is transferred into the mouth by the maxillipeds and then moves through the esophagus, a short tube leading to the cardiac stomach. In this chamber, mechanical digestion occurs via a specialized structure called the gastric mill, which grinds the food [1]. The food is then passed into the pyloric stomach, where mechanical digestion continues. Once broken down into smaller particles, the food enters the intestine, where chemical digestion and nutrient absorption occur. The hepatopancreas, a large digestive gland, produces enzymes and absorbs digested nutrients. Waste material is transported to the rectum for temporary storage and is eventually excreted through the anus [8].

2. Materials and methods

2.1 Anatomical methods

For anatomical study, the mantis shrimp collected in Chonburi province was anesthetized by placing it on ice for 5 minutes. It was then preserved in 70% ethanol. The side of the carapace was removed to facilitate ethanol penetration. Dissection involved removing the head carapace and carefully cutting down the ventral side to examine the hepatopancreas and intestine [4, 5, 6].

2.2 Histological methods

For histological examination, tissue samples approximately 0.5 cm³ in size were collected and fixed in Davidson's solution for 8 hours to preserve tissue structure. The tissues were then dehydrated using a graded alcohol series, embedded in paraffin using paraplast and xylene, and sectioned with a microtome at a thickness of 8–12 microns. Sections were mounted on slides and rehydrated using xylene, butanol, and ethanol in sequence. Staining was performed with hematoxylin to highlight cell nuclei, followed by dehydration, and then counterstaining with eosin to highlight cytoplasm and other cell components. Finally, the slides were dehydrated again and mounted using permount for preservation [4, 5, 6].

3. Result

3.1 Feeding appendages

3.1.1 Oral appendages consist of 3 types of appendages which is shown in Fig: 1 and 2

1. Mandible is the most rigid appendage in the oral cavity, used for chewing. It is arranged at a 90-degree angle. Small teeth-like structure are found on the endopodite side, while the exopodite appears as a filament-like structure.

2. Primary maxilla, the second pair of oral appendages, shaped like a small thin plate. Small teeth-like structure is found on the endopodite side, while the exopodite appears as a filament-like structure.

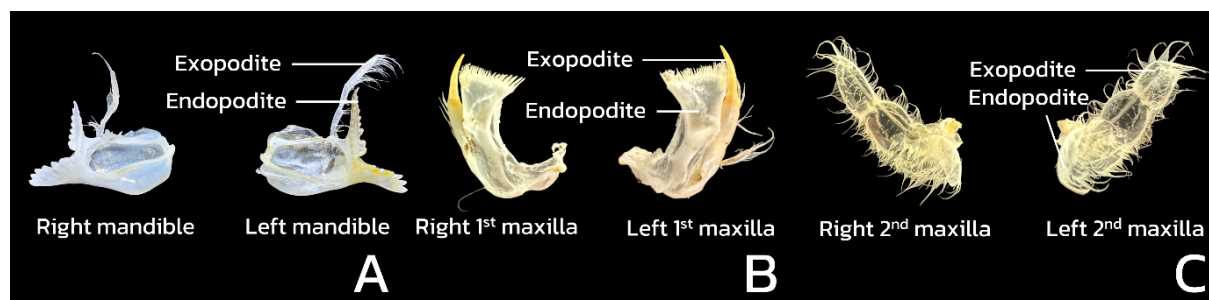


Figure 1 Oral appendages of Mantis shrimp (A) Mandible (B) Primary maxilla (C) Secondary maxilla

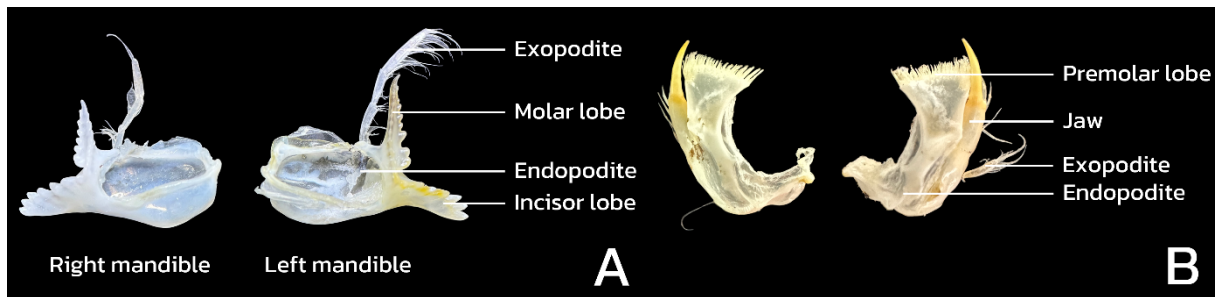


Figure 2 Mantis shrimp teeth (A) Mandible teeth consist of Incisor and molar
(B) First maxilla consists of premolar and jaw

3. Secondary maxilla, the third pair of oral appendages, shaped like a thin, blade-like plate. The endopodite slightly protrudes from the base, and the exopodite is a broad, flat, and thin in structure.

3.1.2 Thoracic appendage consists of feeding appendages and walking appendages consist of 3 types of appendages.

1. Mandibular pulp, a straight appendage composed of segments, used to guide food into the mouth which is shown in Fig: 3.

2. Raptorial claw, an appendage shaped like a claw, used for capturing prey, composed of 7 segments which is shown in Fig: 4

1. Coxapodite, which means the segment closest to the body
2. Basipodite, which means the second segment, following the Coxapodite,

which is also referred to as the first leg segment

3. Ischiopodite, which means the third segment, following the Coxapodite

4. Meropodite, which means the fourth segment, following the Coxapodite

5. Carpopodite, which means the fifth segment, located between the Meropodite and the Propodite

6. Propodite, which means the sixth segment, following the Coxapodite. It also bears 3 Movable spine, and a series of aligned spines called Pectination

7. Dactylopodite, which means the terminal segment at the end of the appendage

3. First to third maxilliped, which are the appendage that are used to handle food. It has a hook-like tips and is composed of 5 segments which is shown in Fig: 3.

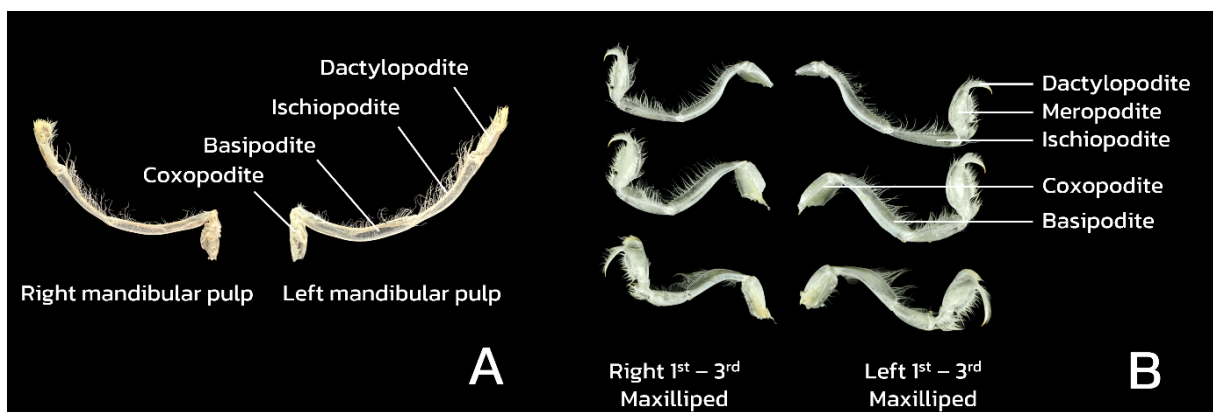


Figure 3 Thoracic appendages (A) The segment of mandibular pulp (B) The segment of Maxilliped

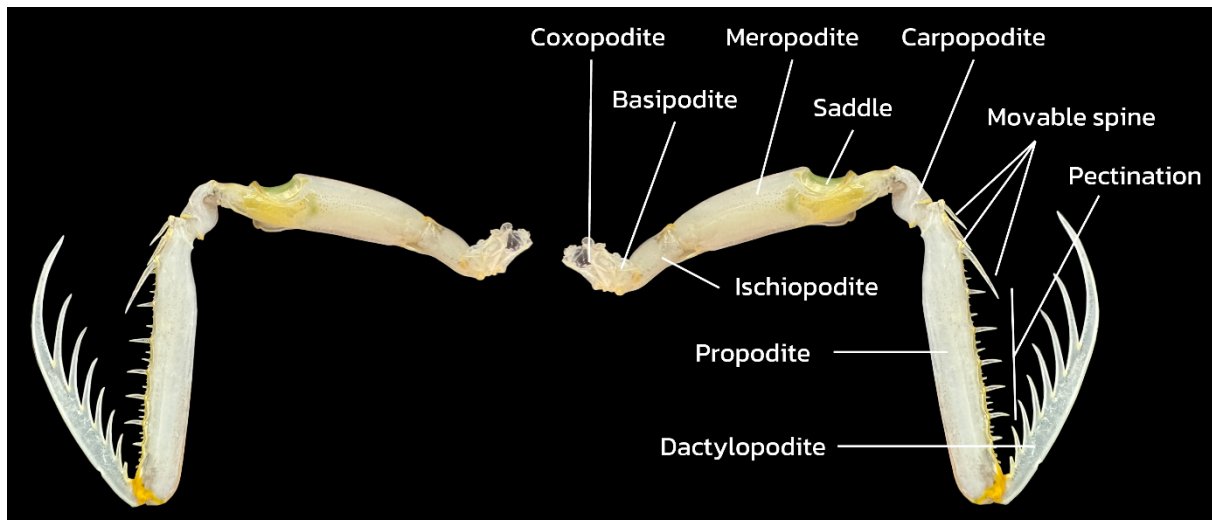


Figure 4 The segment of Raptorial claw

3.2 Anatomical results

The structure of digestive tract of the Japanese mantis shrimp exhibits a straight line. The mouth (M) of the mantis shrimp is located at the ventral side of the carapace, and contains appendages that are associated with eating. These include the oral appendages, consisting of 1 pair each of the Mandible (Md), 1st maxillary (1Mx) and 2nd maxillary. Appendages that assist with eating includes

one pair of mandibular pulp (Mp), which helps bring the food into the mouth, one pair of raptorial claw, used for capturing prey and for defense, and one pair of maxilliped (Ma), which helps in handling food. Food is then transported to the stomach, which is called the cardiac stomach (CS), located in the middle of the carapace and is triangular with the apex pointing forward, with a thin layer of chitin surrounding the stomach. At the posterior end

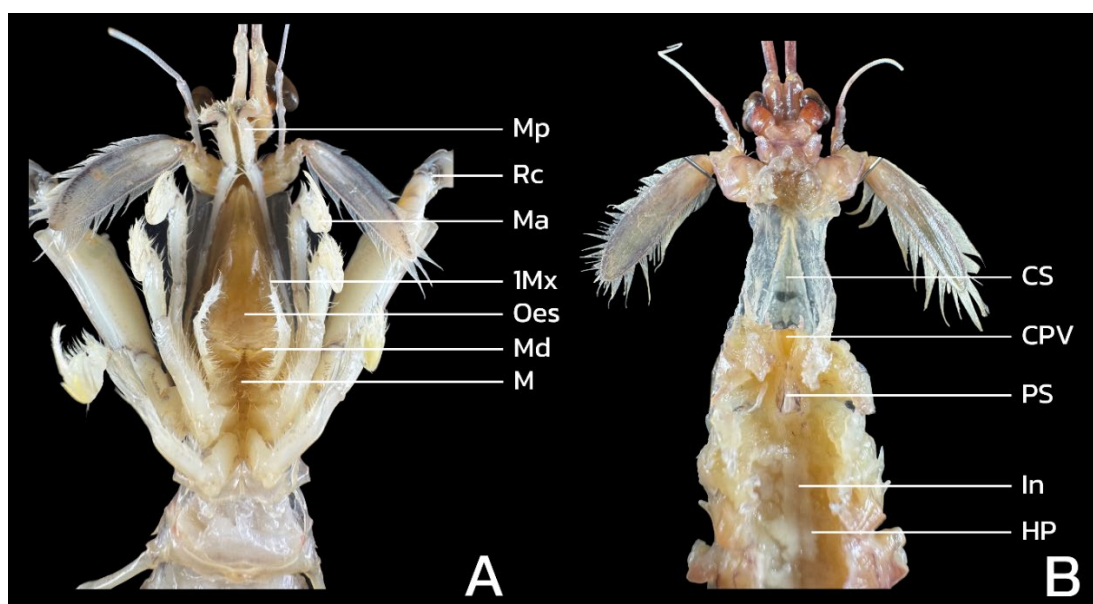


Figure 5 Digestive system of Mantis shrimp (A) Structure of mouth and feeding appendages of the Japanese mantis shrimp and (B) Dissection foregut of mantis shrimp. Anatomical abbreviation: 1Mx, first maxilla; CS, cardiac stomach; CPV, cardio-pyloric valve; In, intestine; M, mouth; Ma, maxilliped; Md, mandible; Mp, mandibular pulp; Oes, oesophagus; PS, pyloric stomach; Rc, raptorial claw

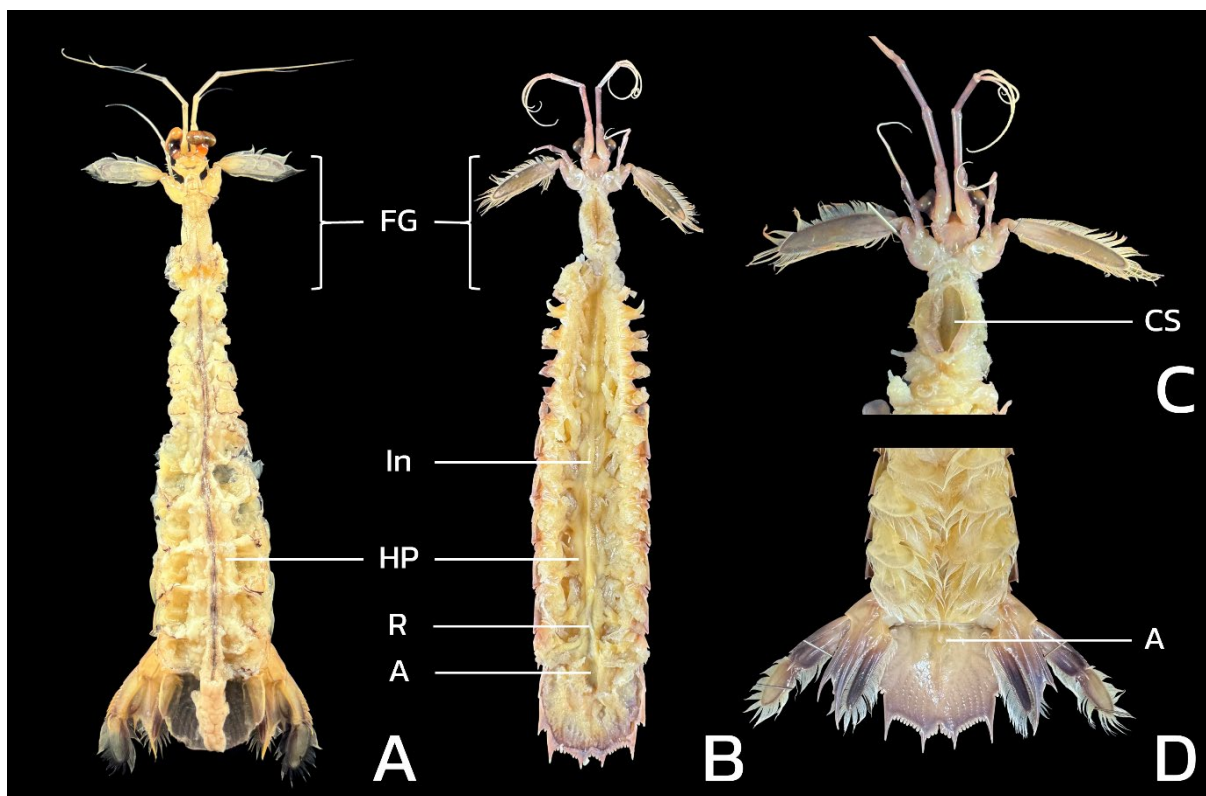


Figure 6 Digestive system of mantis shrimp (A) Dissection of the structure of hindgut on the dorsal side (B) Dissection of the structure of hindgut on the ventral side (C) Dissection of the structure of the tissue in the stomach (D) Dissection of the structure of the anus. Anatomical abbreviation: A, anus; CS, cardiac stomach; FG, foregut; HP, hepatopancreas; In, intestine; R, rectum

of the cardiac stomach lies a valve called cardio-pyloric valve (CPV), which is a thin rigid yellow brown chitinous plate that connects to the pyloric stomach (PS) is a small chamber in which 2 round black melanin pigments are found, on each side. This digestive tract region is called fore gut (FG). Following the pyloric stomach the food is then transported to the intestine (In), which is the longest digestive tract in the mantis shrimp, it compose of thin wall that functions in nutrients absorption with the assistance of the digestive enzyme from the hepatopancreas (HP), which is a large digestive gland with a creamy yellow to grayish-white color and symmetrical branching across the body segments, extending from the pyloric stomach to the telson. After that, the digested food is transported to the rectum (R) for temporary

storage before being excreted through the anus (A) which is shown in Figs 5 and 6.

3.3 Histological results

3.3.1 Oesophagus

Oesophagus is located just behind the mouth; its function is to transport food to the cardiac stomach. 3 lobed lips are present at the entrance, surrounded by a thin layer of chitin (Ch). The ventral lip (VL) is lined with simple columnar epithelium (Co), surrounded by loose connective tissue (CT), and contains longitudinal muscle (LM) and oblique muscle (OM) in the muscularis layer. The right lateral lip (RLL) and left lateral lip (LLL) exhibit similar structure as the ventral lip, and on the lateral side, the oesophageal gland (Oe) is present for creating digestive enzymes for digestion, and nerve plexus (Np) is found for controlling movements of the oral appendages which is shown in Fig 7.

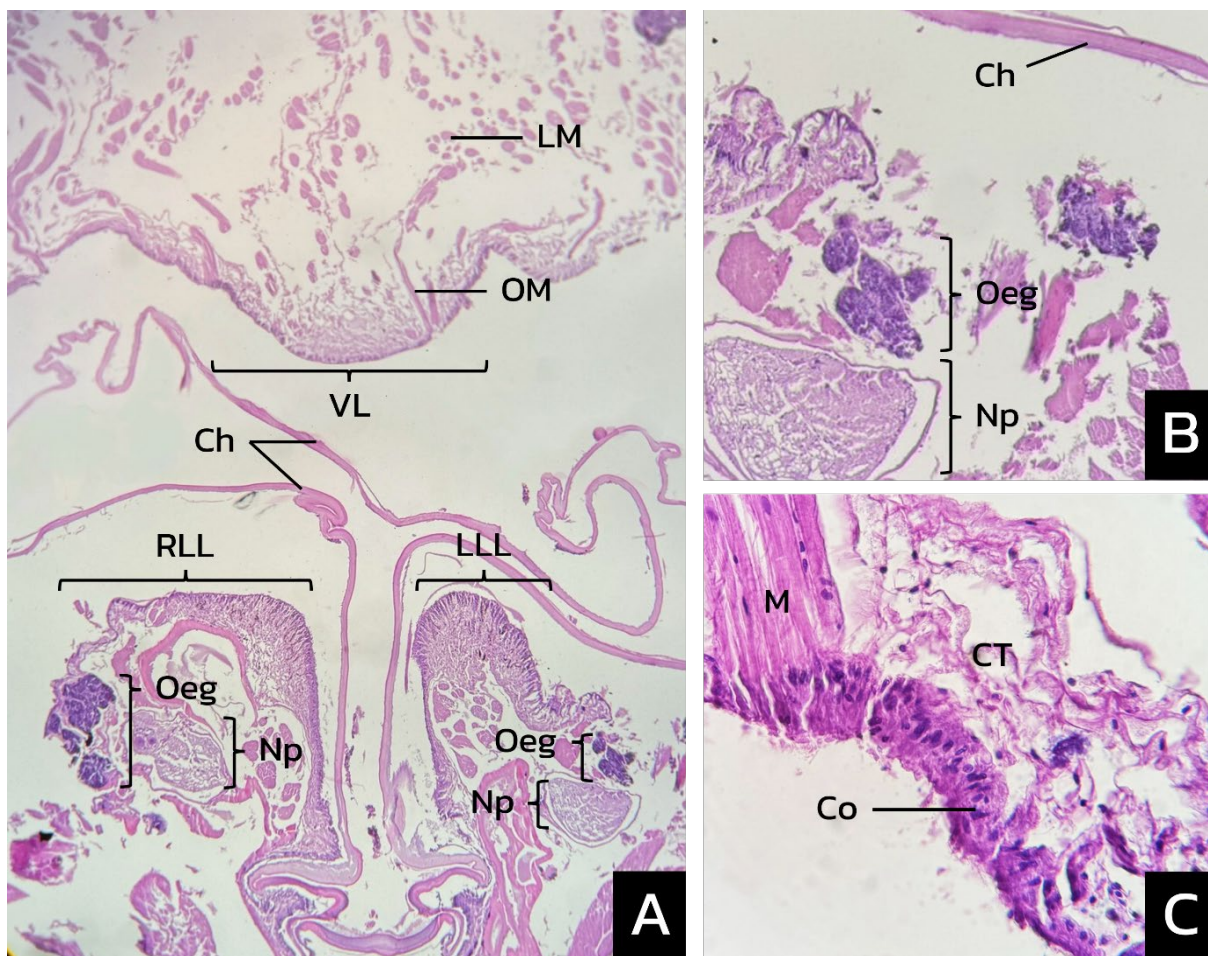


Figure 7 Oesophagus cross section (A) Oesophagus, consisting of Esophageal gland (100X) (B) Oesophagus with nerve plexus (100X) (C) simple columnar epithelium found in Oesophagus (400X). Histological abbreviation: Ch, chitin; Co, columnar epithelium; CT, connective tissue; LLL, left lateral lip; LM, Longitudinal muscle; M, muscle; Np, nerve plexus; Oeg, oesophageal gland; OM, oblique muscle; RLL, right lateral lip; VL, ventral lip

3.3.2 Cardiac stomach

Cardiac stomach is a structure of the frontal stomach, and contains rigid structure composed of chitin called chitinous valve, located at both the dorsal and ventral side. These include the upper chitinous valve (UCV), which serves as a dorsal sphincter, and the lower chitinous valve (LCV), which serves as a ventral sphincter connected to the oesophagus. Both valves function together to process mechanical digestion by muscle contraction the food present in the cardiac stomach (CS). Additionally, the valves consist of an epithelium that was identify as columnar epithelium (Co), fiber (F) can be

observe inside of the connective tissue layer, the apical surface contains a thick layer of chitin (Ch). The cardiac stomach composes of 3 tissue layers, which includes the epithelium, connective tissue, and muscularis layer. The epithelium layer is lined with simple squamous (Sq) epithelium, within which gastric content (GC) can be found. The connective tissue (CT) layer contains loose connective tissue along with the gastric artery (GA) that carries blood from the heart. The muscularis layer consists of circular muscle on the inner side, which surrounds the stomach, and longitudinal muscle on the outer side which is shown in Fig 8.

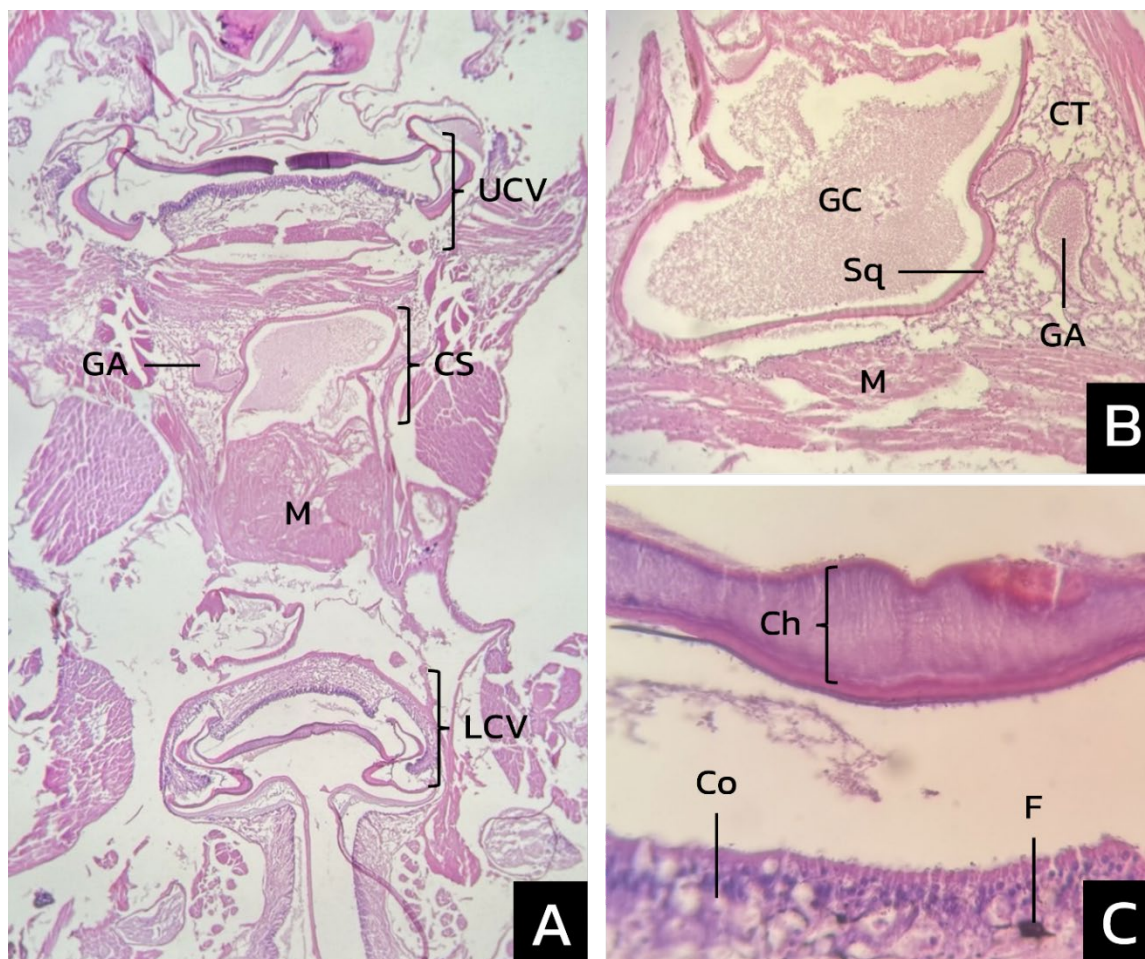


Figure 8 Cardiac stomach cross section (A) Cardiac stomach, consisting of Chitinous valves (40X) (B) Cardiac stomach with gastric artery (100X) (C) Columnar epithelium found in Cardiac stomach (400X).
Histological abbreviation: Ch, chitin; Co, columnar epithelium; CS, cardiac stomach; CT, connective tissue; F, fiber; GA, gastric artery; GC, gastric content; LCV, lower chitinous valve; M, muscle; Sq, squamous epithelium; UCV, upper chitinous valve

3.3.3 Pyloric stomach and Cardio-pyloric valve

Pyloric stomach is a structure in the posterior region of the stomach. The crescent-like structures composed of chitin are found in the digestive cavity (DC). The section of this structure that curves and extend to the front are called Superior ampullary crest (SAC), and another portion that are present on both sides are called ampullary crest (AC). On the sides, a chitinous hair-like structures called setae (SE) are present on the setae plate (SEP). In the epithelial layer found a columnar cell (Co) in the form of pseudostratified columnar epithelium which

are classified into two types, an oval-shaped cell that are found on the base and a cell with round nucleus near the surface layer. connective tissue (CT) is founded in the lower layer as loose connective tissue which is shown in Fig 9.

3.3.4 Hepatopancreas

Hepatopancreas is a large gland responsible for food digestion, it branches into each segment, from thoracic somite to telson. It features a coiled tube structure which is located around the heart (H), consisting of two distinct sizes of tubes. The larger tubes are called hepatopancreatic duct

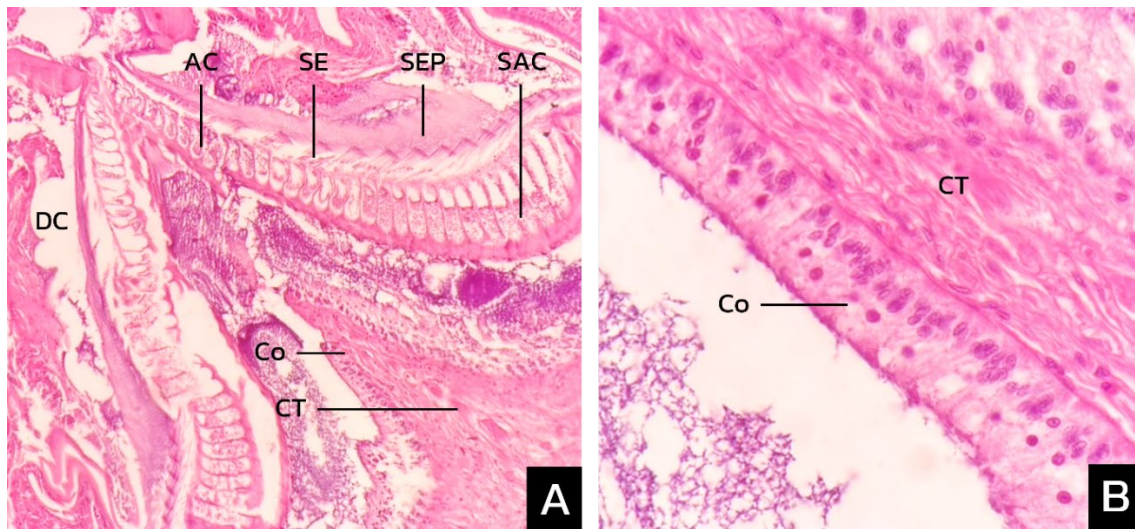


Figure 9 Pyloric stomach and cardio-pyloric valve longitudinal section (A) Rigid structure containing chitin (100X) (B) Columnar epithelium found in Pyloric stomach (400X). Histological abbreviation: AC, ampullary crest; Co, columnar epithelium; CT, connective tissue; DC, digestive cavity; SAC, superior ampullary crest; SE, setae; SEP, setae plate

(HPD) and the smaller tubes are called Lumen (L). Hepatopancreatic acini (HPA) are present inside of the tubes, with connective tissue as basement membrane (BM) and simple columnar epithelium in the epithelial layer which are composed of 3 types of cells. Resorptive cell (RC), a cylindrical shaped cell with a round nucleus centrally located which

play a role in releasing substance for digestion. Supportive cell (SC) is aligned parallel to the basement membrane, this cells assist in the working of other cells. Finally, blister cell (BC), is a cell with large, transparent vacuole that have a membrane that extended outward making the cell non-circular shape which is shown in Fig 10.

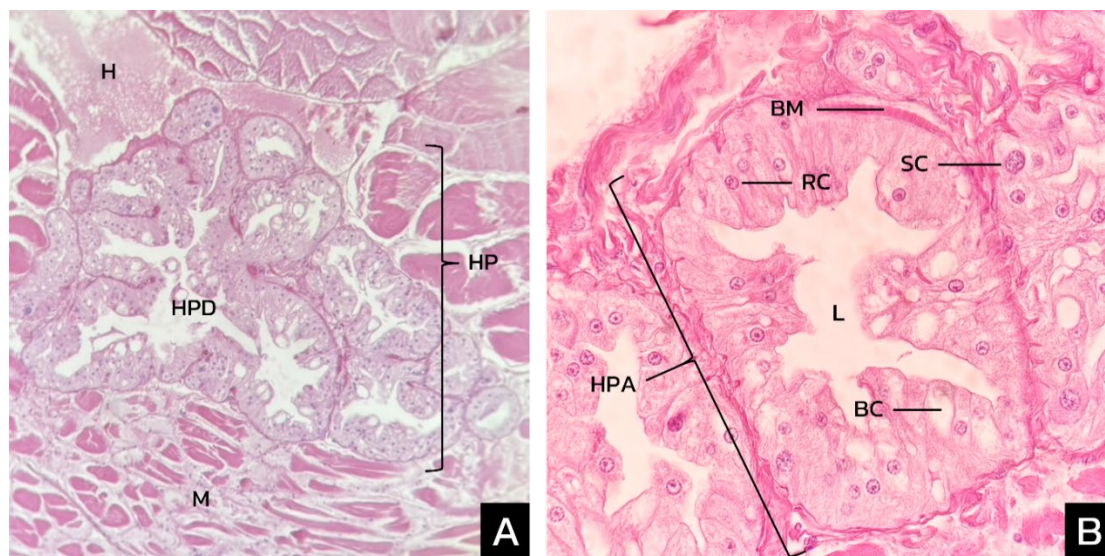


Figure 10 Hepatopancreas cross section show coiled tubule (A) Hepatopancreas that is located near the Heart (100X) (B) Hepatopancreas acini consist of blister cell, supporting cell and resorptive cell (400X). Histological abbreviation: BC, blister cell; BM, basement membrane; H, heart; HP, hepatopancreas; HPD, hepatopancreatic duct; L, lumen; M, muscle; RC, reabsorptive cell; SC, supportive cell

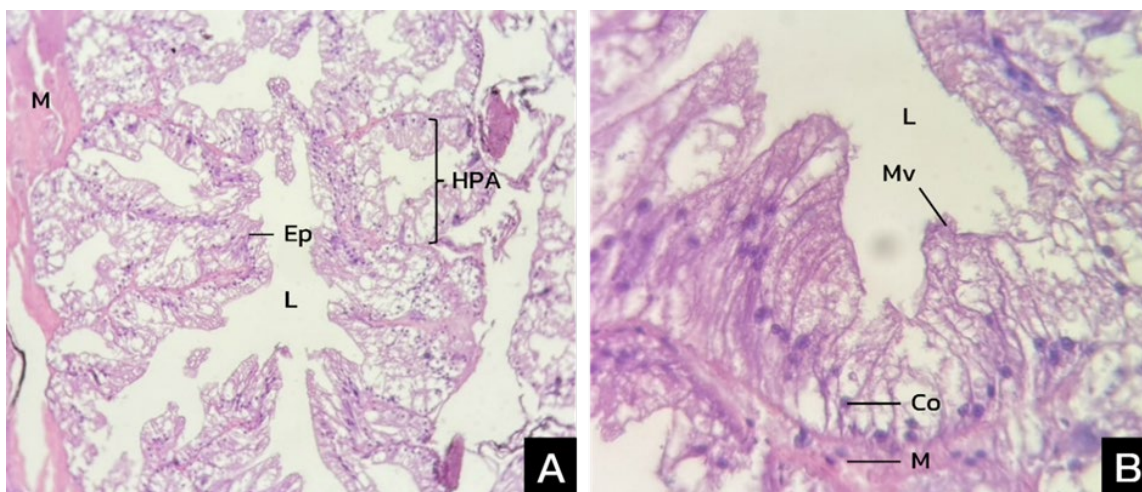


Figure 11 Intestine longitudinal section (A) Intestine surrounding with hepatopancreatic acini (100X) (B) Simple columnar epithelium with microvilli (400X). Histological abbreviation: Co, columnar epithelium; Ep, epithelium; HPA, hepatopancreatic acini; L, lumen; M, muscle; Mv, microvilli

3.3.5 Intestine

The intestine is a straight tube extended from thoracic somite to telson. The interior found a wide lumen (L) beneath the hepatopancreas, so hepatopancreatic acini (HPA) can be found in this structure. The epithelium (Ep) are presented as Simple columnar epithelium (Co) which consist of a centrally placed nucleus. Additionally, microvilli (Mv) are presented on the apical surface for increasing the surface area in the process of digestion and absorption occurring in the intestine. The structure is surrounded by a thin layer of muscle (M) for delivering foods to anus which is shown in Fig 11.

4. Conclusion

In the study of digestive tissues in the Japanese mantis shrimp, it is essential to preserve the tissues rapidly, as the intestine and hepatopancreas contain a high concentration of enzymes. If the specimen is anesthetized with ice and preservation is delayed, tissue degradation may occur. Certain structures, such as the cardiac stomach and pyloric stomach, contain rigid chitinous components, which require fixation with Davidson's fixative, containing glacial acetate, for proper preservation. However, for

other structures, Bouin's fixative alone is sufficient.

Anatomical studies revealed that some structures are highly sophisticated, such as the oesophagus, which is located next to the cardiac stomach, and the hepatopancreas, which lies over the intestine. Additionally, some structures are extremely small, for instance, the chitinous valve in the cardiac stomach and the pyloric valve in the pyloric stomach are both so minute that their mechanisms cannot be explained through anatomical study alone. Therefore, histological methods must be employed for further study.

Histological studies revealed that neither of the two stomachs in the mantis shrimp is involved in chemical digestion, as no enzyme-secreting glands were observed. Instead, thick muscle layers and rigid structures were found, indicating that these regions function solely in mechanical digestion. Chemical digestion takes place exclusively in the intestine, which is lined with simple columnar epithelium bearing microvilli on the apical surface, and in the hepatopancreas, where cells are arranged in acini and function in enzyme secretion that is delivered to the intestine.



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Anatomical and histological insight into homeostatic system of the Common Octopus *Octopus vulgaris* (Octopoda: Octopodidae)

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Abstract

Octopus vulgaris is an invertebrate animal belonging to the class Cephalopoda within the phylum Mollusca characterized by its soft body and body structure, integrating its head and arms. Unlike many other mollusks, octopus possesses a closed circulatory system, which allows the circulatory, respiratory, and excretory systems to work together efficiently that work together to maintain the internal balance. The circulatory system displays three hearts: one systemic heart and two brachial hearts, which facilitate an increase in blood pressure essential for the effective gas exchange process and for transporting the oxygenated blood to various parts of the body. The respiratory system includes gills which feature folded gill lamellae, enhancing the gas exchange capacity. In terms of the excretory system, octopus carries an abundance of small kidney structures known as kidney appendages, located around the lateral vena cava. Additionally, the pericardial gland is present to assist in the secondary filtration of waste at the kidney. In the histology studies, utilizing Bouin's fixative for tissue preservation has provided valuable insights into octopus tissue morphology. These examinations have revealed numerous sinusoids within the tissues along with a thick layer of collagen encircling the blood vessels, but the epithelium is absent which may lend support to the evolutionary theory regarding the development of an open circulatory system to a closed circulatory system.

Keywords: Circulatory system; Respiratory system; Excretory system; Histology; Common octopus

1. Introduction

Common octopus (*Octopus vulgaris*) distribute in the tropical regions of the Atlantic, Pacific, and Indian oceans, as well as the Mediterranean sea; it typically resides in the benthic zone around coral reefs or overhanging rocks. [1] This octopus species is recognized as one of Thailand's significant economic animals, ranking fifth in global exportation. In 2023, the export rate of *Octopus vulgaris* reached 7,531 tons, generating a value of about 1,734.9 million baht. [10]

Common octopus is an invertebrate belonging to the phylum Mollusca [4], characterized by its soft body, and classified under the class Cephalopoda which features

the reduction of its shell into a shell rudiment and integrates their head and foot including *O. vulgaris*, squid, cuttlefish, and *Nautilus* [2]. This species has 4 notable features: the evolution of brain into a complex nervous system, the development of foot into an elastic muscle known as tentacles on the anterior side, the presence of mouth equipped with a large muscle and contains beaks and radular within, and the utilization of jet propulsion, which use water to facilitate their movement [6].

Morphologically, the common octopus is divided into two primary sections: the mantle and tentacles

The mantle has an oval shape; on the ventral side, the skin pattern formed by

chromatophores is presented including mantle spot and head bar, while the dorsal side has densely populated chromatophores, resulting in to darker shade. On the ventral side there has a siphon, a structure that facilitates the movement of the octopus. The dorsal side contains the head and a pair of eyes but does not possess ocelli.

Tentacle composed of muscles, which are used for contraction and shrinkage, and suckers which are arranged in two rows along its length; additionally, there is a type 1A web located between each tentacle. At the base where the tentacle connects to the head, a distinctive pattern called the frontal spot was found, but this area does not feature a web pouch [11].

The common octopus possesses a complex body system that has three main systems (circulatory, respiratory and excretory system) collaborating to maintain physiological stability [3, 4].

1. The circulatory system is divided into two parts: the arterial system and the venous system.

1.1 The arterial system [5] started when the oxygenated blood from the gills is transported to the systemic heart, located between the two kidneys and posterior to the stomach, through two efferent vessels from the left and right gills. The systemic heart consists of two auricles and a ventricle; the two auricles are symmetrical, while the ventricle is asymmetrical and formed by a white muscle with an incomplete vertical septum. Subsequently, the oxygenated blood will be passed out to the body via three main blood vessels: the anterior aorta, the abdominal aorta, and the genital aorta; finally, it reaches the end at arterial capillaries [12].

1.2 The venous system [5] is the transport of deoxygenated blood entering the gills via the vena cava which connects to two branchial hearts - a rounded, purple-shaped organ which has thick spongy walls composed of soft cellular tissues, located at the base of each gill. Then the blood returns to the gills by the afferent branchial vessels, thus completing

the circulation process.

2. Respiratory system

O. vulgaris exchanges gas using gills, located on each lateral side, facing towards the posterior side of the mantle [2]. The skin of the gill is smooth and covered with mucus from goblet cells and microvilli on the surface. Each Lamellae comprises 11 pairs of Primary lamellae, which spread out, giving a thin, cone-like appearance. Each primary lamellae is folded, leading to the procreation of secondary lamellae, tertiary lamellae, and fourth lamellae, respectively.

Blood from the branchial heart [13] passes through the afferent branchial vessel, found in the middle of the back of the gills, into each level of the core of the gill to exchange gas, then returns to the systemic heart by discharge from the gill to the efferent branchial vessel.

3. Excretory system

The excretory system begins with deoxygenated blood, which is filtered through the renal appendage [8]. The filtered liquid will enter the renal sac, while the blood that passes through the renal appendage will undergo a second filtration process at the branchial heart appendage. The filtered fluid from the branchial heart appendage will enter the pericardium which will forward it to the pericardial duct [7]. The waste material from the pericardial duct will be transported to the coelomic cavity at the renal sac; afterward, the waste will be conveyed to the mantle cavity through the orifice at the renal papilla and eliminated via the siphon in ammonia form [12].

2. Materials and methods

2.1 Anatomical preservation and methods

Rinse the octopus with clean water to remove the residual mucus. For studying the respiratory system, the octopus was preserved with 70% Ethanol, which doesn't stiffen the tissue. In contrast, for circulatory and excretory systems, in which related structures

are easily decayed, 4% Formalin is used for preservation [9].

In the dissection part, a junction between the mantle and the pallial aperture is observable on the ventral side of the octopus. Use the scissors to cut the lateral part of the body toward the posterior end, then cut the Median pallial adductor out to open the mantle, revealing the internal organs. To enhance the efficiency of the study, cut the tissue, as it provides clearer observation of the internal structures.

2.2 Histological preservation and methods

Rinse the common octopus thoroughly with clean water to remove mucus and immerse it in 4% formalin solution to preserve the octopus's condition and enhance the integrity of tissues for study of histology. Then remove the section designated for studying approximately 0.5 cubic centimeters in Bouin's fixative at a temperature of 4° Celsius for 24 hours. Tissue dehydration was conducted by utilizing the Alcohol series (50-100%), and the samples were cleared by using Butanol: xylene and Xylene respectively. Subsequently, the sample will be embedded in paraplast and then sectioned using a Rotary microtome at a thickness of 6-8 microns. Finally, staining the tissue by using Haematoxylin and Eosin, followed by mounting and sealing onto slides to prepare

for imaging with a compound light microscope [9].

3. Result

3.1 Anatomical results

3.1.1 Circulatory and excretory system

Octopus vulgaris displays a closed circulatory system that results in blood flow within blood vessels. This species contains three distinct hearts: two branchial hearts and one systemic heart. The branchial hearts (BH) are rounded organs with various colors from purple to dark brown, located above each side of the gill. The systemic heart (SH) is a triangular-shaped organ that consists of two Auricles (Ar) and one Ventricle (Vt); it is encased in a protective membrane known as the Pericardium. The circulatory system begins with the deoxygenated blood entering the branchial heart (BH) via the Lateral vena cava (LV), after exchanging gases with the body; it passes through the kidneys (K), which are small, white, fluffy organs responsible for filtering waste in the Ammonia form. Subsequently, the blood will undergo a gas exchange process at the gill (G) through the Afferent vessel (AV). After exchanging gas, oxygenated blood flows into the systemic heart (SH) via the Efferent vessel (EV) before passing out to the body through the Anterior aorta (AA) which is shown in Fig: 1.

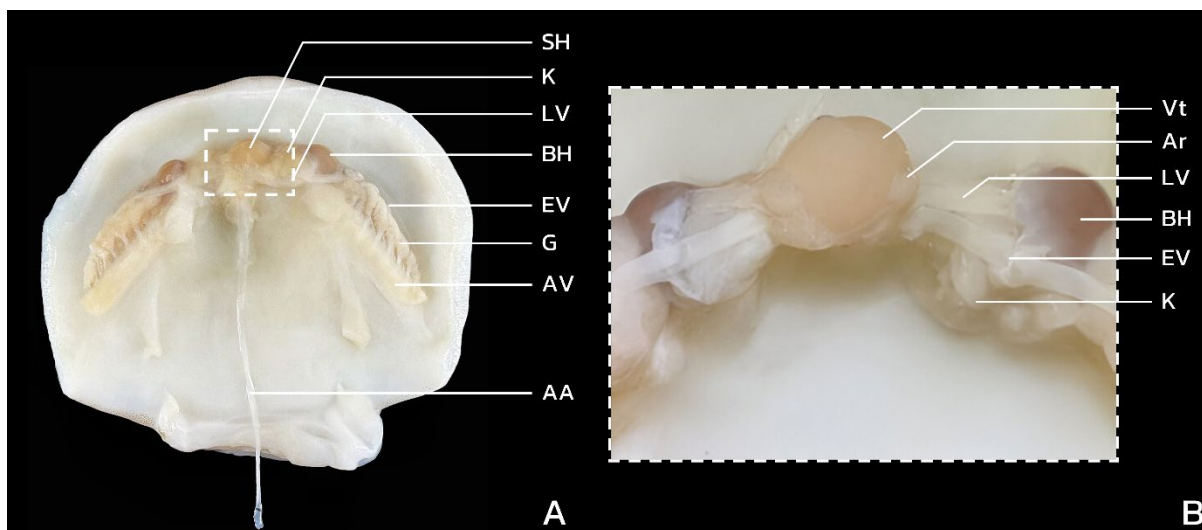


Figure 1 Octopus mantle dissection (A) The Circulatory system and Excretory system of common octopus (B) The chambers of systemic heart consist of two auricles and one ventricle. Anatomical abbreviation: AA, Anterior aorta; Ar, Auricle; AV, Afferent vessel; BH, Branchial heart; EV, Efferent vessel; G, Gill; K, Kidney LV, Lateral vena cava; SH, systemic heart; Vt, Ventricle

3.1.2 Respiratory system

Octopus vulgaris respiratory system features two gills, which display a pale yellow to grey coloration; each gill comprises overlapping gill lamellar which play a significant role in the gas exchange process. The respiratory system begins with the deoxygenated blood from branchial hearts (BH) will be transported to gills via Afferent vessels (AV) which can be divided into two types: the Primary afferent vessel (1 AV) and the Secondary afferent vessel (2 AV). The Primary afferent vessel (1 AV) is a larger vessel surrounded by collagen, while the Secondary afferent vessel (2 AV) is smaller and facilitates the flow of deoxygenated blood to the Gill lamella (GL) to enter the gas exchange process. The number of Secondary afferent vessel (2 AV) and Gill lamella (GL) is equal, with both numbering 13. After achieving the oxygenation, the oxygenated blood will be passed to the systemic heart (SH) through the efferent vessel (EV) which is shown in Fig: 2.

3.2 Histological results

3.2.1 Systemic heart

Systemic heart function is performed through the transportation of oxygenated blood throughout the body via the aorta, its structure consisting of two Auricles (Ar) and one Ventricle (Vt). The cardiac wall can be categorized into three layers: Epicardium (Epc), Myocardium (Myc), and Endocardium (Enc). The external layer, known as the Epicardium (Epc), consists of a thin connective tissue. Followed by the Myocardium (Myc), this layer contains various cardiac muscles and cardiac nerves (CN) that play a significant role in regulating the heartbeat. The internal layer is called the Endocardium (Enc), which encircles the internal space of the heart, and it is composed of simple columnar epithelium. Additionally, the Endocardium (Enc) contains the Cardiac ganglia (CG) which can be divided into two layers: the Granular layer (Gr), the Ganglionic cell characterized by small cell with a large nucleus is present in this layer, and the Molecular layer (Mo) which serves regulation of systemic heart, but the nervous cell is absent in this layer which is shown in Fig: 3.

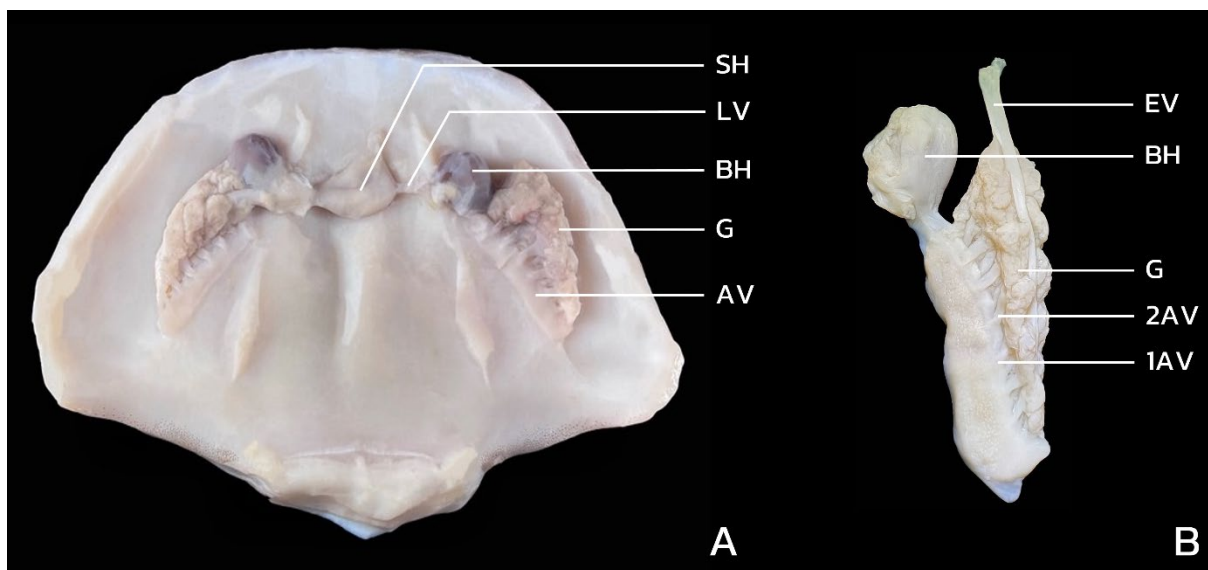


Figure 2 Octopus mantle dissection (A) The Respiratory system of common octopus (B) The isolated gill with afferent vessel and efferent vessel. Anatomical abbreviation: 1AV, Primary afferent vessel; 2AV, Secondary afferent vessel; AV, Afferent vessel; BH, Branchial heart; EV, Efferent vessel; G, Gill; LV, Lateral vena cava
SH, systemic heart

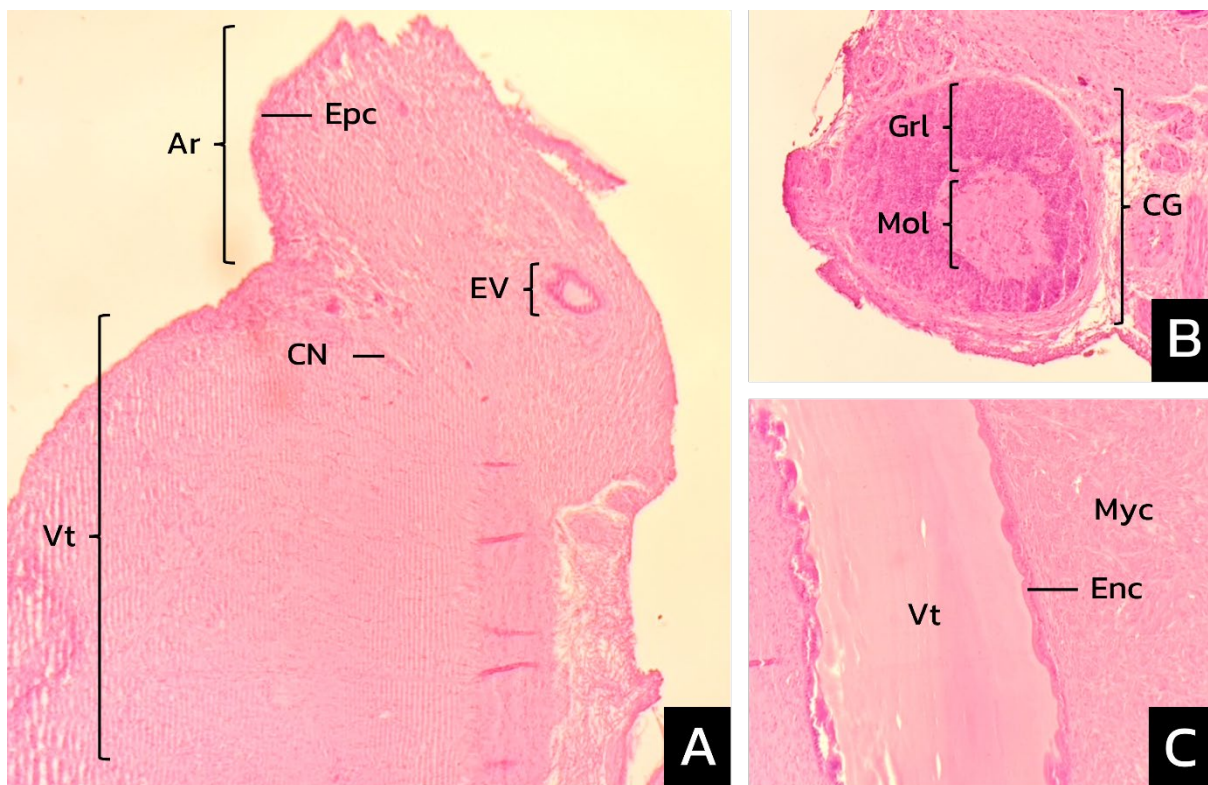


Figure 3 Systemic heart cross section (A) The systemic heart chambers consist of two auricles and one ventricle (40X) (B) The histological of cardiac ganglia (100X) (C) The systemic heart wall consist of epicardium, myocardium and endocardium (100X). Histological abbreviation: Ar, Auricle; CG, Cardiac ganglia; CN, Cardiac nerve; Enc, Endocardium; Epc, Epicardium; EV, Efferent vessel; Gr, Granular layer; Mo, Molecular layer; Myc, Myocardium; Vt, Ventricle

3.2.2 Branchial heart

The branchial hearts play a crucial role in transporting deoxygenated blood to the gills via the Lateral vena cava; the structure of their wall consists of three layers: Epicardium (Epc), Myocardium (Myc), and Endocardium (Enc). The Epicardium (Epc), external layer, is composed of a thin layer of Connective tissue (CT). Beneath the Epicardium lies the Myocardium (Myc) that contains a thin layer of Muscle (M). The internal layer known as the Endocardium (Enc), the Inner cell mass

(ICM), which consists of sponge-like cells with a triangular shape and small nucleus, and the Granule (Gr) are present. Furthermore, muscles called Trabeculae (Tb) and Sinusoid (Si), which function as a blood sinus, are featured in between the Inner cell mass (ICM) area; they also contain the Heamocyte (HC), a blood cell characterized by a horseshoe-shaped nucleus. The Endocardium (Enc) possesses an internal space that facilitates the flow of Blood (B) to the gills which is shown in Fig: 4..

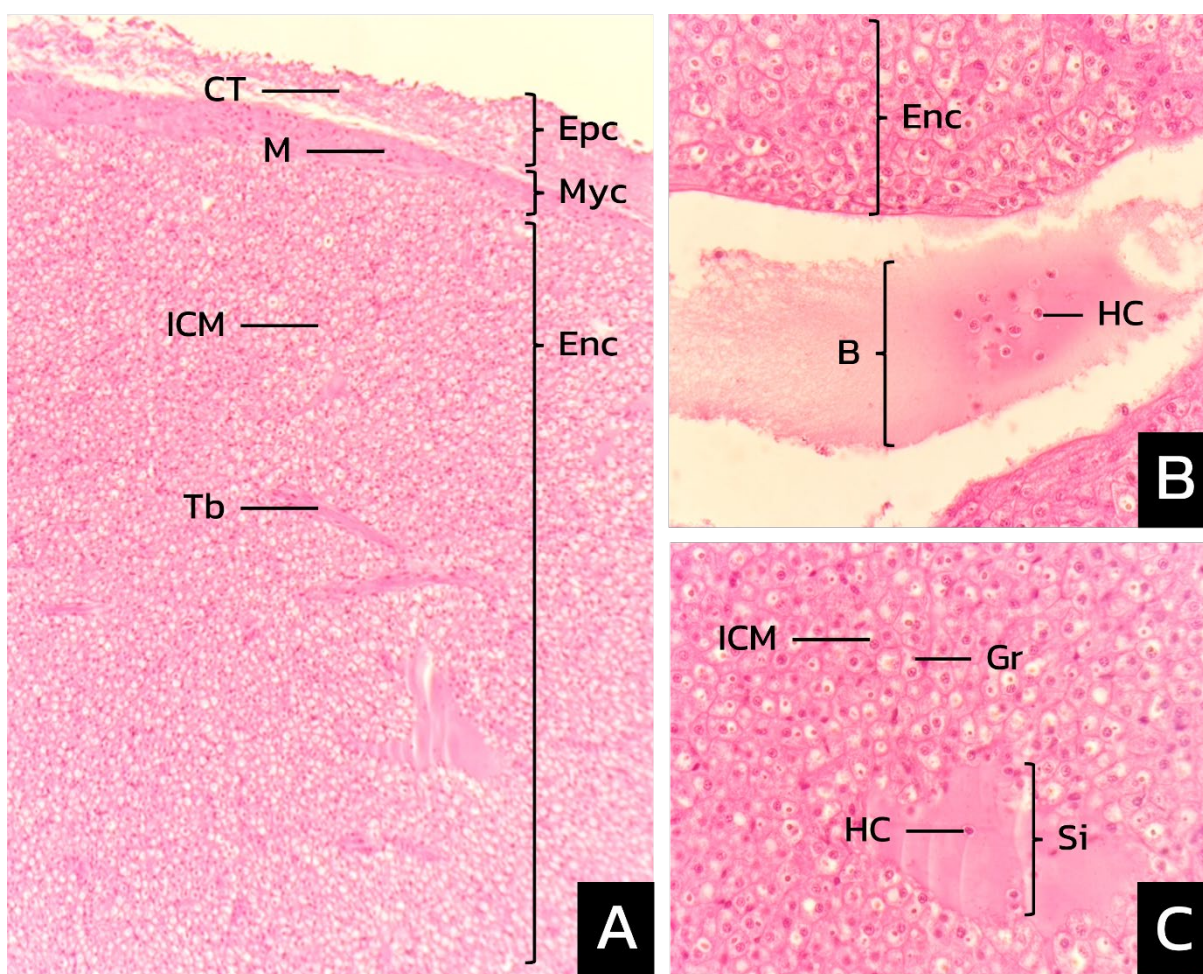


Figure 4 Branchial heart cross section (A) The three wall layers of branchial heart (40X) (B) Blood in branchial heart chamber (400X) (C) The characteristic of inner cell mass (400X). Histological abbreviation: B, Blood; CT, Connective tissue; Epc, Epicardium; Enc, Endocardium; Gr, Granule; HC, Heamocyte; ICM, Inner cell mass; M, Muscle; Myc, Myocardium; Si, Sinusoid; Tb, Trabecular

3.2.3 Kidney

The kidney excretes metabolic waste in the form of Ammonia through a small sac surrounded by Connective tissue (CT) referred to as the Kidney appendage (KA). Within the kidney appendage, a small coiled tubule known as the Nephron tubule (NT) was found. The epithelial tissue in the kidney is composed of Simple cuboidal epithelium (Cu) with Microvilli (Mv), which are dome-shaped cells, resting upon the Connective tissue (CT). During the blood filtration process, the kidney relies on the Lateral vena cava (LV) to receive blood from various parts of the body, which is characterized by the thick connective tissue with a wide Lumen (L) which is shown in Fig: 5.

3.2.4 Pericardial gland

The pericardial gland receives blood from the Branchial heart and directs it to the kidney for the second time filtration process. Structurally, the pericardial gland consists of 2 tissue layers: the epithelial layer and the connective tissue layer. Epithelium (Ep) is a Simple tall columnar epithelium (Co) type, characterized by Cell processes at the Apical surface. Connective tissue (CT) is composed of Loose connective tissue. The Capillary (Cp) is also present in this layer which is shown in Fig: 6.

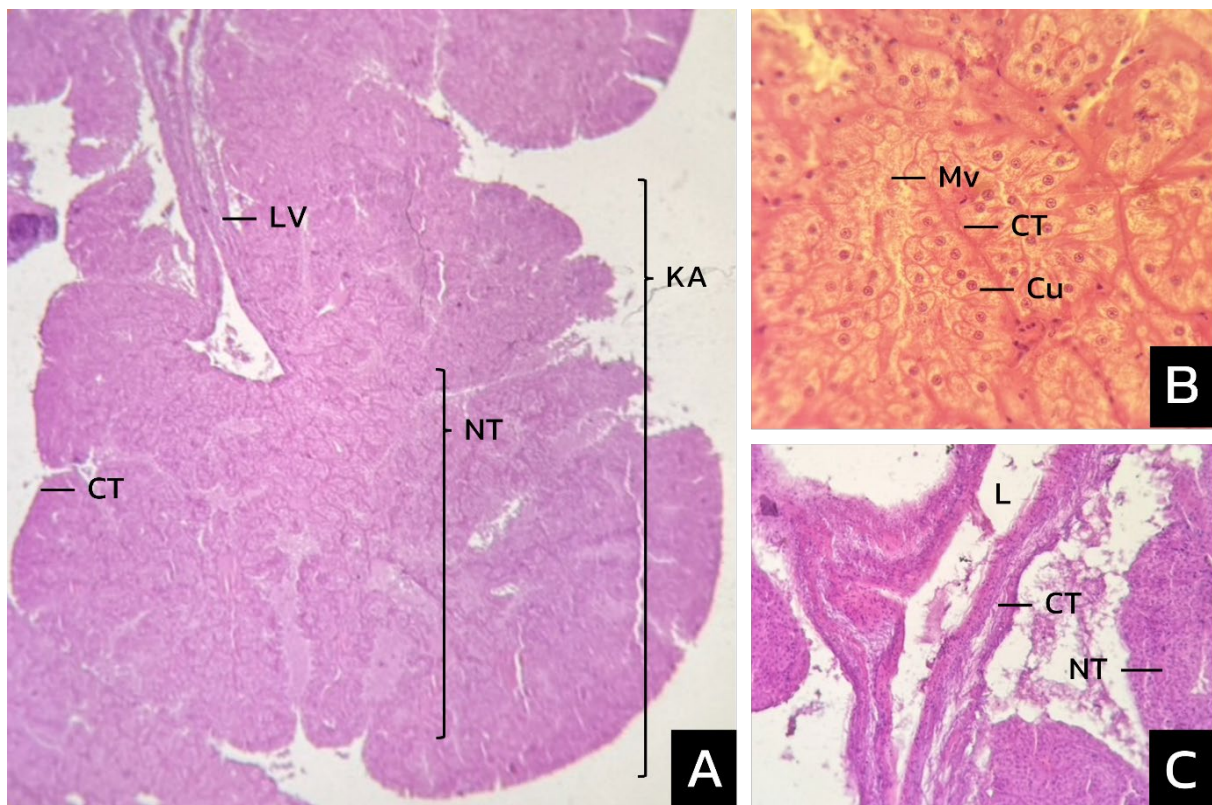


Figure 5 Kidney cross section (A) The kidney appendage contains the numerous nephron tubule (40X) (B) The simple cuboidal epithelium found in nephron tubule (400X) (C) The characteristic of lateral vena cava (400X). Histological abbreviation: CT, Connective tissue; Cu, Cuboidal epithelium; KA, Kidney appendage; L, Lumen LV, Lateral vena cava; Mv, Microvilli; NT, Nephron tubule

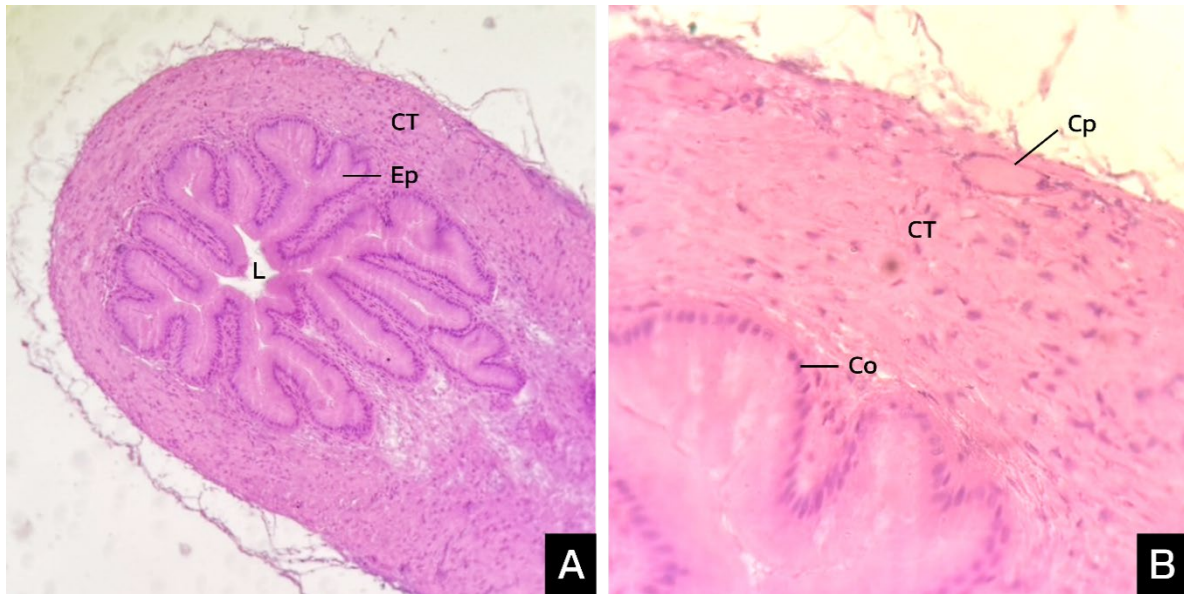


Figure 6 Pericardial gland cross section (A) The short tubular structure near branchial heart called pericardial gland (40X) (B) The characteristic of kidney gland (100X). Histological abbreviation; Co, Columnar epithelium; Cp, capillary; CT, Connective tissue; Ep, Epithelium; L, Lumen

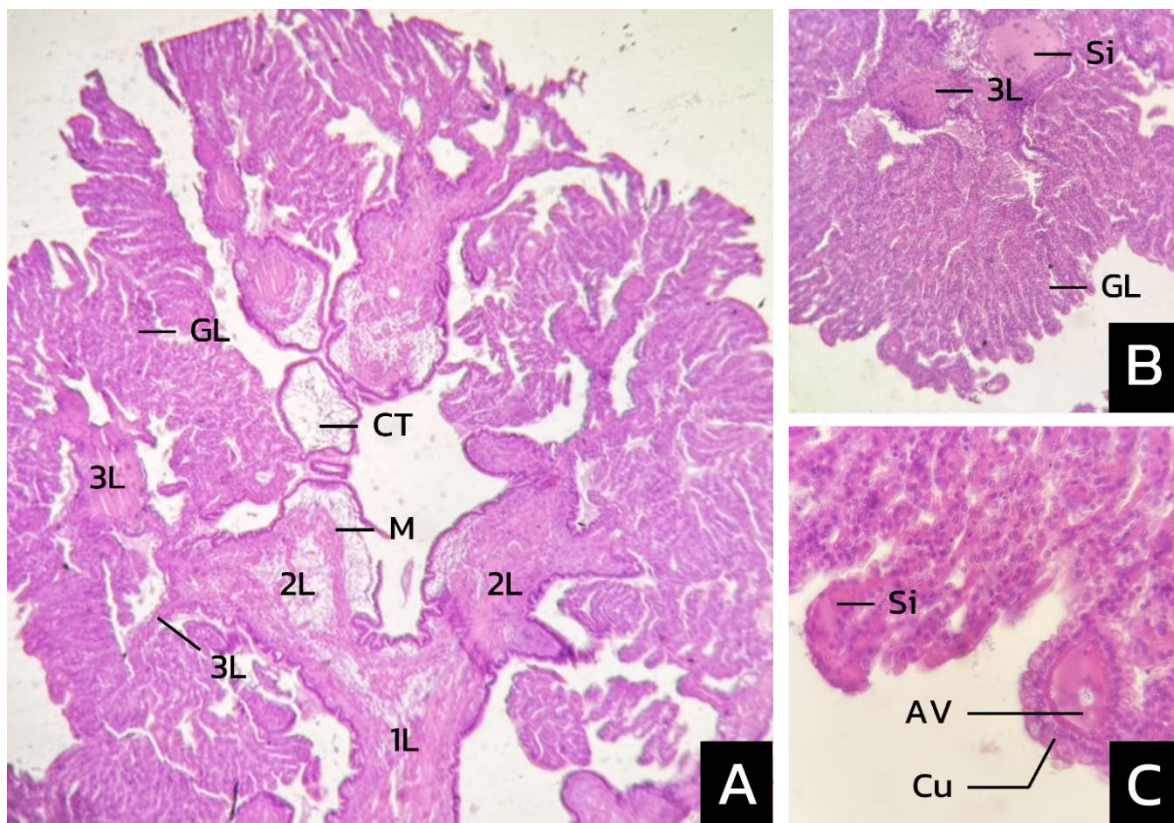


Figure 7 Gill longitudinal section (A) The dichotomous branching of lamella (40X) (B) The characteristic of gill lamella (100X) (C) The tip of gill lamella consists of numerous sinusoid (400X). Histological abbreviation: 1L, Primary lamella; 2L, Secondary lamella; 3L, Tertiary lamella; AV, Afferent vessel; CT, Connective tissue; Cu, Cuboidal epithelium; GL, Gill lamella; M, Muscle; Si, Sinusoid

3.2.5 Gills

Octopus vulgaris gills are located laterally alongside the digestive tract. Each gill consists of the central axial known as Lamella and features the Dichotomous branching which possesses the main central axial called the Primary lamella (1L), containing the Connective tissue (CT) and Muscle (M). The Primary lamella (1L) further branches into Secondary lamella (2L) and continues the branching process into Tertiary lamella (3L); these two types of lamella are located within the Sinusoid (Si), a blood sinus designed to accommodate blood. The gill lamella (GL) is characterized by a finger-like structure, which increases the surface area for the gas exchange process. Additionally, at the tip of each Gill lamella, the Afferent vessel (AV) is found encircled by a layer of Simple cuboidal epithelium (Cu); it receives the deoxygenated blood from the Lateral vena cava and directs it toward the gills for oxygenation.

4. Conclusion

According to the research, the organs that are integral to the circulatory, respiratory, and excretory systems of *Octopus vulgaris* are located within the mantle, and encased in a protective membrane in two distinct regions: the kidney sac and the pericardium. Consequently, a careful dissection with small scissors is essential to avoid damage to the organs, during the examination. Additionally, preserving the organs in formalin or alcohol for more than two days results in discoloration of the kidney appendages to gray and shrinkage of the systemic auricle heart, which impedes further study. Therefore, it is recommended to anesthetize the octopus using ice and conduct the examination promptly.

In anatomical studies still encounter limitations in explaining certain structures; for instance, the pericardial gland, a small duct that extends from the brachial heart functions by delivering some blood to the kidneys for the filtration process, has a similar

appearance to the kidney appendages. This similarity complicates the observation of the organ structure; accordingly, histological methods are necessary to indicate the understanding of these structures.

The histological studies revealed that connective tissues, which are composed of collagen, and plenty of sinusoids are features of a significant structure of the tissue. This observation may reflect the evolutionary development, since the octopus represents the only group within the Phylum Mollusca that possesses a closed circulatory system, leading to incompletely connected blood vessels. The study of the excretory system reveals that the octopus uses multiple kidney appendages to filter the metabolic waste. These appendages contain numerous nephron tubules, which may impede the excretion process due to a lack of consolidation into a single kidney structure, unlike other mollusks. The kidney appendages are presumed to be inefficient, necessitating the pericardial gland to facilitate the additional filtration of the blood.

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Anatomical and Histological Study of the Circulatory, Respiratory, and Excretory Systems of the Crucifix crab *Charybdis feriatus* (Decapoda: Portunidae)

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Abstract

The crucifix crab (*Charybdis feriatus*) is considered one of the economically important species for consumption. From an anatomical perspective, crabs possess a relatively large heart compared to other malacostracans, with clearly defined ostia, which are openings that allow hemolymph to enter the heart. This characteristic makes them suitable specimens for studying the open circulatory system. In addition, their gills are orderly arranged, and their green glands are easily observable, making them ideal for studying homeostatic systems. For histological preservation, tissue samples were fixed in Bouin's fixative for 24 hours and preserved in Davidson's fixative for 2 hours before dehydration. They were then stained with hematoxylin and eosin. The heart tissue of a crab consists of three layers: the epicardium, myocardium, and endocardium, all of which are enclosed by pericardium. The muscular layer is relatively thin, with muscle found primarily around the margins, which is characteristic of the crab's cardiac structure. This study is the first report describing the histological structure of the green gland in this family.

Keywords: Circulatory; Respiratory; Excretory; Crucifix crab; Histology

1. Introduction

Charybdis feriatus (Linnaeus, 1758), commonly known as the crucifix crab, is a marine animal within the phylum Arthropoda. Characteristic features of this organism include a robust exoskeleton, a segmented body plan, and jointed appendages [9]. As a member of the class Malacostraca, *C. feriatus* exhibits a segmented body where each segment contains internal organs and appendages, forming tagmata. The eyes are positioned on motile eyestalks [9]. Belonging to the order Decapoda, its body is distinctly divided into two primary regions: the fused head and thorax, termed the cephalothorax, and the abdomen. Decapod species possess five pairs of legs, each referred to as pereopods [1,3]. Order Decapoda contains

two main infraorders, Brachyuran crabs (infraorder Brachyura) and Anomuran crabs (infraorder Anomura). Brachyuran crabs can easily be separated from Anomuran crabs by four visible pairs of well-developed pereopods. While Anomuran crabs always found only three pairs of clearly visible pereopods, as the last pair is very small, normally hard to notice [1]. The Embryos of Brachyuran crabs possess one pair of appendages per segment. However, this characteristic is not retained throughout development, as a reduction in appendage count occurs during maturation. Crucifix crabs are within the family Portunidae, a group recognized for its adaptations of thoracic appendages optimized for functions such as hunting and self-defense [8]. Their

abdominal appendages, the pleopods, are specialized to facilitate embryo culture and reproduction [8]. Consequently, mature males typically exhibit 15 pairs of appendages, while mature females possess 17. Each appendage types can be categorized by its characteristics and function [8].

The geographic distribution of *C. feriatus* spans the Indo-Pacific region, including Thailand, extending to the coasts of East and South Africa, the Gulf of Oman, the Western Persian Gulf, and encompassing areas such as Pakistan, India, Sri Lanka and Indonesia [9]. These crabs are benthic organisms, inhabiting a range of depths from shallow to mid-depth waters, specifically within the sublittoral zone, where they are found on muddy or sandy substrates, as well as in rocky and coral reef environments. Typical depths for this species range from approximately 10 to 60 meters [9]. Crucifix Crabs are significant for the Thai Economy. They account for approximately 0.73% of total catch from crab nets, and they are also raised in aquaculture farms [9]. Most of them are exported to East Asian countries [9].

The crucifix crabs have several key features for identification. Their carapace is ovate with a smooth surface and a striking pattern of brown and orange stripes, often with an orange cross mark in the center of the gastric region. The carapace can reach a maximum width of 20 centimeters in their adulthood [4, 8]. Moreover, the width of the frontal margin is less than the maximum carapace width. The posterior edge of the carapace is curved and serrated. There are five teeth (epibranchial teeth) on each side of the carapace's lateral margin, with the slightly notched first tooth [1]. The area between the eyes on the front of the carapace features six serrated teeth, and each pincer (claw) has four spines. Finally, a unique characteristic is the presence of numerous white spots scattered across its legs and claws [8].

This species features an open circulatory system, where hemolymph passes through the hemocoel. The significant organ within the

system is the heart, located in the dorsal midline of the cephalothorax [8]. It has a smooth and jelly-like appearance with 3 small openings, called ostia. The ostia appear in 2 pairs on the posterior of the heart and another pair on the anterior [9]. These ostia function as the holes for the hemolymph in the hemocoel to pass into the heart. Oxygen-rich hemolymph is transported through the arteries during the heart contraction, while Carbon dioxide-rich hemolymph is sent to the sinus before it is transported to the gills for gas exchange [8]. Crabs possess hemocyanin, a respiratory pigment that is clear when deoxygenated but turns blue upon binding with oxygen [9].

Crucifix crabs possess five arterial systems consisting of 1) Anterior aorta, originating from the anterior dorsal surface of the heart to the optic arteries, delivering hemolymph to the cerebral ganglia and eyestalks. 2) Anterolateral arteries, which arise from the anterior dorsal surface of the heart. These transport hemolymph to the green glands, mandibular muscle, hepatopancreas, stomach, gonads, and hypodermis of the anterior cephalothorax. 3) Hepatic arteries, originating both from the anterior and posterior of the heart and branching throughout the hepatopancreas, with a smaller branch, the pyloric hepatic artery, delivers hemolymph to the pyloric stomach and midgut. 4) Posterior aorta, the smallest artery, arises from the posterior ventral surface of the heart, then fuses with the inferior abdominal artery near the second abdominal segment to transport hemolymph to the hindgut and abdomen. 5) Sternal artery, the largest artery, originates from the ventral surface of the heart and branches into the ventral thoracic artery to deliver hemolymph to the mouthparts, chelae, and pereopods [3].

Crucifix crab's heart comprises three tissue layers. Epicardium is the outermost layer, covering the cardiac muscle. Myocardium is composed of cardiac muscle, involved in contraction and relaxation of the heart to deliver blood to the body parts.

Endocardium is the innermost tissue, smooth and very thin. It covers the interior of the heart [8].

The respiratory system in the crucifix crab contains phyllobranchiate gills as the main organ for gas exchange [8]. This gills feature a leaf-like appearance; each gill has a gill axis and a lot of lamellae densely arranged to increase the surface area. The gills are found attaching to the base of the thoracic appendages in the branchial region of the carapace. There are about 8 to 10 pairs of gills within the branchial chamber [2,4]. Each gill is composed of 1) Scaphognathite (Gill bailer), the fan-like structure located at the coxa. 2) Branchiostegite, the thin tissue that covers the lamellae on both sides of the branchial chamber, allows water to flow and protects the gills from contaminants. 3) Gill cleanser, the flagellated part, assists in gill cleaning. 4) Afferent and efferent vessels for blood transportation [7,11]. Gills can be categorized by their location: 1) Podobranch, which are the gills attached to the coxa of thoracic appendages. 2) Arthrobranch, the gills located on the articular membrane between the coxa and pleuron. 3) Pleurobranch, the gills attached to the pleural wall of the cephalothorax at the base of the appendage [8].

The structure of the gill tissue consists of a thin, clear outer layer known as the epithelium, responsible for gas exchange, which has microvilli to increase the surface area, together with tight junctions that control the passage of substances, and pillar cells that connect between the afferent and efferent vessels and control the distance between the lamellae. Within the gills, the hemocoel is located between each lamella, serving as the pathway for blood circulation [2, 10].

In crucifix crabs, the excretory system contains a pair of green glands as the main functional organs. They are characterized by a small, oval-shaped structure found at the base of each antenna [8]. The green glands are responsible for maintaining homeostasis, filtering and excreting metabolic wastes, and

aiding in osmoregulation. They are found connected to the excretory pores for waste elimination. At the tissue level, the green gland consists of 1) Labyrinth, which has net-like, anastomosing tubules, lined with simple cuboidal cells. It is distributed around the proximal and distal tubular structures. 2) Coelomosac, which features a spherical sac, containing special cells called podocytes, distributed inside labyrinth. 3) Bladder, which is lined with single-layered vacuolated epithelial cells [5].

2. Materials and methods

2.1 Anatomical methods

Crucifix crab samples were collected from Samut Prakan, Thailand, and anesthetized with ice for 30 minutes, then rinsed with clean water. The ventral shell was then punctured to create a hole, and 4% formalin was injected to preserve the internal organs. The Crucifix crabs were then fixed in 70% ethanol.

The crab was positioned dorsally for dissection. A forceps was then used to carefully dissect out other muscles and membranes to reach the gills, heart, and green glands. The heart is located in the dorsal midline of the cephalothorax, and the gills are found in the branchial region of the carapace. Meanwhile, the green glands can be found near the orbital under the hepatopancreas [10].

2.2 Histological methods

Crucifix crab samples were collected from Samut Prakan, Thailand, and anesthetized with ice for 30 minutes, then rinsed with clean water. The ventral shell was then punctured to create a hole, and 4% formalin was injected to preserve the internal organs. The crucifix crabs were then fixed in 4% formalin to prepare the tissues for histological examination. The desired structures were then dissected into approximately 0.5 cubic centimeters in size and placed in Bouin's fixative at 4 degrees Celsius for 24 hours and preserved in Davidson's fixative for 2 hours. For structures containing chitin, Davidson's fixative with a high concentration of glacial

acetic acid was used to thin the shell. The tissues were then dehydrated with an alcohol series (50 – 100%) and cleared with butanol: xylene and xylene, respectively. The tissues were then embedded in paraplast and sectioned with a rotary microtome at a thickness of 6-8 μm . Finally, the sections were stained with hematoxylin and eosin, and slides were mounted to prepare for imaging under a compound light microscope [10]

3. Result

3.1 Anatomical results

3.1.1 Circulatory system

Crucifix crabs have an open circulatory system containing hemolymph, which contains the blue pigment called hemocyanin. Hemolymph circulates within the hemocoel and passes into the heart (H) through 3 pairs of small openings known as ostia (Os). Heart contraction pumps hemolymph to different regions of the body through the primary

arteries consist of: 1) Ventral thoracic artery (VTA): supplies hemolymph to the mouthparts and pereopods. 2) Anterior aorta (AA): supplies hemolymph to the eyes. 3) Anterior lateral artery (ALA): supplies hemolymph to the gonads and stomach. 4) Posterior aorta (PA): supplies hemolymph to the abdomen which is shown in Fig 1.

3.1.2 Respiratory system

The gills of crabs, responsible for gas exchange, are located under hepatopancreas (Hp) and the gonads (ovary (Ov) or testis). *C. feriatus* possesses 8 pairs of phyllobranchiate gills (1Pb – 8Pb) characterized by their leaf like morphology. The first pair of gills attaches to the second maxilliped. Each phyllobranchia has a central gill axis (GA) that forms the core of the gill and features densely arranged gill lamellae (GL), serving as the primary sites of gas exchange which is shown in Fig 1.

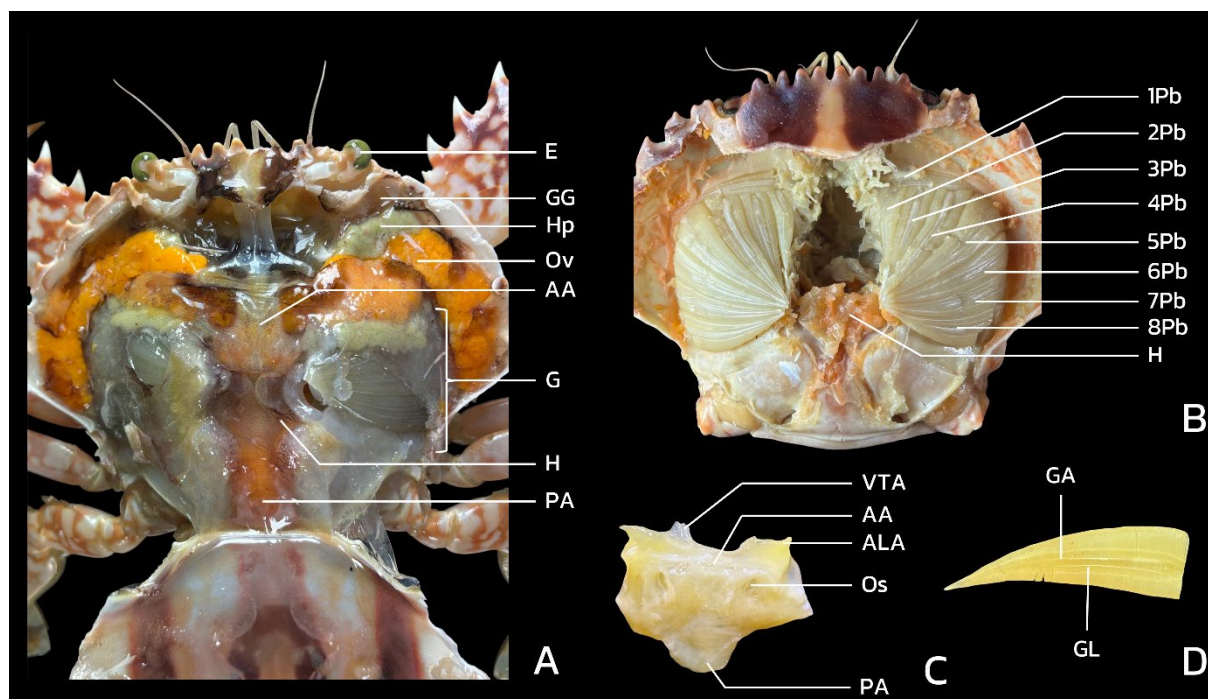


Figure 2: Crucifix crab heart longitudinal section. (A) The layers of the heart tissue (40X) (B) Detailed view of muscle and squamous epithelium (400X) (C) Cross section showing sinus and hemocytes (400X). Histological abbreviation: CT, connective tissue; Enc, endocardium; Epc, epicardium; HC, hemocytes; M, muscle fibers; Myc, myocardium; Pec, pericardium; Si, sinusoids; Sn, sinus; Sq, squamous epithelium

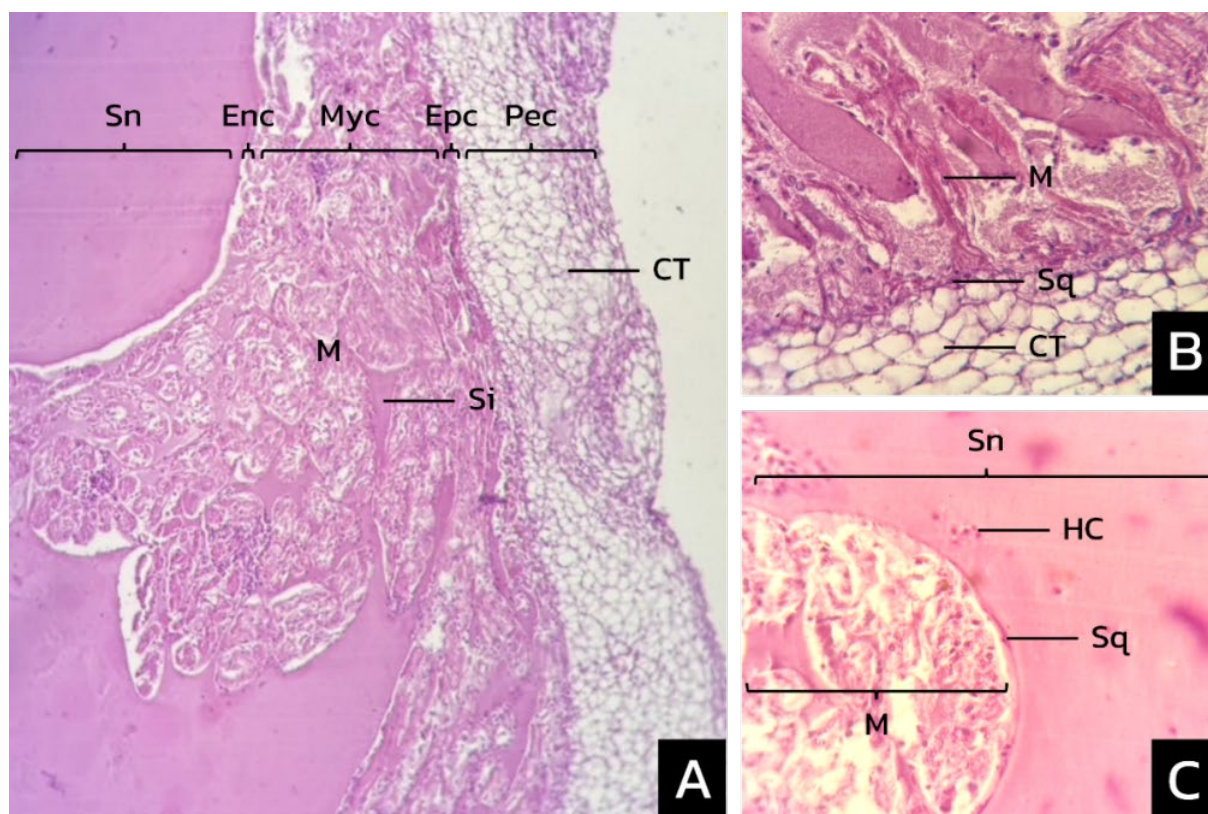


Figure 2: Crucifix crab heart longitudinal section. (A) The layers of the heart tissue (40X) (B) Detailed view of muscle and squamous epithelium (400X) (C) Cross section showing sinus and hemocytes (400X). Histological abbreviation: CT, connective tissue; Enc, endocardium; Epc, epicardium; HC, hemocytes; M, muscle fibers; Myc, myocardium; Pec, pericardium; Si, sinusoids; Sn, sinus; Sq, squamous epithelium

3.1.3 Excretory system

The main excretory organ in crabs is the green gland (GG), primarily responsible for eliminating ammonia waste. The green gland is located under the eye above hepatopancreas (Hp). The green gland can be characterized by red to brown oval and features tiny opening to the base of the antenna, known as the excretory pore which is shown in Fig: 1.

3.2 Histological results

3.2.1 Heart

The heart receives and delivers hemolymph to various tissues and organs. The pericardium (Pec) is the thick-walled membrane covering the heart. Within the pericardium, loose connective tissue (CT) is found. The cardiac tissues are categorized into three layers: 1) Epicardium (Epc): The outermost cardiac tissue consists of Simple squamous

epithelium (Sq) 2) Myocardium (Myc): The middle cardiac tissue contains disorganized muscle fibers (M) and connective tissue. This layer contains sinusoids (Si), which contains hemolymph. 3) Endocardium (Enc): The inner cardiac tissue consists of simple squamous epithelium (Sq), possesses sinuses (Sn), carrying hemolymph from ostia. It also features haemocytes, tiny cells with small nuclei carrying oxygen. which is shown in Fig 2.

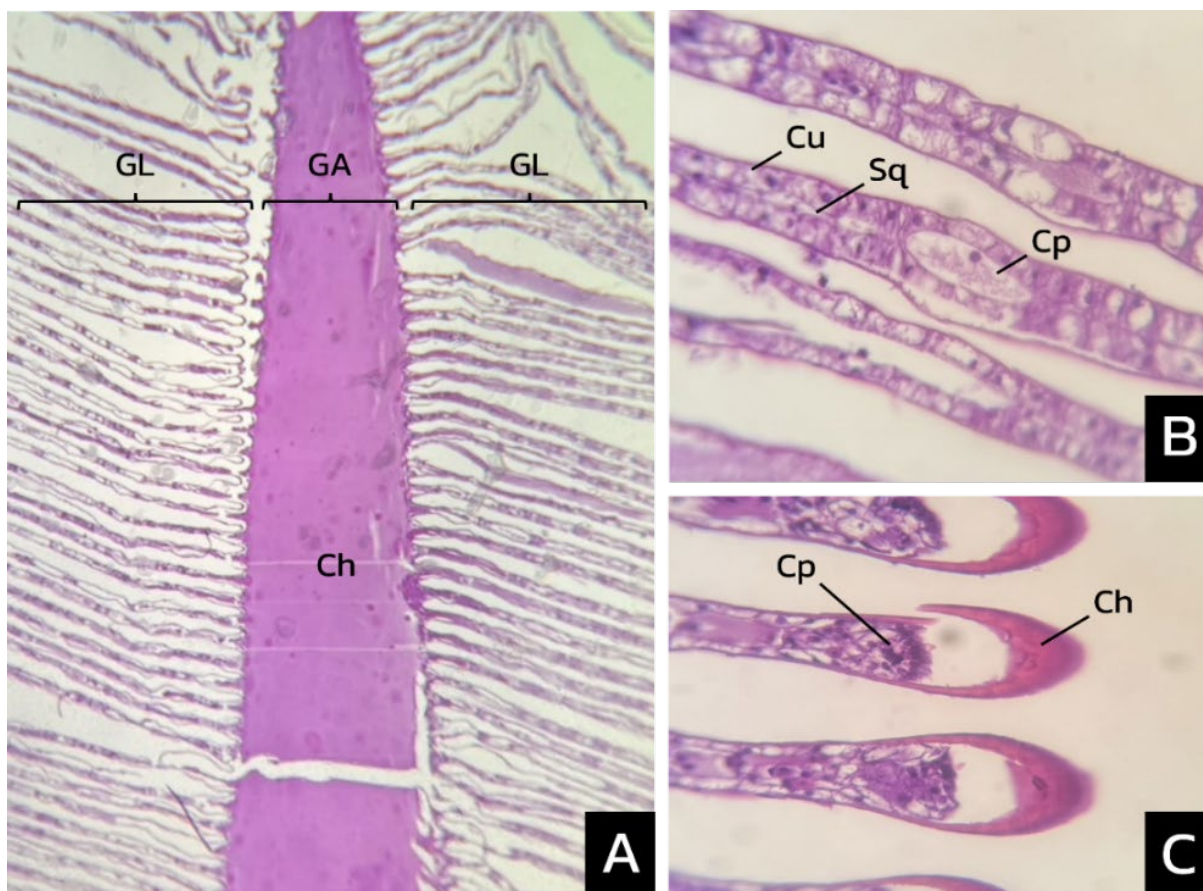


Figure 3: Gill longitudinal section. (A) Longitudinal section of a gill showing the gill axis and lamellae (40X). (B) Detailed view of gill lamellae shows capillaries (400X). (C) Distal end of gill lamellae (400X). Histological abbreviation: Ch, chitin; Cp, capillary; Cu, cuticle; GA, gill axis; L, gill lamellae; Sq, squamous epithelium

3.2.2 Gill

The gills are responsible for gas exchange, divided into two regions: 1) Gill axis (GA): The core structure serving as the central support structure of the gill. Gill axis is constructed with chitin (Ch) 2) gill lamellae (GL): These structures, positioned on the gill axis, are the sites of gas exchange, consisting of simple cuboidal epithelium (Cu) and simple squamous epithelium (Sq) surrounding around capillary (Cp). At the distal end of gill lamella, chitin (Ch) is also found surrounding connective tissue (CT) to protect the edge of gills which is shown in Fig 3.

3.2.3 Green gland

The green gland is involved in the excretion of waste in the crabs. Within green gland, the folding tubules are found known as

the labyrinth (Lb), containing simple cuboidal epithelium (Cu) which features Microvilli (Mv) surrounding extending into the lumen (L). It possesses the primary responsibility to filter and reabsorb the substances. Loose connective tissue (CT) and an excretory tubule are found, connecting to the base of antenna to eliminating the waste through collecting duct. The collecting duct is widely lined by lumen (L), Simple columnar epithelium (Co) which is shown in Fig: 4.

4. Conclusion

To prepare the crucifix crab specimens for the study of both the circulatory and respiratory systems, the crab can be anesthetized using ice and preserved in 4% formalin. However, for studying the excretory system, the green gland can easily disintegrate. Therefore, it is necessary to

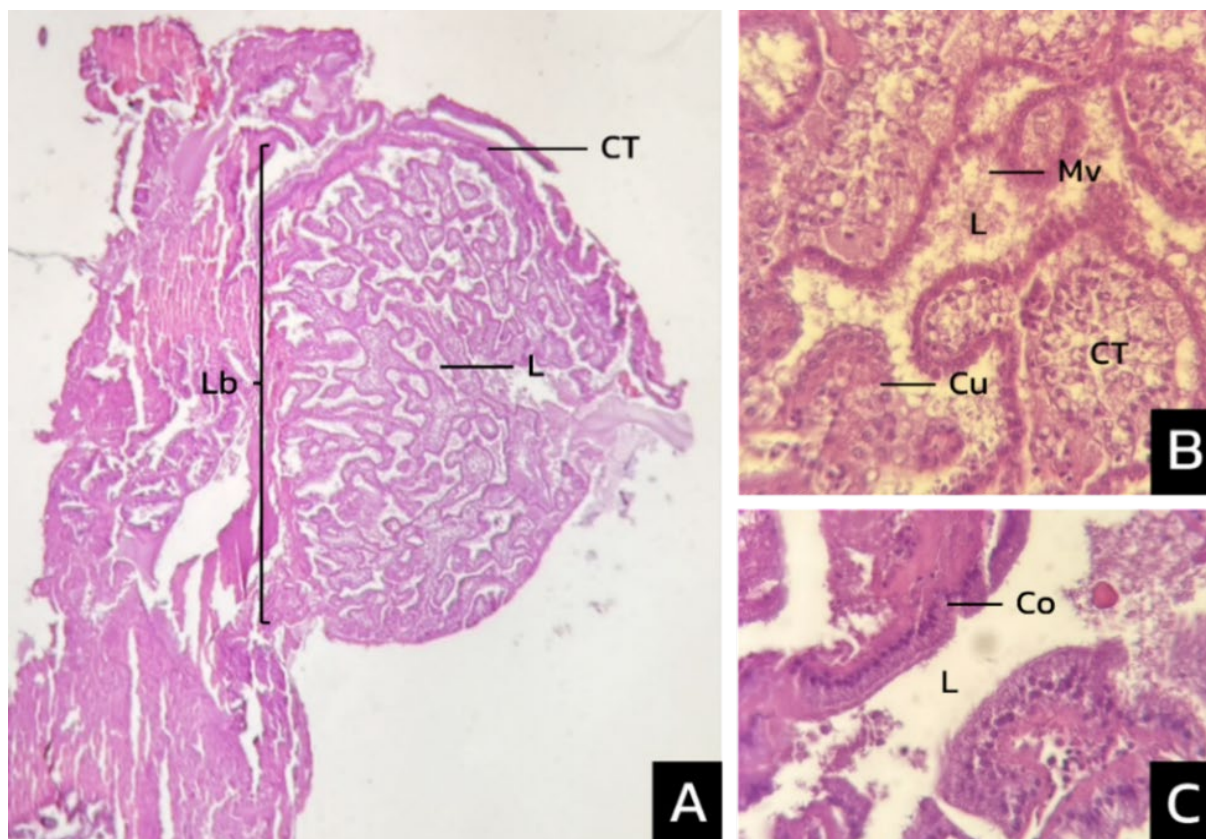


Figure 4: Green gland cross section. (A) Cross section of the green gland showing labyrinth and lumen (40X).

(B) Detailed view of the green gland (400X). (C) Lumen lined with simple columnar epithelium (400X).

Histological abbreviation: Co, simple columnar epithelium; CT, connective tissue; Cu, cuticle; L, lumen;

Lb, labyrinth; Mv, microvilli

immediately dissect the crab to collect the tissue samples after the crab is anesthetized. Additionally, the green gland is a small, brownish colored gland that, when fixed in 70% ethanol or 4% formalin, turns white, making it hard to distinguish from its surrounding muscles. Identifying its position during the very first dissection is therefore quite challenging, which is why histological methods were used to help in the study.

From an anatomical perspective, each organ in crucifix crabs shows up distinguishably, making them suitable specimens for studying the morphology of malacostracans. When dissecting, it is important to be careful not to tear the thin membrane that covers the internal organs, or else the blood vessels would be damaged.

In terms of histology, this report presents the first documentation of the tissue structure of the green gland in this family, revealing that it consists of numerous small, coiled tubules, which are significantly different from those found in shrimps and mantis shrimps. More studies using biochemistry testing or antibody labeling specific to green gland cells are recommended for a more precise structural identification and a better understanding of the excretory system of other malacostracans. The heart tissue of the crab has a muscle layer that is thick at the margins, contrasting with shrimps and mantis shrimps, which have a thinner muscle layer that relies on lateral muscular contractions for pumping. This is one of the features that helps differentiate crabs from other organisms within the malacostraca class

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Anatomical and Histological insights into the Alimentary tract and accessory structure of the Sand worm *Perinereis nuntia* (Phyllodocida: Neriediformia)

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Abstract

The sand worm (*Perinereis nuntia*) has a cylindrical body composed of segments with the same internal structure, called chaetiger. A mature sand worm has approximately 200-220 segments. Sand worms belong to polychaete group which is the only class within Annelida known to be carnivorous. As a result, they possess well-developed digestive structures in the head region, including jaws, denticles, and pharynx that can be extended and retracted. During sample preparation, 95% ethanol is used for euthanasia in order to preserve the tissue integrity and to rapidly induce unconsciousness, preventing the sand worm from biting itself. Specimens are then transferred to 70% ethanol for preservation. Anatomical studies revealed that the digestive tract of the sand worm consists of the mouth, pharynx, oesophagus, intestine, and anus. These organs distinct internal structures that aid in identification. Additionally, a small coiled tubular organ known as the pharyngeal gland assists in digestion. Histological studies revealed that the epithelial tissue throughout the digestive tract is composed of simple columnar epithelium. Variation in the elevation and folding of the underlying connective tissue layer may provide further insights into the digestion mechanism of sand worm.

Keywords: Digestive system; Sand worm; Denticle; Oesophageal gland; Histology

1. Introduction

Perinereis nuntia is a segmented worm invertebrate that lives on the sandy shore in saltwater [3]. It is widely distributed in coastal areas of the Southern Hemisphere and the tropical Indo-Pacific region [16]. In Thailand, it is often found in the coastal areas of the Gulf of Thailand and the Andaman Sea, especially in intertidal and shallow waters along the coast. This is because it is a scavenger [2,7] or a beach trash scavenger [13]. In addition, sand worm is an economic animal used as food for shrimp farming in Thailand, accounting for up to 78% [8]. This is because nutrients are essential for ovarian development and reproductive maturity in marine shrimp. To reduce the import of shrimp parent stock from abroad [7].

Perinereis nuntia is a marine invertebrate. Its main characteristics are bilateral symmetry, triploblastic tissue, true coelom, and sexual reproduction of trochophore larvae [1]. Its body is segmented, which is an important characteristic of annelids. Each segment consists of a protruding structure called parapodia containing many chaetae for movement and gas exchange, which is a characteristic of the Polychaeta class. The movement of sand worms depends on undulation and contraction of the longitudinal muscles of the body wall from the rear to the front, which works in opposition to the annular muscles, causing the body to twist, bend to move forward and used in swimming [10]. Sand worms have up to 8,000 species [4]. A distinctive feature of

animals in the class Polychaeta is the presence of parapodia on both sides of each body segment. Parapodia usually consist of two parts: notopodium (upper) and neuropodium (lower). Both parts usually have chaetae, stiff hairs that function in movement, adhesion, and assist in gas exchange. Another important characteristic for classification is the retractable pharynx. Some species have jaws or teeth used to capture prey. The characteristics of the pharynx are diverse and can be classified according to their feeding style, such as predators, scavengers, or filtering food from the water [15]. *Perinereis nuntia* is in the family Nereidae. The distinctive features are the head structure (prostomium) with one pair of antennae and palps that are clearly divided into two segments. Another distinctive feature is the structure of the pharynx and jaws. Nereididae have hard jaws similar to teeth on the pharynx. It also consists of paragnaths arranged in different areas. There are various shapes such as cones, bands or crowns. Another distinctive feature is the chaetae such as spinigers and falcigers, which are subdivided according to the attachment characteristics of the base (homogomph, heterogomph, sesquigomph). In addition, some Nereididae have a clear change in shape during the breeding season, becoming an epitoke stage to increase the efficiency of breeding [17]. Sandworms tend to live in groups during the breeding season in March - May [3].

Sand worms have the following important characteristics 1) They have a flat and long body with a clear division between the head and body 2) They have a body divided into clear segments 3) Each segment is made up of parapodia [3]. *Perinereis nuntia* has a distinctive row of paragnaths, which are rod-shaped and arranged in a curve on area VI [16]. *Perinereis nuntia* has a completely segmented body with each segment clearly divided by Intersegmental septa. This characteristic is an important feature that distinguishes *P. nuntia* from other

polychaetes. Additionally, parapodia plays an important role as a site for germ cells to accumulate and grow. Since *Perinereis nuntia* has complete segmentation, germ cells produced from the pygidium will be sent to the new segments formed at the anterior border of the pygidium during growth. Moreover, *P. nuntia* also has epitoky, which will change its body shape to be suitable for swimming and releasing germ cells. This change combined with the characteristics of complete parapodia, and septa are distinctive features of *P. nuntia* [9].

The sandworm has a complete digestive tract [13]. Marine annelids are known as scavengers, and the digestive system typically includes specialized regions such as a proboscis, pharynx, esophagus, intestine, and the rectum [6]. The proboscis contains structures external to the pharyngeal bulb that allow for eversions and retractions. The pharyngeal bulb has a dorsoventrally flattened prolate spheroid shape, which is located within the anterior of the foregut. Normally, the jaws are embedded on either left or right side of the anterior mouth, which is called the pharyngeal opening that extends via the center of the bulb to exit at the esophagus [14]. Food material is initially located within the muscular region of the esophagus before it passes through the subsequent glandular region. The pharynx and esophagus are the important structures, primarily responsible for the secretion of the digestive system. Digestion of food particles occurs within the intestine, involving both intracellular and extracellular processes. The remaining indigestible particles are subsequently handled by specialized cells that deposit within various tissues, including the epidermis, peritoneal cells, intravasal tissue, coelom, and the lumen of the gut before being expelled [6,11]

Anatomical study

The research from Jenkins et al. (2002) mentions the digestive tract in *Galpagomystides aristate*, which can be divided into a foregut and midgut, with no hindgut appearing [5].

The foregut has thin walls, is flexible, and has pale colors. The front of the foregut is covered with cilia and consists of a proboscis that is eversible with the diameter around 160 μm . The foregut is located at the connection point of pharyngeal sheath and pharynx. The midgut has the structure of a lobular structure with its brown color and no septa appearing. The structure of the midgut finger-like is connected with the body wall using a mesenterial strand on the ventral side. The midgut joins the pharynx at the 12th segment.

The research mentions the anterior digestive tract of *Eulalia viridis* consists of the pharynx and esophagus, which contain one-third of the length of the digestive system, and the other two-thirds are the posterior part that consists of the intestine rectum and anus. Between the two alimentary parts, there is a bend that allows for eversion of the proboscis [11].

2. Materials and methods

2.1 Anatomical methods

The samples of sand worms were taken from Chonburi province and were kept in sand to prevent them from biting each other. Afterward, sterilize them with 95% ethanol for 30 seconds to allow the pharynx part to be clearly elongated. If using a concentration of alcohol that is too low, it will cause the sand worms to lose the concentration and make the sandworm's body wall rupture and internal structures be damaged. Only 1-2 sand worms should be anesthetized at a time to prevent too much changed in the alcohol concentration. Use 4% formalin injected via the mouth into the body until the body stretches into the shape of a cylinder, using a syringe. Lastly, maintain with 70% ethanol [12].

To begin the operation, place the sand worm dorsally. Using operating scissors, cut

the lateral wall starting from segment 30 toward the head to avoid damaging the pharyngeal gland, then start to cut down. Use a scalpel to slowly dissect the digestive tract from the body wall and make it clearer.

2.2 Histological methods

The sand worm samples, which were taken from Chonburi province, were maintained in sand to keep them from biting each other. After that, sterilize them for 30 seconds with 95% ethanol to make the pharynx portion visible and maintain them with Bouin's fixative at the temperature of 4 degrees Celsius for 24 hours. Then denature with an alcohol series (50–100%) and make the tissue transparent with butanol : xylene and xylene, respectively. Embed the tissue in Paraplast and excise with a rotary microtome at a thickness of 6-8 μm , then stain with haematoxylin and eosin and mount slides to prepare for imaging with a compound light microscope [12].

3. Result

3.1 Morphological results

Sand worms are an animal with a trunk-like structure and has many segments and can be divided into three regions. First, the anterior end is the region where the head is distinct from the body and contains prostomium that has a cephalization. Besides, in this region includes the first segments that are located between the head body called peristomium. Eyes of sandworm can be found in peristomium, which functions as a light receptor. It can be classified into two types based on its shape. For upper eyes, they can be categorized by their crescent moon-like shape, whereas lower eyes are in a circle shape, and six pairs of sensory appendages can be seen besides the eyes. Moreover, in the peristomium can be found a pair of jaws that function similarly to teeth, which are everted from a pharynx and work in gripping. Beside the jaws, denticle, which is a rigid structure, can be seen in the predental pharynx and postdental pharynx and functions to help grind food. On the ventral side, around the

mouth, is found a maxillary ring composed of the small, tooth-like structures arranged in a ring. The main structure of the maxillary ring is for grasping prey and for movement. Oral ring is found close to peristomium and encircles the mouth, which helps in finding food which is shown in Fig 1.

Trunk is the part where they have many repeated segments and found an appendage in each segment, which play a role in motility and gas exchange called parapodia. Lastly, posterior end is the smallest segment that is involved in producing segments in trunk region. In addition, mature sand worms have approximately 200-220 segments.

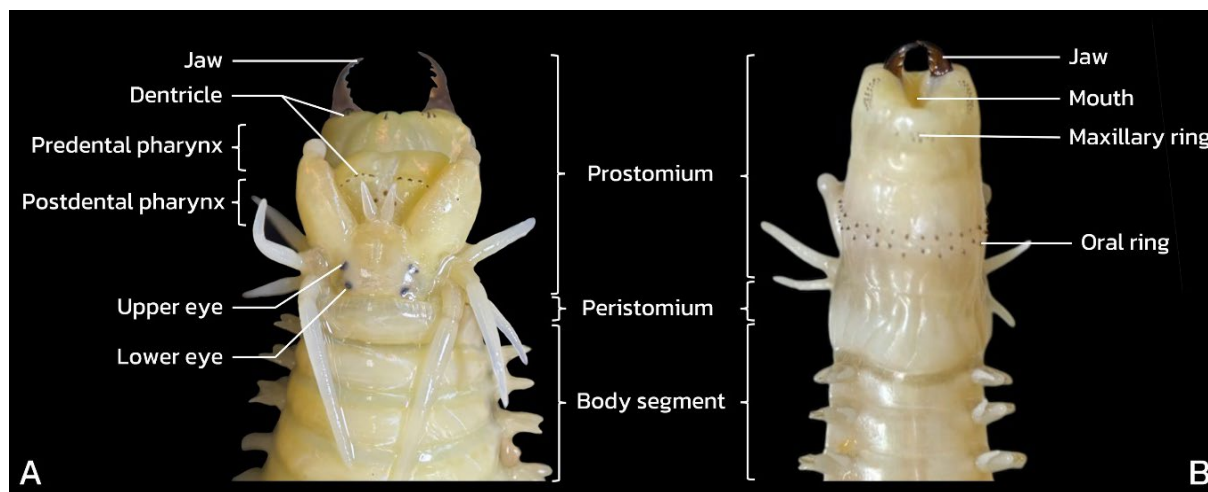


Figure 1 Sandworm head morphology (A) characteristic of sand worm dorsal head morphology
(B) characteristic of sand worm ventral head morphology

3.2 Anatomical results

Sandworm has a complete digestive tract with a straight tubular structure. The food will enter through the mouth (M) and then be transported to the pharynx, which has a thick wall which can be extended through the mouth for catching prey (Everted pharynx). The pharynx is divided into two areas, the first, predental pharynx (Prp), which is held by the protractor muscle (Ptm), inside consists of a structure used for catching prey called denticles (Dt) are small tooth-like structures made of chitin, arranged in ring pattern called oral ring. Second postdental pharynx (Pop), which is held by the retractor muscle (Rtm). Inside, found denticles arranged in ring pattern called maxillary ring and found Jaw, which is a large fang with six teeth used to hold prey. Food will be sent to the oesophagus (Oes) is a yellowish tube with a rectangular wave-like fold wall called papillae (Pp). On the side, found oesophageal

gland (Oeg) is a pair of small, coiled tubes that create enzymes for digestion. Before food is sent to the Intestine (In), it must pass through the oesophageal intestinal junction (OIJ), which is the connected area of the esophagus and intestines. Then the food is sent to the Intestine (In), which is a large, thin-walled tube with villi (Vi) that is used to digest and absorb food then send waste to the anus. Furthermore, when dissecting the live sand worm chloragogue cells were found around the intestine, causing different colors such as green, blue, and brown, which will differently depending on the area which is shown in Fig 2.

3.3 Histological results

3.3.1 Pharynx

The pharynx is a thick muscular tube that can be everted. It consists of a central hollow space called the lumen (L), which is divided into two parts: the predental pharynx (Prp)

and the postdental pharynx (Pop). The predental pharynx (Prp) is found in base of the upper jaw (J) and contains simple columnar epithelium (Co) that is covered with a layer of cuticle (C). In this region, small tooth-like structure made of chitin called denticle (Dt) which is shown in Fig: 3.

3.3.2 Oesophagus

The thick-walled tube called the oesophagus is covered by muscle (M) and the lateral-oesophageal vessel (LAV), which is a capillary that is located between the dorsal blood vessel (DBV) and the ventral nerve cord (VNC). The tissue that protrudes from the epithelium of the esophagus, called papillae (Pp), within contains a lumen (L) for transporting food. The lumen consists of four layers tissues, the epithelium is made of single layer of columnar cells called simple columnar epithelium (Co), which is covered

with a thin layer of cuticle (C). The connective tissue layer (CT) is made of loose connective tissue, circular muscle can be found in muscle layers (M), and the outermost layer (Serosa) also has the thin layer of loose connective tissue which is shown in Fig: 4.

3.3.3 Oesophageal gland

Oesophageal gland (Oeg) is a coiled tubular shaped gland found along the side of oesophagus (Oes) and above the ventral nerve cord (VNC). It is surrounded by Lateral-oesophageal vessel (LAV) and composed of simple columnar epithelium (Co) surrounding the lumen (L). Oesophageal gland functions in the production of digestive enzymes and there is a layer of disorganized Smooth muscle (Sm) arranged beneath it which is shown in Fig 5.

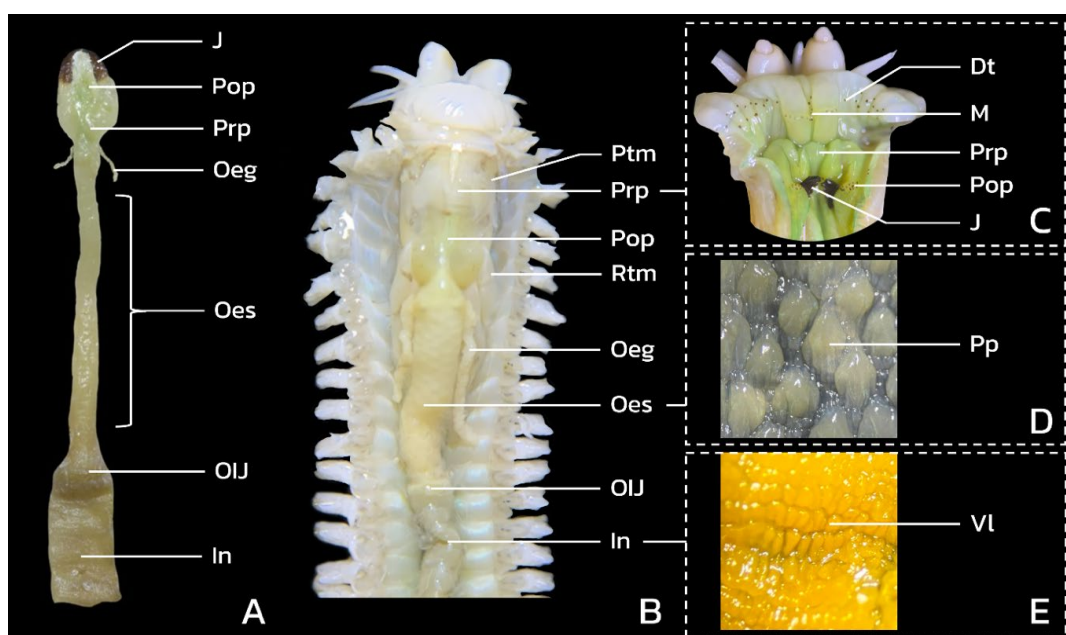


Figure 2 sandworm digestive tract (A) digestive tract with everted pharynx (B) digestive tract with everted pharynx (C) characteristic of wall in pharynx (D) characteristic of wall in oesophagus (E) characteristic of wall in Intestine. Anatomical abbreviation: D, Denticle; In, Intestine; J, Jaw; M, Mouth; Oeg, Oesophageal gland; OIJ, Oesophageal intestinal junction; Oes, Oesophagus; Pop, Postdental pharynx; Pp, Papillae; Prp, Predental pharynx; Ptm, Protractor muscle; Vl, Villi

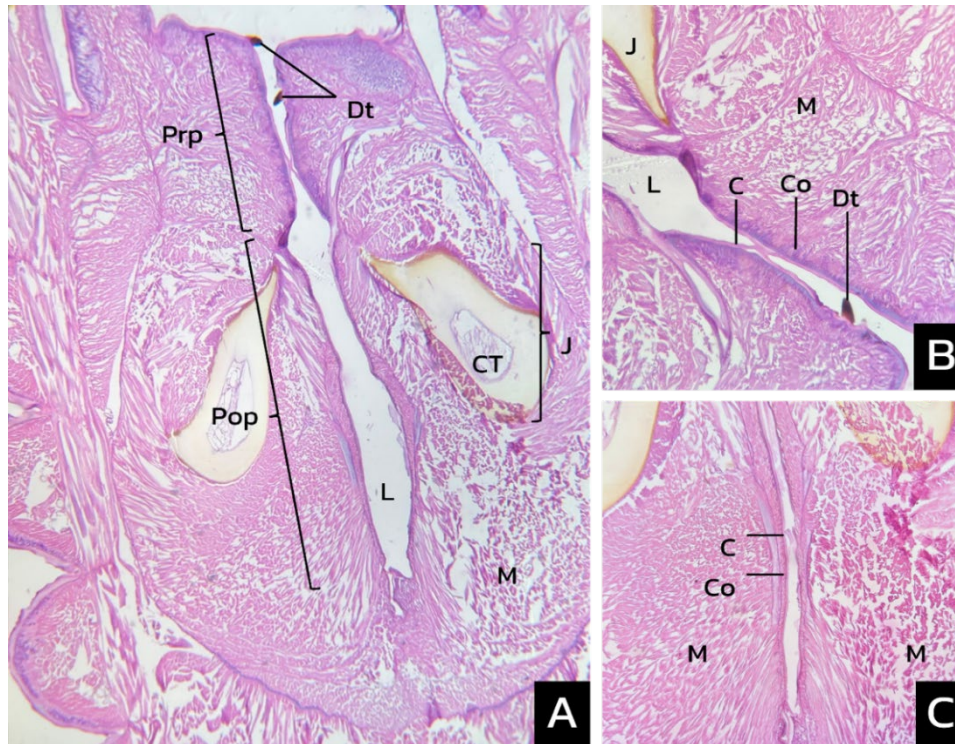


Figure 3 Sand worm pharynx longitudinal section (A) of the pharynx which is divided into 2 parts (40X) (B) Characteristic of predental pharynx and denticle (100X) (C) Characteristic of postdental pharynx and jaw (100X). Histological abbreviation: C, Cuticle; Co, simple columnar epithelium; CT, Connetissue; DT, Denticle; L, Lumen; M, Muscle; J, Jaw; Pop, Postdental pharynx; Prp, Predental pharynx

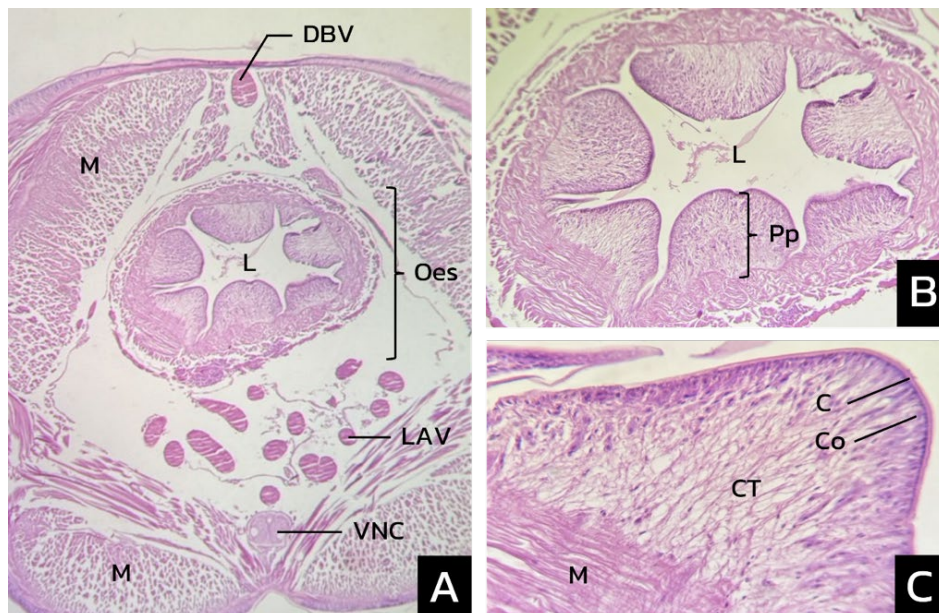


Figure 4 Sandworm oesophagus Cross section (A) Oesophagus between Dorsal blood vessel and Ventral nerve cord (40X) (B) papillae inside Oesophagus (100X) (C) Charateristic of Papillae (400X).

Histological abbreviation: C, Cuticle; Co, simple columnar epithelium; CT, Connective tissue; DBV, Dorsal blood vessel; L, Lumen; LAV, Lateral-oesophageal vessel; M, Muscle; Oes, Oesophagus; Pp, Papillae; VNC, ventral nerve cord

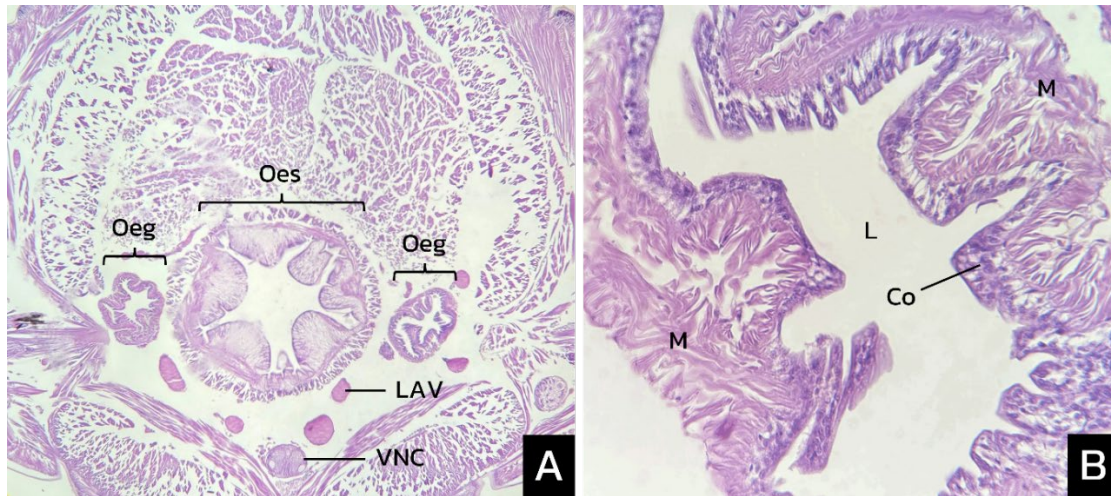


Figure 5 Oesophageal gland of Sand worm Cross section (A) Oesophageal gland on the side of esophagus (40X) (B) Characteristic of oesophageal gland with simple columnar epithelium tissue (400X).
Histological abbreviation: Co, simple columnar epithelium; L, Lumen; LAV, Lateral-oesophageal vessel; M, Muscle; Oeg, Oesophageal gland; Oes, Oesophagus; VNC, ventral nerve cord

3.3.4 Oesophageal-intestinal junction

Oesophageal-intestinal junction is the area between oesophagus (Oes) and Intestine (In). Oesophageal valve (Oev) with smooth muscle arrangement is found in this area. oesophageal sphincter muscle (Osp) is used to control the flowback of food. Simple

columnar epithelium (Co) and a thick layer of loose connective tissue (CT) are found in oesophagus. Simple columnar epithelium is also found in intestine, but connective tissue is thinner compared to the connective tissue of oesophagus which is shown in Fig 6.

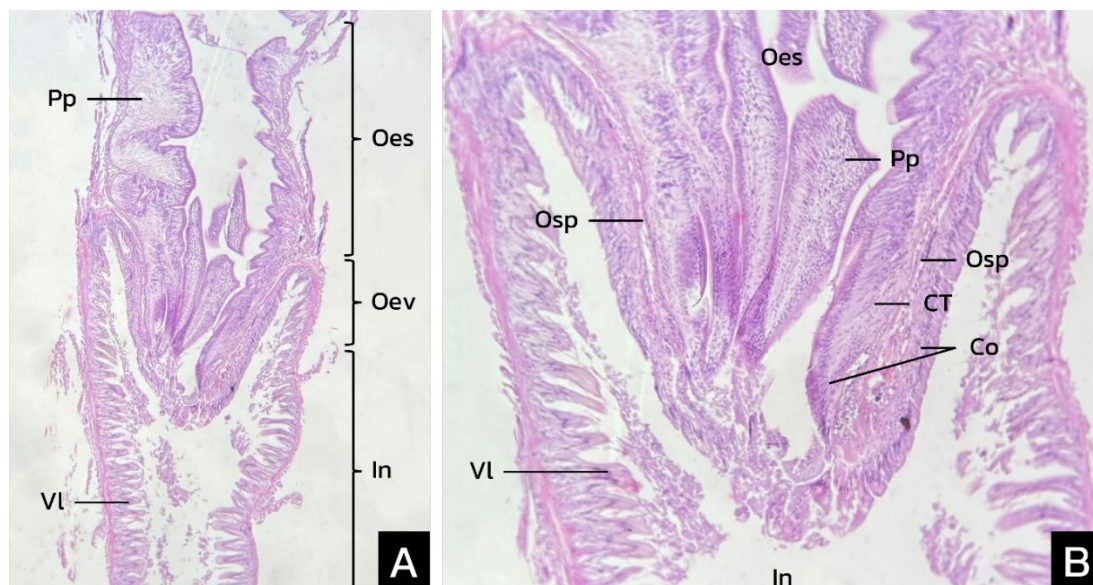


Figure 6 Oesophageal-intestinal junction Longitudinal section (A) Junction between oesophagus and intestine (100X) (B) Characteristic of sphincter with Simple columnar epithelium and Oesophageal sphincter muscle (400X). Histological abbreviation: Co, simple columnar epithelium; CT, Connective tissue; In, Intestine; Oes, Oesophagus; Oev, Oesophageal valve; Osp, Oesophageal sphincter muscle; Pp, Papillae; Vl, Villi

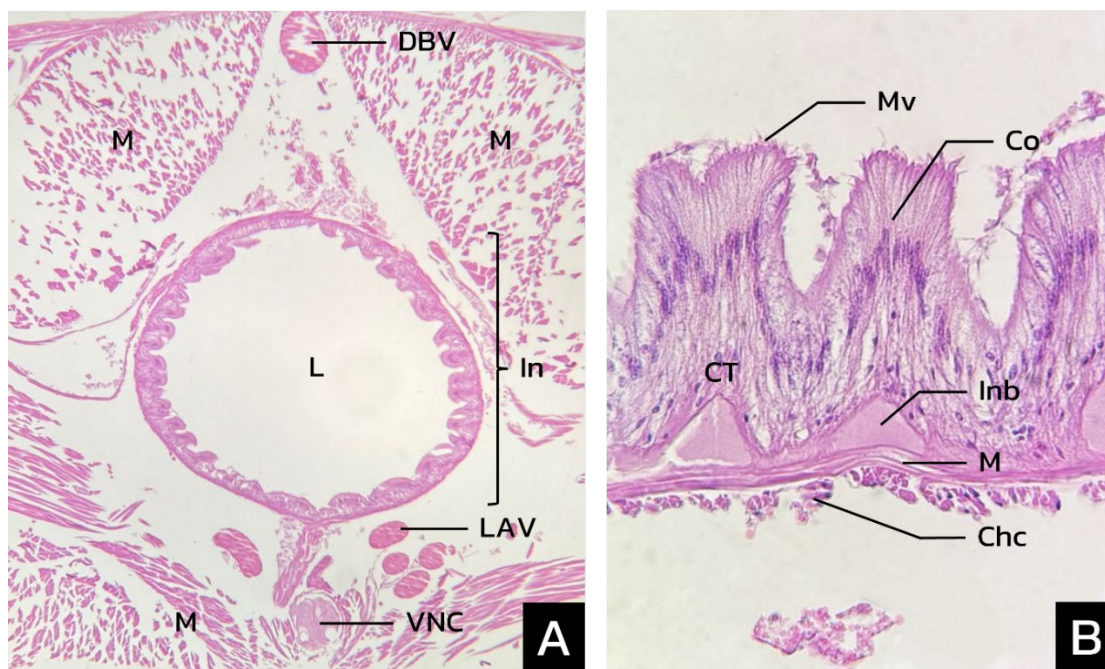


Figure 7 Characteristic of sandworm intestine Cross section (A) Intestine between dorsal blood vessel and ventral nerve cord (100X) (B) Characteristic of epithelium in simple columnar epithelium and chloragogue cell (400X). Histological abbreviation: Chc, Chloragogue cell; Co, simple; columnar epithelium; CT, Connective tissue; DBV, Dorsal blood vessel; In, Intestine; Inb, Intestinal blood vessel; L, Lumen; LAV, Lateral-oesophageal vessel; M, Smooth muscle; Mv, Microvilli; VNC, Ventral nerve cord

3.3.5 Intestine

Intestine (In) is formed as a large tube with thin wall and contains a lumen (L). It is located between the dorsal blood vessel (DBV) and the ventral nerve cord (VNC). Intestine was found from segment 15 onward and surrounded by lateral blood vessels (LAV). The structure of an epithelium is simple columnar epithelium (Co) with microvilli (Mv). Smooth muscle (M) is arranged with 1-3 cells thickness in muscularis layer and can be found Intestinal blood vessel (Inb). In addition, the outer layer of the intestine found a chloragogue cell (Chc), which plays a role in making yellow and green color in the intestine which is shown in Fig 6.

3.3.6 Rectum

Rectum (R) is the final part of a digestive tract before the food residue is eliminated by anus, located in pygidium. The structure of rectum is thin wall tube and wide lumen (L). epithelium presents a simple columnar cell

(Co) with a lack of microvilli (Mv). In connective tissue (CT) layer found thin layer of loose connective tissue which raised in form of plica circularis and surrounded by muscle (M) in order to help eliminate food residue which is shown in Fig 7.

4. Conclusion

From the study it was found that sandworms are the only group of polychaetes in the Annelida that have developed a head. That resulted in structures that aid in feeding including 1 pair of jaws and 2 rings of denticles around the pharynx, which is one of the characteristics of carnivorous animals. Those characteristics are different from the Oligochaete which are detritivores and the Hirudinea group which are blood-sucking animals. From an anatomical study, the digestive tract of sandworms is a long straight tube which requires the size of the tube and the internal folding patterns to differentiate the various parts. However, if sandworms have been preserved for a long time these

characteristics may not be distinguished so it is necessary to use histological methods to classify.

In terms of histology, the epithelial tissue in the digestive tract is entirely Simple columnar epithelium. The classification relies on the characteristics of the connective tissue, such as papillae and Plica circularis. In the pharynx, no connective tissue elevation is found. In the oesophagus, elevation is found in the form of Papillae. In the intestine, elevation is found in the form of plica

circularis. In the rectum, elevation is found in the form of Plica circularis and lesser compared to the Intestine.

It is recommended to select sandworms for examination. Sandworms with more than 200 segments should be used to ensure complete internal organs. They should be preserved in 95% ethanol to prevent self digestion and injected with formalin orally and in some parts of the body until the body is straightened and harden the structure, making it suitable for study. Then, they should be maintained in 70% ethanol.

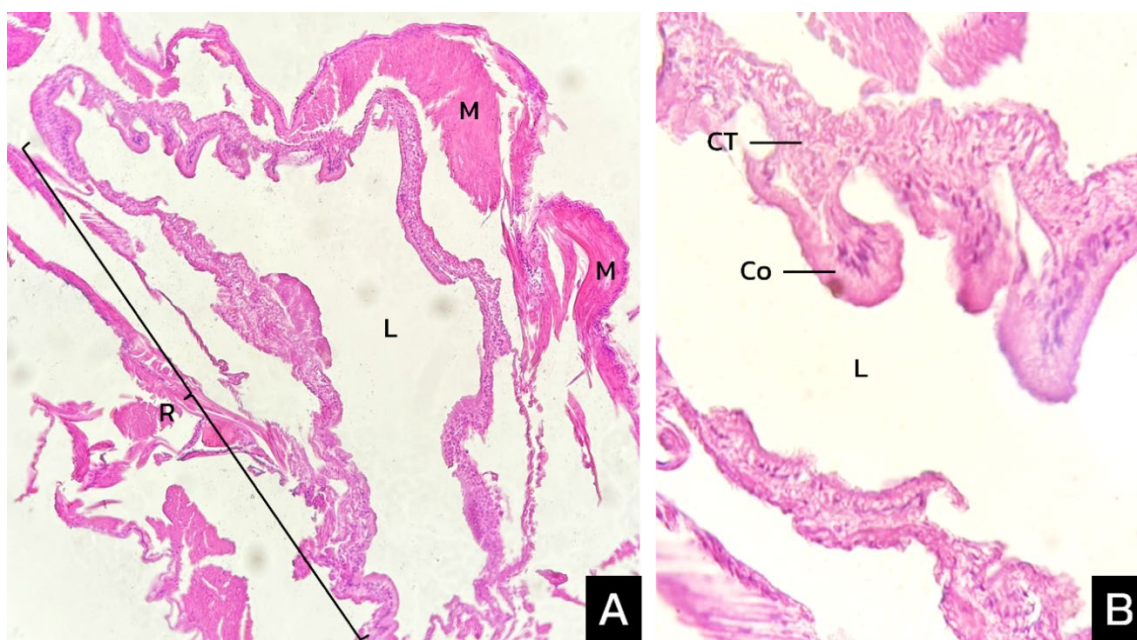


Figure 8 Characteristic of sandworm rectum Cross section (A) Rectum in pygidium (100X) (B) Characteristic of epithelium in simple columnar epithelium without microvilli (400X). Histological abbreviation Co, simple columnar epithelium; CT, Connective tissue; L, Lumen; M, muscle; R, Rectum

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Antimicrobial peptides temporin PF loaded chitosan nanoparticles exhibit antibacterial activity *in vitro* against methicillin-resistant *Staphylococcus aureus*

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Abstract

Methicillin-resistant *Staphylococcus aureus* (MRSA) is a significant clinical challenge due to its multidrug resistance and involvement in skin and soft tissue infections. Antimicrobial peptides (AMPs) have shown promise as alternatives to conventional antibiotics, owing to their broad spectrum activity and low tendency to induce resistance. However, their clinical use is limited by low stability and potential cytotoxicity. In this study, temporin PF (TPF) was selected based on its high anti-MRSA score (529.92) predicting by using a webserver SCMRSA program. To improve its stability and efficacy, TPF was incorporated into chitosan nanoparticles (CSNPs), a biocompatible and biodegradable carrier with intrinsic antimicrobial properties. TPF-loaded CSNPs were prepared using ionic gelation with sodium tripolyphosphate and showed favorable physicochemical properties. *In vitro* broth microdilution assays demonstrated that the formulation effectively inhibited MRSA strain 3-124 at one eighth of the minimum bactericidal concentration (MBC). Moreover, the nanoparticles exhibited low cytotoxicity toward A549 epithelial cells under equivalent conditions. These results suggest that TPF-loaded CSNPs offer a promising therapeutic strategy against MRSA associated infections, combining enhanced peptide stability, prolonged antibacterial activity, and reduced cytotoxicity.

Keywords: Methicillin-resistant *Staphylococcus aureus*; Antimicrobial peptides; Drug delivery system; Chitosan nanoparticles

1. Introduction

Methicillin-resistant *Staphylococcus aureus* (MRSA) is a Gram-positive coccus that typically forms clusters resembling grape-like structures. *Staphylococcus aureus* is commonly found on the skin and in the nasal passages of healthy individuals without causing harm (1). However, under certain conditions, it can cause a wide range of infections, including skin and soft tissue infections (such as boils and cellulitis), as well as more severe conditions like pneumonia and endocarditis (2). One of the critical factors contributing to the danger of *S. aureus* is its remarkable ability to develop resistance to antibiotics. This includes methicillin-resistant strains (MRSA), which

have acquired mechanisms to inactivate antibiotics particularly beta-lactam antibiotics such as penicillin, methicillin, and oxacillin making MRSA infections especially difficult to treat (3). The increasing resistance of *S. aureus* strains to multiple antibiotics poses a major challenge in clinical settings, driving the urgent need for new therapeutic strategies. One such approach involves the use of antimicrobial peptides (AMPs), a bioactive peptide found in the immune systems of a wide range of organisms and play a crucial role in fighting bacterial and pathogenic infections (3). The primary mechanism of AMPs involves disrupting the bacterial cell membrane and interfering with essential intracellular processes such as protein and

DNA synthesis, ultimately leading to bacterial cell death (4). One of the key advantages of AMPs is their lower tendency to induce bacterial resistance compared to traditional antibiotics (5). Among the various AMPs, Temporin-PF derived from frog skin secretions has gained significant attention. This peptide possesses an α -helical structure that facilitates its penetration through bacterial membranes, particularly in Gram-positive bacteria such as *S. aureus* (6). Temporin-PF has also demonstrated anti-biofilm activity against MRSA, which is crucial for overcoming antibiotic protection mechanisms (7). However, despite its high antimicrobial potential, temporin PF exhibits hemolytic activity and a tendency to aggregate, both of which limit its antimicrobial efficacy and therapeutic applicability (6). To overcome these challenges, advanced drug delivery systems such as chitosan nanoparticles (CSNPs) have emerged as promising vehicles to protect AMPs from enzymatic degradation, enhance antibacterial activity against MRSA (8).

CSNPs are increasingly being explored as efficient drug carriers due to the favorable properties of chitosan, a biopolymer derived from chitin (9). Chitosan exhibits excellent biocompatibility, biodegradability, and mucoadhesive properties, which help facilitate the targeted delivery of AMPs to infected areas (10). Moreover, chitosan possesses inherent antimicrobial activity by interacting with bacterial membranes, thus improving AMP permeability (11). CSNPs can improve peptide stability and reduce enzymatic degradation of AMPs, thereby enhancing their overall antibacterial efficacy against MRSA. Previous studies have shown that CSNPs can enhance the stability of AMPs and reduce their cytotoxicity. Moreover, encapsulating AMPs in CSNPs significantly protected them from protease degradation and prolonged their bioactivity (12). Therefore, the use of CSNPs to deliver Temporin-PF may help overcome the limitations of AMPs and significantly

improve their therapeutic potential in treating MRSA infections.

2. Materials and methods

2.1 Materials

2.1.1 Bacterial strains and growth conditions

The clinical isolate MRSA strain 3-124 was obtained from patients at Srinagarind Hospital, Khon Kaen University, Thailand, under the approval of the Human Ethics Committee (Project No. HE661395). The bacteria were cultured on blood agar plates at 37 °C for 18 h. A single colony was then inoculated into Muller Hinton broth and incubated at 37 °C with shaking at 200 rpm for 18 h prior to antibacterial assays.

2.1.2 Peptide synthesis and preparation

The anti-MRSA peptide TPF (sequence: FLPLIAGLFGKIF) was selected according to their high predicted anti-MRSA score derived from the SCMRSA model (13). The peptide was synthesized using solid-phase Fmoc chemistry and purified by HPLC (>95% purity). Peptide purity and mass were confirmed by analytical HPLC and ESI-MS. Stock solutions (5 mg/mL) were prepared in deionized water and stored at -20 °C until use; dilutions were freshly prepared before experiments.

2.1.3 Adenocarcinoma lung epithelial cells line (A549)

Human lung adenocarcinoma epithelial cells (A549, ATCC® CCL-185™) were cultured in RPMI medium supplemented with 10% fetal bovine serum (FBS) until 90% confluence. Cells were detached with trypsin-EDTA, neutralized with RPMI containing 2% FBS, centrifuged, and resuspended in RPMI + 10% FBS. Cell density was adjusted to 2.5×10^5 cells/mL, and 100 μ L (2.5×10^4 cells) was seeded into 96-well plates. Cells were incubated at 37 °C with 5% CO₂ for 18 h prior to MTT assay.

2.2 Methods

2.2.1 Synthesis of (TPF-loaded CSNPs)

TPF-loaded CSNPs were prepared by ionic gelation, exploiting electrostatic interaction between chitosan (degree of deacetylation $\geq 75\%$, dissolved at 1 mg/mL in 1% acetic acid, pH 5.6) and sodium tripolyphosphate (TPP, 1 mg/mL in water). The TPF peptide (5 μ M) was added to the chitosan solution prior to nanoparticle formation. TPP solution was added dropwise under magnetic stirring, and the mixture was stirred at room temperature (160 rpm) for 24 h. Nanoparticles were purified by centrifugation at 18,000 g for 10 min at 25 °C, washed, and resuspended in deionized water for characterization.

2.2.2 Characterization of TPF-loaded CSNPs

Particle size distribution and polydispersity index (PDI) were measured by dynamic light scattering (DLS), while zeta potential was determined using a Zetasizer NanoZS (Malvern Instruments). Morphology was observed via field emission transmission electron microscopy (FE-TEM, Thermo Scientific Talos F200X G2).

2.2.3 Determination of minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) of TPF-loaded CSNPs

The antibacterial activity of TPF-loaded CSNPs against MRSA strain 3-124 was assessed using the standard broth microdilution method. Briefly, overnight bacterial cultures were diluted in MHB and adjusted to an optical density at 600 nm corresponding to approximately 1×10^6 CFU/mL. In sterile 96-well microplates, 200 μ L of TPF-loaded CSNP, CSNPs, and TPF alone suspension were added to the first well and serially diluted two-fold across the wells. Subsequently, 100 μ L of the bacterial suspension diluted 1:1 with phosphate-buffered saline (PBS) was added to each well, resulting in a final inoculum density of approximately 5×10^5 CFU/mL per well.

Control wells included growth control (bacteria without antimicrobial agent) and sterility control (broth only). Plates were incubated at 37 °C for 24 h under static conditions. The MIC was defined as the lowest concentration of TPF-loaded CSNPs at which no visible bacterial growth (turbidity) was observed. To determine the MBC, aliquots from wells at and above the MIC (no visible growth) were plated MHA plates and incubated at 37 °C for 24 h. The MBC was the lowest concentration that resulted in $\geq 99.9\%$ reduction in CFU/mL, indicating bactericidal activity. All assays were performed in triplicate to ensure reproducibility.

2.2.4 Determination of the cytotoxicity TPF-loaded CSNPs on A549 cells

The cytotoxicity of TPF-loaded CSNPs was evaluated in A549 human lung epithelial cells using the MTT assay. Cells were seeded into 96-well plates at a density of 2.5×10^4 cells/well and incubated for 18 h at 37 °C in a 5% CO₂ atmosphere. After attachment, cells were treated with serial two-fold dilutions of TPF-loaded CSNPs, CSNPs, and TPF peptides alone for 24 h. Following treatment, 100 μ L of MTT solution (0.5 mg/mL) was added to each well and incubated in the dark for 4 h. Formazan crystals formed by metabolically active cells were then solubilized with 100 μ L of DMSO. The plates were incubated for 15 min, and cell viability was measured by a microplate reader (OD 540 nm). % Cell viability was calculated according formula (1)

$$\% \text{Cell viability} = \left[\frac{\text{OD sample (540 nm)}}{\text{OD control (540 nm)}} \right] \times 100 \quad (1)$$

3. Results

3.1 Synthesis and characterization of TPF-loaded CSNPs

The nanoparticles were prepared through the ionic gelation technique. All formulations, including TPF-loaded CSNPs and blank CSNPs, were analyzed using dynamic light scattering (DLS). The results

revealed that incorporation of the TPF peptide into the nanoparticles slightly increased the average particle size to approximately 633.9 nm, compared to 565 nm for the CSNPs alone (Table 1). The polydispersity index (PDI) values for TPF-loaded CSNPs and CSNPs were 0.625 and 0.533, respectively, suggesting a narrow size distribution

appropriate for nanoparticle applications. Both types of nanoparticles carried positive surface charges, with zeta potentials of +32.5 mV for the TPF-loaded CSNPs and +30.2 mV for CSNPs. This positive charge, primarily due to the cationic properties of chitosan, indicates that the TPF-loaded CSNPs possess good colloidal stability.

Table 1 The particles size, PDI, and zeta potential of the TPF-loaded CSNPs and CSNPs alone

Formulations	Size (nm)	Zeta potential (mV)	PDI
CSNPs	565	+30.2	0.533
TPF-loaded CSNPs	633.9	+32.5	0.625

Abbreviation: CSNPs, chitosan nanoparticles; TPF-loaded CSNPs, temporin-PF loaded chitosan nanoparticles; PDI, polydispersity index

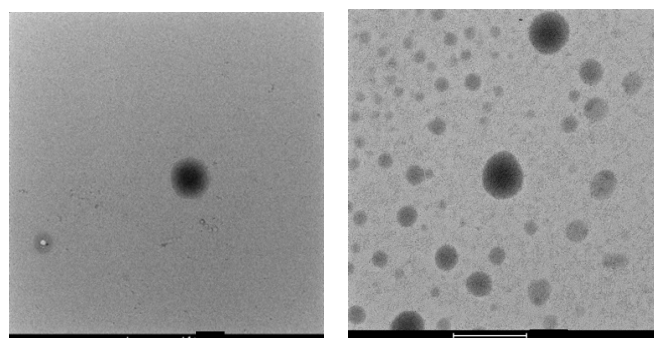


Figure 1 TEM images of (A) CSNPs and (B) TPF-loaded CSNPs

3.2 Morphology study of TPF-loaded CSNPs

The surface morphology of the synthesized nanoparticles was evaluated using field emission transmission electron microscopy (FE-TEM). Both types of nanoparticles appeared spherical with smooth and well-defined surfaces (Figure 1). The particles were uniformly dispersed, suggesting favorable colloidal stability and minimal aggregation. Notably, the particle sizes visualized via TEM were consistent with those obtained from dynamic light scattering analysis, supporting the successful incorporation of TPF peptide into the nanoparticle system.

3.3 Antibacterial activity of TPF-loaded CSNPs

The antibacterial activity of TPF-loaded CSNPs against MRSA strain 3-124 was examined using the broth microdilution assay (Figure 2). Among all tested groups, TPF-loaded CSNPs showed the greatest activity, with MIC and MBC values of X/16 and X/8, respectively, as presented in Table 2. In comparison, CSNPs alone were less effective, displaying MIC and MBC values of X/8 and X/4. TPF peptides alone, tested at a starting concentration of 2.5 µM equivalent to that used in the nanoparticle formulation, showed no observable inhibition, as all wells remained turbid. These results indicate that TPF-loaded CSNPs at X/8 are the most efficient in suppressing MRSA growth.

Figure 2 The antibacterial activity of TPF-loaded CSNPs compared to CSNPs alone and TPF peptides against MRSA strain 3-124 after incubated for 24 h. The experiments were conducted in triplicated.

Note: Concentration X was defined as a mixture of chitosan (5.3 mg/mL) and TPF peptide (5 μ M)

Table 2 The MIC and MBC values of TPF-loaded CSNPs, CSNPs alone, and TPF peptides

Fomulation	MIC	MBC
TPF-loaded CSNPs	X/16	X/8
CSNPs	X/8	X/4
TPF peptides	>X	>X

3.4 Cytotoxicity of TPF-loaded CSNPs on human epithelial cells (A549)

The cytotoxicity of TPF-loaded CSNPs was evaluated in A549 cells using the MTT assay following 24 h of exposure at various concentrations (Figure 3). The results showed a dose-dependent response, where higher concentrations of TPF-loaded CSNPs led to a decrease in cell viability. At X concentration, cell viability was lowest but remained above the cytotoxic threshold. At lower concentrations, particularly from X/8 to X/16, cell viability exceeded 90%, indicating good biocompatibility. CSNPs alone showed a similar trend, although TPF-loaded CSNPs exhibited slightly reduced viability at the highest dose. These findings suggest that TPF-loaded CSNPs are well tolerated by A549 cells at concentrations effective for antibacterial activity.

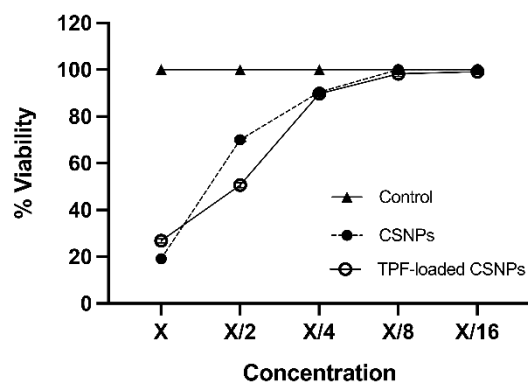


Figure 3 Percentages of cell viability of CSNPs and TPF-loaded CSNPs on A549 cells assessed by MTT assay. Cell viability was evaluated after 24 h of treatment with various concentrations (X to X/16). The experiments were conducted in triplicate, and the data were presented as the mean $\pm$ SD.

4. Discussion

The emergence and rapid spread of multidrug-resistant pathogens, particularly MRSA, continue to undermine the effectiveness of conventional antibiotic therapies worldwide (14). Despite ongoing efforts to develop new antibiotics, the alarming pace at which resistance develops severely limits treatment options and contributes to increased morbidity and mortality (15). This pressing challenge underscores the urgent need to explore alternative therapeutic strategies capable of overcoming resistance mechanisms. In this context, AMPs have emerged as promising alternatives to conventional antibiotics due to their rapid bactericidal action and low propensity for resistance. Among them, TPF exhibits potent anti-MRSA activity, attributable to its amphipathic α -helical conformation and high hydrophobicity, which facilitate membrane disruption (16). MRSA membranes are known to possess increased surface hydrophobicity and reduced net negative charge (17), enhancing their interaction with high hydrophobicity and low positively charged peptides like TPF. These features support the potential of TPF as a selective agent against resistant strains (18).

In this study, the TPF peptide was encapsulated within CSNPs to enhance its stability, low toxicity, and improve antibacterial efficacy against MRSA. TPF-loaded CSNPs were prepared via ionic gelation and extensively characterized. The addition of TPF slightly increased the nanoparticle size compared to blank CSNPs with average size diameters of 633.9 and 565 nm, respectively. The prepared NPs also preserving a narrow size distribution and positive zeta potential of +32.5 mV, indicating good colloidal stability and suitability for biological applications. These results are consistent with Anna M Piras et al., where the loading of temporin B into CSNPs caused structural enlargement due to molecular interactions and surface binding. While nanoparticles in the range of 50-500

nm are generally more favorable for efficient skin penetration, the particle size obtained here remains suitable for topical delivery, offering a balance between stability and effective interaction with the skin surface.

To enhance antibacterial activity of TPF-loaded CSNPs, their formulations were optimized. As expected, the TPF-loaded CSNPs exhibited stronger activity against MRSA strain 3-124 than either CSNPs alone or free TPF peptide, which showed MIC and MBC values of X/16 and X/8. This finding aligns with the study of Fahimirad and colleagues, who investigated the antibacterial activity of a recombinant LL37 peptide incorporated into CSNPs (LL37-CSNPs) against *S. aureus*. Their study revealed that encapsulation significantly improved the peptide's potency, as reflected by a lower MIC value (8 μ g/mL) compared to either blank CSNPs (64 μ g/mL) or the free LL37 peptide (32 μ M) (19). These results reinforce the role of CSNPs in enhancing the efficacy of AMPs through improved antibacterial performances and stability of the AMPs.

In addition to antimicrobial efficacy, the safety profile of nanoparticle-based therapeutics is a critical consideration for clinical translation. Cytotoxicity testing on A549 epithelial cells showed that TPF-loaded CSNPs were well tolerated at antibacterial effective doses, supporting their safety for therapeutic applications. At the highest tested dose, cell viability decreased modestly but remained above the cytotoxic threshold. At lower concentrations (particularly from X/8 to X/16 MIC), viability consistently exceeded 90%, indicating acceptable biocompatibility. A similar trend was observed with CSNPs alone, though slightly higher viability was maintained. These results are consistent with prior studies that emphasize the safety of chitosan-based delivery systems. For instance, Thulshan Jayatilaka and colleagues reported that free Octoprophobitin peptides reduced HEK293 cell viability at concentrations between 50 and 400 μ g/mL, with the highest cytotoxicity observed at 400

µg/mL (83.14% viability). However, when the peptide was encapsulated within CSNPs (Octoprophibitin-CSNPs), no significant cytotoxic effects were observed, even at the highest tested dose, indicating the protective effect conferred by chitosan encapsulation (20). Similarly, Haitao Yu et al. demonstrated that microcin J25 peptides delivered via chitosan nanoparticles did not cause cytotoxicity in either HEK293T or Caco-2 cells at any concentration, further confirming the biocompatibility and low toxicity of chitosan-based nanocarriers (21).

Therefore, these findings support that TPF-loaded CSNPs are a promising nanomedicine candidate for MRSA treatment. Future research should focus on in vivo validation, elucidating antibacterial mechanisms, and advancing clinical development.

5. Conclusion

TPF-loaded chitosan nanoparticles were successfully prepared with suitable size, narrow distribution, and positive surface charge, confirming good colloidal stability and effective peptide encapsulation. These nanoparticles demonstrated enhanced antibacterial activity against MRSA compared to CSNPs alone or free TPF peptide. Cytotoxicity tests showed good biocompatibility with human epithelial cells at effective antibacterial concentrations. Overall, TPF-loaded CSNPs represent a promising and safe therapeutic approach for treating MRSA infections, warranting further *in vivo* and mechanistic studies.

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Metal-organic framework composite hydrogel sorbent beads for miniaturized dispersive solid-phase extraction of phthalate esters in micellar cleansing water

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Abstract

An iron-based metal–organic framework (MIL-100) incorporated into alginate hydrogel was developed as composite sorbent beads for miniaturized dispersive solid-phase extraction (dSPE) of phthalate esters. The fabricated sorbent was characterized, extraction parameters were optimized, and analytes were quantified using high-performance liquid chromatography (HPLC). MIL-100 facilitated enhanced adsorption of phthalate esters via π – π stacking and hydrophobic interactions. Under optimized conditions, the method exhibited good linearity in the ranges of 0.20–50 $\mu\text{g L}^{-1}$ for benzyl butyl phthalate and 0.50–50 $\mu\text{g L}^{-1}$ for dibutyl phthalate, di-2-ethylhexyl phthalate and di-n-octyl phthalate, with limits of detection between 0.05 and 0.20 $\mu\text{g L}^{-1}$. The method achieved satisfactory recoveries ranging from 91.1% - 96.9% with relative standard deviations below 5% in micellar cleansing water samples. The sorbent beads were simple to prepare, and the vortex-assisted extraction format provided a convenient and efficient approach for trace-level phthalate analysis.

Keywords: Phthalate esters, micellar cleansing water, dispersive solid-phase extraction, HPLC-DAD

1. Introduction

Phthalate esters (PAEs) are synthetic compounds widely employed as plasticizers in cosmetic packaging materials, particularly polyethylene terephthalate (PET) and low-density polyethylene (LDPE). As these additives are not covalently bound to the polymer matrix, they are susceptible to migration into cosmetic formulations over time. This poses significant concern for products stored in plastic containers such as micellar cleansing waters that are applied directly to the skin and used frequently. Recent studies have confirmed that residual PAEs, including dibutyl phthalate (DBP), di-2-ethylhexyl phthalate (DEHP) and benzyl butyl phthalate (BBP) can leach from packaging into aqueous cosmetic products, presenting a risk of dermal exposure [1].

Upon skin contact, especially in the presence of surfactants common in cleansing formulations, these compounds can penetrate the epidermal barrier. This is particularly concerning given that PAEs are known endocrine disruptors linked to hormonal imbalances, reproductive toxicity, and immune dysfunction [2]. Several sensitive analytical methods have been developed to detect PAEs leaching from packaging, verifying their presence under simulated cosmetic conditions [3, 4]. These findings highlight the critical need to monitor phthalate contamination in both cosmetic ingredients and packaging, which may represent a concealed source of consumer exposure. For formulations designed for sensitive or disease-prone skin, such as micellar cleansing water, it is essential that

packaging materials do not contribute to phthalate contamination. Ensuring product safety and therapeutic efficacy requires strict adherence to regulations like EU Regulation (EC) No. 1223/2009, which prohibits several phthalates in cosmetic products. Utilizing phthalate-free packaging and conducting routine migration testing are effective strategies to mitigate health risks and bolster consumer trust [5].

Recent advancements in sample preparation have facilitated the development of a hyper-crosslinked polymer–alginate hydrogel composite sorbent, synthesized via microwave-assisted polymerization, for dispersive solid-phase extraction (dSPE) of PAEs from PET and LDPE packaging [6]. This substance allows for rapid and selective extraction of BBP, DBP, DEHP, and DNOP from cosmetic simulants. Quantification by high-performance liquid chromatography with diode array detection (HPLC-DAD) demonstrated excellent linearity ($R^2 > 0.999$), low limits of detection (0.05–0.15 $\mu\text{g/L}$), and good recoveries between 90.0 and 100.6%. The method showed strong repeatability and reusability over 11 cycles, supporting its viability for routine phthalate monitoring.

Additional studies affirm the reliability of dSPE-HPLC-DAD for phthalate analysis. For instance, magnetic solid-phase extraction coupled with HPLC-DAD has been applied to detect PAEs in edible oils, achieving detection limits as low as 0.55 $\mu\text{g/kg}$ [7]. Similarly, hollow fiber microextraction integrated with HPLC-DAD has proven effective for trace PAE detection in environmental samples, demonstrating significant enrichment and precision [8].

Despite the widespread use of traditional solid-phase extraction (SPE) in contamination analysis, it suffers from limitations such as poor selectivity, clogging, and limited reusability [9, 10]. These drawbacks compromise analytical accuracy and increase operational costs, especially in cosmetic safety testing.

To overcome these challenges, researchers have explored advanced sorbent materials, including metal-organic frameworks (MOFs) integrated into hydrogel matrices. MIL-100, an iron-based MOF with high surface area, tunable porosity, and strong affinity for PAEs through $\pi - \pi$ and hydrophobic interactions [11]. Additionally, the MIL-100 can be synthesized under mild conditions using a nontoxic precursor [12].

In this study, MIL-100 was synthesized and incorporated into calcium alginate to fabricate MIL-100/hydrogel beads sorbent. The sorbent was characterized and employed in dSPE for the isolation of PAEs from micellar cleansing water samples. Target analytes were quantified using HPLC-DAD. Both sorbent fabrication and extraction conditions were systematically optimized. The method was validated and successfully applied to the quantification of PAEs in real cosmetic samples.

2. Materials and Methods

2.1 Chemicals and materials

Standard benzyl butyl phthalate (BBP), dibutyl phthalate (DBP), di-2-ethylhexyl phthalate (DEHP), di-n-octyl phthalate (DNOP) and 1,3,5-Benzenetricarboxylic acid (BTC) were purchased from Tokyo Chemical Industry (Tokyo, Japan). Alginic acid and iron (III) nitrate ($\text{Fe}(\text{NO}_3)_3$) were sourced from Sigma-Aldrich (Steinheim, USA). Calcium chloride (CaCl_2) and hydrochloric acid were obtained from Merck (Darmstadt, Germany). Sodium hydroxide (NaOH) was supplied by ChemSupply (Gillman, Australia). Solvents, including acetone, dichloroethane, methanol, ethanol, ethyl acetate, and acetonitrile, were from RCI Labscan (Bangkok, Thailand). Standard solutions at varying concentrations were prepared by a serial dilution of stock solutions using acetonitrile as the solvent.

2.2 Instruments and chromatographic conditions

Materials characterization is included. Fourier transform infrared spectrometry (FTIR, BX FTIR) and scanning electron microscopy (SEM) utilizing the X-max 150 system from Oxford Instruments, UK. Analysis of PAEs was conducted using a ThermoScientific UltiMateTM 3000 HPLC system (USA) with a C18 column (4.6 x 150 mm, 5.0 μ m particle size; Fortis Technologies, UK). The chromatographic separation utilized a gradient elution with acetonitrile and water as the mobile phase, adapted from prior research [6, 13], as detailed below: The mobile phase comprised 90% acetonitrile from 0 to 6 minutes, increasing linearly to 100% from 6 to 8 minutes, maintained at 100% from 8 to 20 minutes, and returning to 90% between 20 and 30 minutes. The flow rate was sustained at 1.0 mL min⁻¹. Detection utilized a diode array detector (DAD) calibrated to a wavelength of 226 nm. The injection volume of the sample was 20 μ L.

2.3 Preparation of the MIL-100/hydrogel beads sorbent

To synthesize MIL-100 under the hydrothermal method according to the previous method [12], 5.00 g of Fe(NO₃)₃ and 2.50 g of BTC were dissolved in 60 mL of deionized water and then combined in a Teflon-lined stainless-steel vessel. The vessel was sealed, and hydrothermal synthesis was performed at 180°C for a duration of 12 h. The MIL-100 product was subjected to filtration, followed by two washes with methanol and deionized water, and then dried using microwave irradiation at 500 W for 30 minutes. **Figure 1a** depicts the preparation procedure of MIL-100. The MIL-100/hydrogel beads sorbent was prepared by modifying from previous work [14] by dispersing 2.00 g of the synthesized MWHCP into 200 mL of a 2.0% (w/v) sodium alginate solution, employing ultrasonication for 30 minutes to ensure homogeneity. The suspension was then loaded into a syringe and

added dropwise to 200 mL of a 5.0% (w/v) CaCl₂ solution. The process led to the swift formation of hydrogel beads, with MIL-100 encapsulated in the alginate matrix. **Figure 1b** provides a schematic representation of the sorbent preparation process.

2.4 Extraction procedure

500 mg of the MIL-100/hydrogel beads sorbent was introduced into a tube containing 10.0 mL of sample solution. The mixture underwent vortex agitation at 1,000 rpm for 5 minutes to enhance adsorption. Subsequently, the sorbent was isolated by gently removing the supernatant with a syringe fitted with a needle. For desorption, 1,000 μ L of acetonitrile was added directly to the same tube, which was subsequently agitated at 1,000 rpm for 5 minutes. The eluate was filtered, placed into a sample vial, and examined via the HPLC system.

2.5 Real sample analysis

Micellar cleansing water samples were obtained from local retailers and stored in low-density polyethylene (LDPE) containers. A recovery study was performed to assess the accuracy of the method developed for quantifying PAEs. This process included the fortification of samples using standard solutions at three distinct concentration levels. The relative recovery was calculated using the following formula: Recovery is determined by the formula

$$\frac{CF - CR}{CA} \times 100 \quad (1)$$

Where *CF* is the concentration measured in the spiked sample, *CR* is the concentration detected in the unspiked sample and *CA* is the concentration of the spiked standard. Mean recovery values were obtained from three independent replicates.

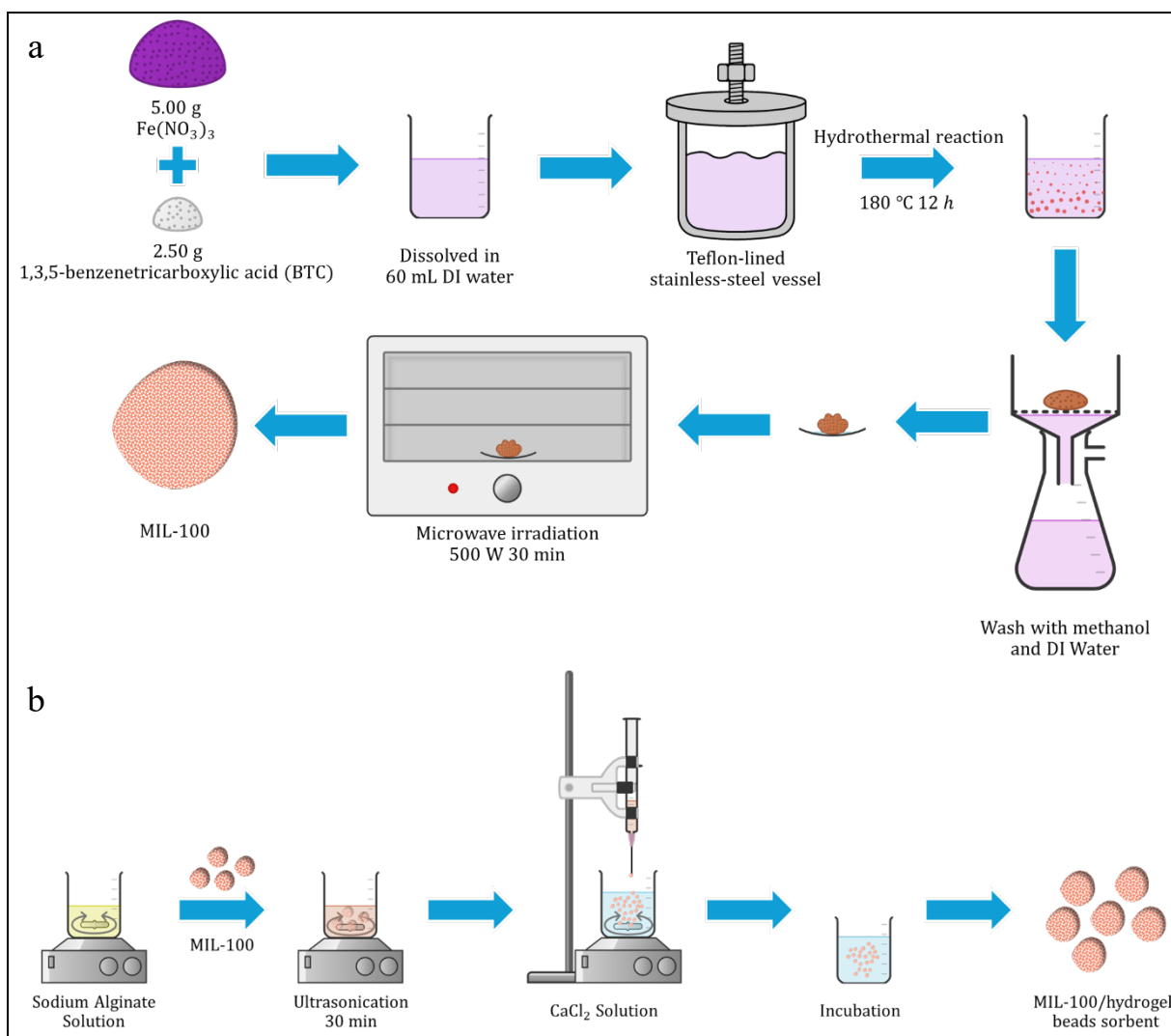


Figure 1 Schematic representations of (a) the preparation procedure of MIL-100 and (b) the MIL-100/hydrogel beads sorbent preparation

3. Results & discussion

3.1 Characterization

The FTIR spectrum of the alginate hydrogel (**Figure 2a**) displays a broad band at 3434 cm^{-1} , attributed to O–H stretching, and peaks at 1633 , 1432 , and 1022 cm^{-1} , corresponding to C=O, C–H, and C–O stretching vibrations, respectively. The FTIR spectrum of MIL-100 (**Figure 2b**) exhibits absorption bands characteristic of dicarboxylic and aromatic functional groups. Peaks at 1350 cm^{-1} and 1620 cm^{-1} are attributed to C–O and C=C stretching vibrations of dicarboxylates, while bands at 710 cm^{-1} and 760 cm^{-1} correspond to C–H

stretching of the benzene ring. The FTIR spectrum of the MIL-100/hydrogel beads sorbent (**Figure 2c**) shows an overlapping band at 3434 cm^{-1} , resulting from the combined O–H stretching vibrations of both alginate hydrogel and MIL-100. The presence of characteristic peaks from both components confirms the successful incorporation of MIL-100 into the alginate hydrogel.

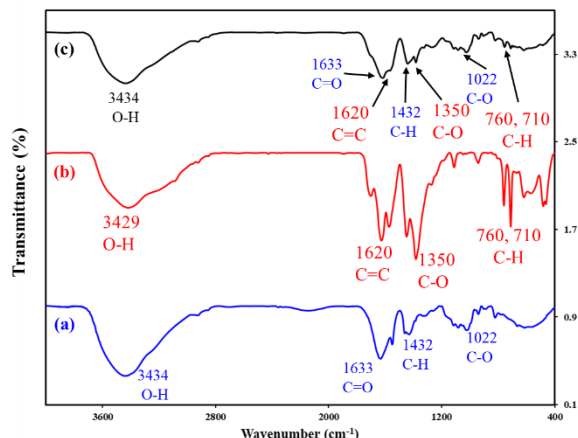


Figure 2 FTIR spectra of alginate hydrogel (a), MIL-100 (b) and MIL-100/hydrogel beads sorbent. (c)

A photograph of the alginate hydrogel beads and MIL-100/hydrogel beads sorbent is shown in **Figure 3a** and **Figure 3d**,

respectively. The average diameter of the beads was 2.0 ± 0.1 mm. SEM was employed to investigate the surface morphology of the materials. SEM images of the alginate hydrogel beads at different magnifications are presented in **Figure 3b-c**. Notably, **Figure 3c** reveals a relatively smooth surface. In contrast, SEM images of the MIL-100/hydrogel beads sorbent at different magnifications are shown in **Figures 3e-f**. **Figure 3f** demonstrates a much rougher surface morphology, and the inset highlights the characteristic octahedral structure of MIL-100 [15]. These observations confirm the successful incorporation of MIL-100 into the alginate hydrogel.

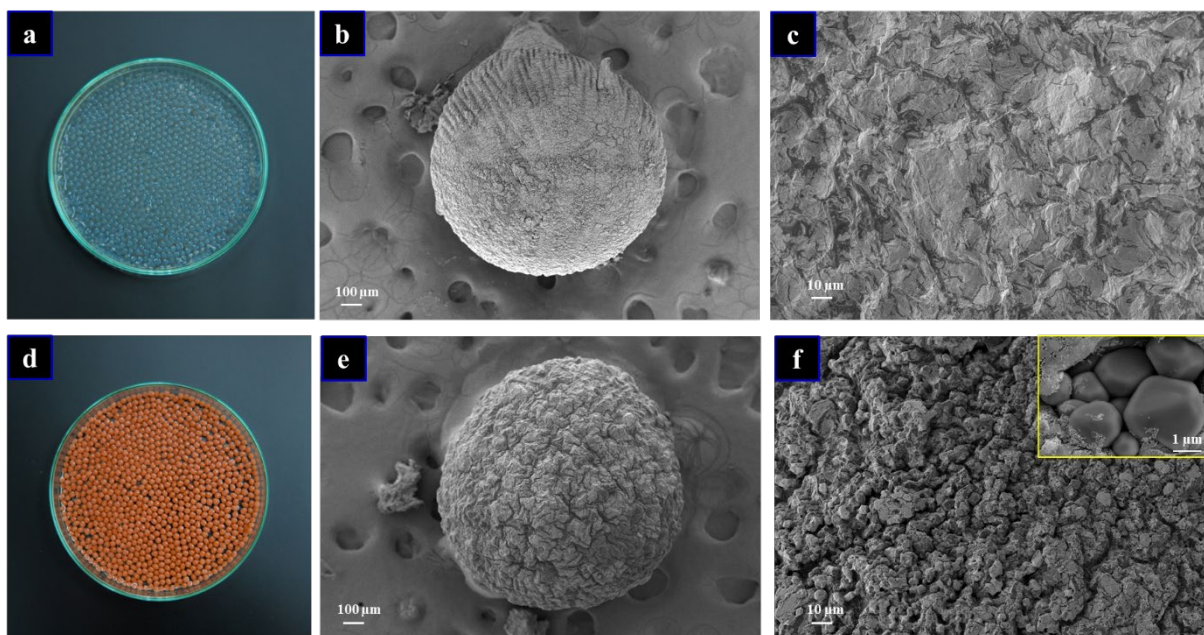


Figure 3 Photographs of alginate hydrogel beads (a), SEM images of alginate hydrogel beads at $\times 50$ and $\times 500$ magnifications (b, c), a photograph of MIL-100/hydrogel beads sorbent (d), and SEM images of MIL-100/hydrogel beads sorbent at $\times 50$ and $\times 500$ magnifications (e, f). Inset (f) shows a magnification of $\times 20,000$.

3.2 Optimization

3.2.1 Amount of MIL-100/hydrogel beads sorbent

The amount of MIL-100/hydrogel beads sorbent markedly affects the extraction efficiency of PAEs. **Figure 4a** demonstrates that increasing the sorbent mass from 250 mg to 500 mg markedly improved recoveries for all analytes. Increasing the dosage to 750 mg resulted in only minimal improvement, suggesting possible saturation of the sorbent surface. Thus, 500 mg was identified as the optimal quantity of sorbent for effective extraction while reducing material usage.

3.2.2 Vortex speed

The velocity of vortex agitation influences the rate of mass transfer and the dispersion of sorbent [16]. **Figure 4b** indicates that recoveries improved as the speed increased from 800 to 1000 rpm. This indicates a greater interaction between the sorbent and the analytes. At 1200 rpm, recovery decreased marginally, likely due to turbulent flow hindering interactions. A speed of 1000 rpm was determined to be optimal for dispersion.

3.2.3 Desorption solvent

The efficiency of analyte desorption from the sorbent was assessed using methanol, acetonitrile, and acetone. **Figure 4c** demonstrates that acetonitrile achieved the highest recoveries for all PAEs, surpassing both methanol and acetone. This advantage is due to its intermediate polarity and enhanced solvation capacity, which effectively disrupted interactions between the analyte and the sorbent. Therefore, acetonitrile was identified as the most suitable elution solvent.

3.2.4 Extraction time

The impact of extraction duration on recovery was evaluated at 2.0, 5.0, and 10.0 minutes. **Figure 4d** illustrates that maximum recoveries for all analytes were attained at 5.0 minutes, with no substantial improvement

observed at extended durations. This suggests that adsorption equilibrium was reached [17] in 5.0 minutes. Consequently, 5.0 minutes was determined to be the optimal extraction time to achieve a balance between efficiency and throughput.

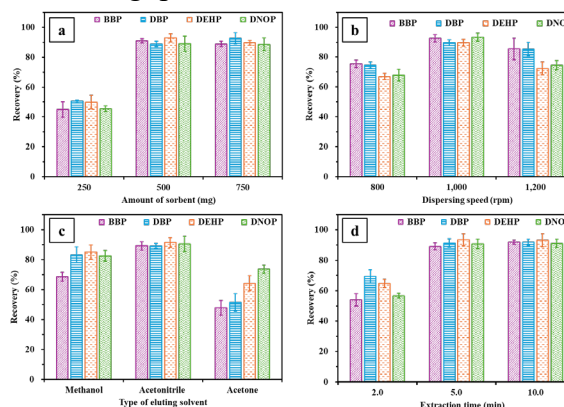


Figure 4 Influence of sorbent amount (a), dispersing speed (b), type of eluting solvent (c), and extraction time (d) on the extraction recoveries of PAEs.

3.3 Analytical performances

The analytical performance of miniaturized dispersive solid-phase extraction using MIL-100/hydrogel beads as a sorbent for the extraction of PAEs was assessed under optimized conditions, as detailed in **Table 1**, prior to determination by HPLC-DAD. The linear ranges were 0.20 to 50 $\mu\text{g L}^{-1}$ for BBP and 0.5 to 50 $\mu\text{g L}^{-1}$ for DBP, DEHP, and DNOP, with coefficients of determination (R^2) greater than 0.9970 for all analytes. Limits of detection (LODs), established at a signal-to-noise ratio of 3, were between 0.05 and 0.20 $\mu\text{g L}^{-1}$. Conversely, limits of quantification (LOQs), assessed at a signal-to-noise ratio of 10, ranged from 0.20 to 0.50 $\mu\text{g L}^{-1}$. Intra-day precision was assessed through experiments ($n=3$), resulting in relative standard deviations (RSDs) ranging from 3.1% to 4.4%, indicating high repeatability.

Table 1 The analytical performances of the MIL-100/hydrogel beads sorbent for the extraction of PAEs for determination by HPLC-DAD.

Analytes	Linear range	Equation	R ²	LOD (µg L ⁻¹)	LOQ (µg L ⁻¹)	Precision (%RSD)
BBP	0.20-50	y = 6.24x + 5.62	0.9970	0.05	0.20	3.6
DBP	0.50-50	y = 1.76x + 2.28	0.9982	0.20	0.50	4.4
DEHP	0.50-50	y = 1.14x + 0.36	0.9997	0.20	0.50	3.3
DNOP	0.50-50	y = 1.12x + 0.72	0.9989	0.20	0.50	3.1

3.4 Real sample analysis

Analysis of PAEs in real samples

The established method was utilized for the extraction and quantification of PAEs in samples of micellar cleansing water. PAEs concentrations were below the limit of quantification in both samples. The recoveries of PAEs, achieved by spiking standard solutions at concentrations of 2.0 µg L⁻¹ into

real sample solutions, varied from 91.1% to 96.9%, with relative standard deviations (RSDs) between 1.8% and 4.4% in **Table 2**. This confirms the reliability of the proposed method utilizing MIL-100/hydrogel beads as a sorbent for miniaturized dSPE coupled with high-performance liquid chromatography with diode-array detection (HPLC-DAD).

Table 2 Recoveries of extracted PAEs in micellar cleansing water samples using the MIL-101/hydrogel beads sorbent

Phthalates esters	Recovery (%)	
	Sample 1	Sample 2
BBP	92.3 ± 3.1	91.1 ± 4.4
DBP	92.1 ± 2.4	96.7 ± 3.0
DEHP	96.9 ± 1.8	93.9 ± 2.3
DNOP	94.3 ± 2.2	94.5 ± 3.6

4. Conclusion

The sorbent beads based on a MIL-100–alginate hydrogel composite were successfully fabricated and applied for miniaturized dispersive solid-phase extraction of phthalate esters using vortex-assisted extraction. The extracted analytes were quantified by HPLC with diode array detection, achieving satisfactory recoveries ranging from 91–97%, low detection limits, and good precision. The sorbent beads were easy to prepare, and the vortex-assisted format offered a rapid and efficient method for trace-level phthalate analysis. This approach demonstrates strong potential for adaptation to other target compounds in personal care products through modifications to the sorbent fabrication strategy.

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Effects of Water Deficiency on Phenolic, Flavonoid Contents and Lupeol and Antioxidant Activity in Snake Grass (*Clinacanthus nutans* (Burm.f.) Lindau) Leaves

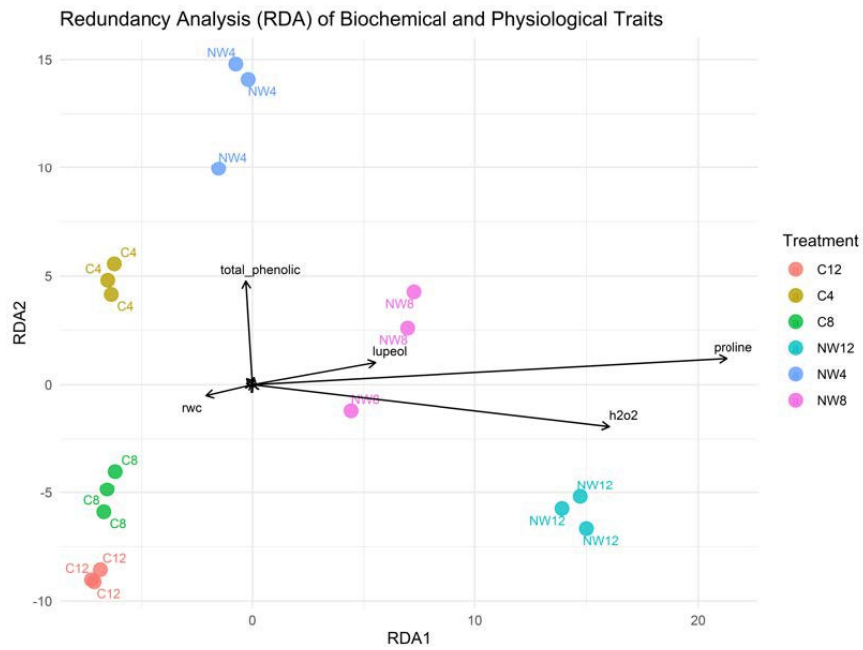
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Abstract

Clinacanthus nutans is a medicinal plant widely recognized for its antioxidant, anti-inflammatory, and antiviral properties. Drought is a critical abiotic stress that affects plant physiology and the biosynthesis of secondary metabolites. This study aimed to investigate the physiological and biochemical responses of *C. nutans* under drought conditions, focusing on survival rate, oxidative stress markers, and antioxidant-related compounds. Seedlings were pretreated with 500 ppm indole-3-butyric acid (IBA) to promote root development and subsequently subjected to water deprivation for 4, 8, 12, 16, and 20 days. The results showed that IBA significantly enhanced root and leaf formation, which contributed to increased drought resilience in the early phase. Relative water content (RWC) and chlorophyll levels decreased with longer drought duration, while hydrogen peroxide (H₂O₂) and proline content increased, indicating oxidative and osmotic stress. Antioxidant activity, measured by DPPH, ABTS, and FRAP assays, peaked at day 4–8 under drought stress and positively correlated with phenolic and flavonoid content, particularly schaftoside. Triterpenoid lupeol was also significantly accumulated under drought. These findings suggest that short- to moderate-term drought can stimulate the accumulation of bioactive compounds in *C. nutans*, but prolonged stress reduces biosynthetic potential and plant survival. This research provides valuable insight for enhancing the quality of medicinal plants grown under limited water conditions and supports the development of drought-adaptive cultivation strategies.

Keywords: *Clinacanthus nutans*, drought stress, antioxidant activity, phenolic compounds, schaftoside, lupeol



Redundancy analysis (RDA) showing relationships between biochemical and physiological traits in *Clinacanthus nutans* leaves under control (C) and drought (NW) conditions at 4, 8, and 12 days. Replicates are color-coded by treatment. NW12 correlated with H₂O₂ and proline, while NW4 and NW8 associated with total phenolics, flavonoids, schaftoside, and lupeol, indicating varied responses to drought severity.

Characterization of pectin-based biopolymer film from orange, lime, and pomelo peels of citrus agro-industrial waste

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Abstract

This study develops and characterizes pectin-based biopolymer films from citrus agro-industrial wastes specifically orange, lime, and pomelo peels. Pectin was extracted using hot acid extraction, and the resulting films were cast and evaluated for their functional and structural properties. Film thickness ranged from 0.32 to 1.20 mm, with elongation at break of 20–25%. Tensile strength varied from 0.06 to 0.60 MPa, and all films exhibited good optical properties. Water solubility was 49.10% (orange), 50.47% (lime), and 40.86% (pomelo). FTIR analysis confirmed the presence of key pectin functional groups. Pomelo peels yielded the highest pectin content but produced films with the lowest tensile strength. In contrast, lime-based films had the highest tensile strength, while pomelo-based films had the lowest solubility. These films show potential for eco-friendly packaging applications due to their mechanical and barrier properties. Utilizing citrus waste offers a low-cost, biodegradable alternative to synthetic packaging while promoting environmental sustainability. Future research should explore improving shelf life and production scalability for commercial use in biodegradable packaging.

Keywords: biopolymer; pectin ; agro-industrial waste; citrus peel; biodegradable packaging

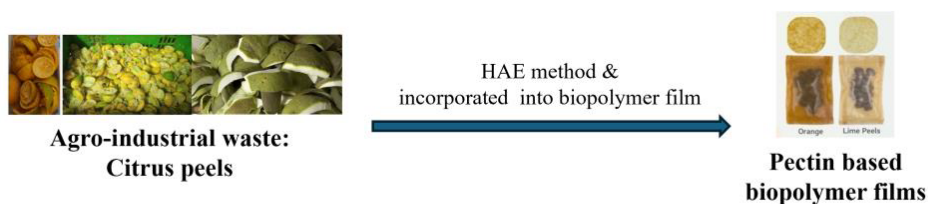


Figure 1 Concept of this research

Parameters	Biopolymer Films		
	Lime Peels	Orange Peels	Pomelo Peels
Thickness (mm)	0.82 ± 0.09 ^b	0.32 ± 0.02 ^c	1.20 ± 0.24 ^a
Color L*	79.47 ± 1.07 ^a	72.12 ± 0.94 ^b	80.12 ± 0.66 ^a
Color a*	-0.19 ± 0.01 ^b	3.36 ± 0.50 ^a	-0.10 ± 0.34 ^b
Color b*	22.37 ± 0.58 ^b	44.19 ± 0.50 ^a	22.30 ± 0.35 ^b
Water Solubility (%)	50.47 ± 2.28 ^a	49.10 ± 6.87 ^{ab}	40.86 ± 2.79 ^b
Elongation at Break (%)	23.57 ± 0.57 ^a	22.89 ± 0.23 ^a	21.45 ± 0.06 ^b
Tensile Strength (MPa)	0.59 ± 0.01 ^a	0.19 ± 0.01 ^b	0.07 ± 0.00 ^c

Table 1 Physical and mechanical properties of biopolymer films from citrus peels.

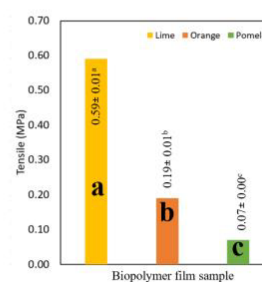


Figure 2 Tensile strength



Transforming Indoor Hygiene: How Sparking Technology Enhances Antimicrobial Wallpaper Effectiveness

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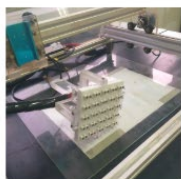
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Abstract

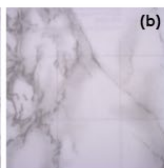
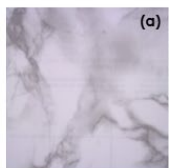
This research aims to enhance the antimicrobial function of wallpaper by introducing titanium dioxide (TiO₂) to its surface using a solvent-free sparking technology. The nanoparticles of TiO₂ were deposited on the polyvinyl chloride (PVC) wallpaper surface through 15 to 60 sparking cycles. Surface characteristics of the sparked wallpaper were investigated *via* water contact angle and antibacterial activity. The sparking method to deposit TiO₂ nanoparticles onto wallpaper surfaces increased water contact angles, indicating improved waterproofing. The antibacterial activities of the sparked wallpaper against *Staphylococcus aureus* and *Escherichia coli* were determined by artificially inoculating the target bacteria on the surface and using the swabbing technique to enumerate the survival numbers. LIVE/DEAD® BacLight™ staining confirmed bacterial viability with fluorescence microscopy. The TiO₂-deposited wallpaper with 60 cycles showed the most potent antibacterial activity against *E. coli*, reducing it by 93% within 30 min and by 99% within 24 h, and at the same time, reducing *S. aureus* by 63.7% within 24 h. The findings indicate that the sparking method offers a practical and eco-friendly solution for improving the waterproofing and antibacterial characteristics of wallpapers, thereby contributing to enhanced indoor hygiene.

Keywords: antibacterial activity; sparking technology; titanium dioxide; wallpapers; waterproofing

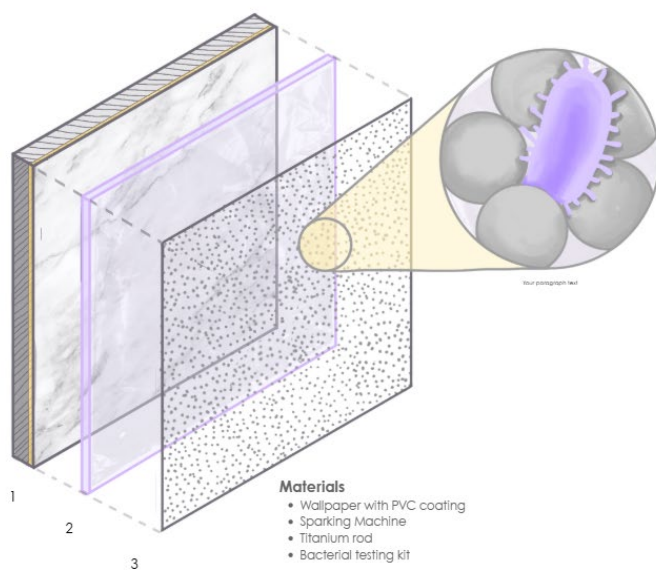
Transforming Indoor Hygiene: How Sparking Technology Enhances Antimicrobial Wallpaper Effectiveness



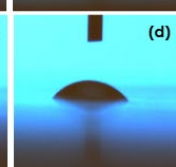
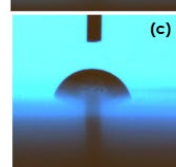
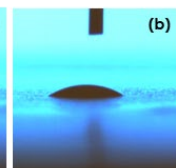
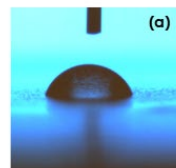
The sparking method is to let electricity reach the end of the titanium rod to create TiO₂ nanoparticles and deposit them on the surface.



The (a) untreated wallpaper (control) and (b) TiO₂ deposited wallpaper have the same appearance, so the sparking method did not change the appearance or texture of the surface.



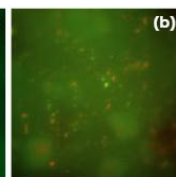
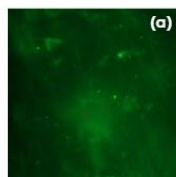
1. Paper-based wallpaper has beautiful patterns and designs that are easy to apply.
2. PVC coating is easy to clean, water resistant, and maintain.
3. TiO₂ nanoparticles deposited from the sparking method increase the waterproofing and antimicrobial properties of wallpapers.



Water dynamic contact angle of untreated wallpaper at (a) 0 sec and (b) 25 min, and TiO₂ deposited wallpaper at (c) 0 sec and (d) 25 min. These pictures prove that TiO₂-deposited wallpaper increases waterproof property.

A table shows the percentages of bacterial reduction of the TiO₂-deposited wallpapers with 30 and 60 cycles after the bacterial cells were contacted for 30 min and 24 h.

Sparking cycles	E. coli		S. aureus	
	30-min	24-h	30-min	24-h
30X	79.8	97.3	38.9	56.3
60X	93.2	99.2	38.7	63.8



Fluorescence microscopy of live/dead-stained *Staphylococcus aureus* cells on the surface of (a) wallpaper, showing living cells of most *S. aureus* cells on the wallpaper surfaces (fluorescent green), and (b) TiO₂-deposited wallpaper for 60 cycles, showing an increase in dead cells (fluorescent red).



Extraction of Proteins from *Moringa oleifera* Seed using Novel-Assisted Technologies: Composition, Techno-functions and Digestibility

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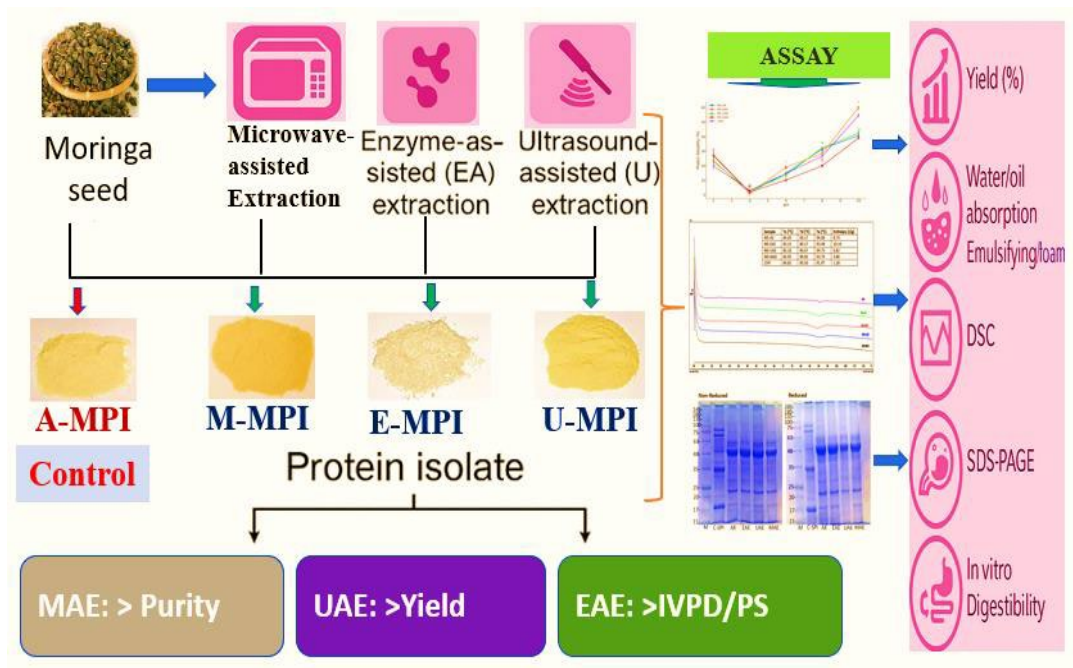
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Abstract

Moringa oleifera seeds are rich in protein, yet their potential as plant-based protein in food remains underutilized. This study evaluated the extraction efficiency of moringa seed protein isolate (MPI) using enzyme-assisted (EAE), ultrasonic-assisted (UAE), and microwave-assisted extraction (MAE) methods. EAE was performed with viscozyme (2%, pH 8, 50 °C, 2 h) and papain (1%, pH 7, 50 °C, 1 h), UAE, at 40% amplitude, (20 kHz, 20 min), and MAE at 800 W, (50 °C, 90 s). All extraction methods significantly improved protein yield (14.60–30.08%), and purity (80.47–86.61%), with UAE recording the highest yield. Protein solubility (40.78–60.09% at pH 10), and functional properties also improved. EAE gave MPI with the highest solubility, while MAE slightly reduced solubility compared to control. Phytates (0.83–0.49 g/100 g) and trypsin inhibitor activity (4.48–1.92 U/mg), were decreased ($p < 0.05$). Yellowness increased (39.22–46.48), while lightness reduced, except for EAE. SDS-PAGE showed major protein bands at 17, 25, 48–63 kDa, in non-reducing condition. EAE showed reduced intensity at ~63 kDa, suggesting partial hydrolysis. In vitro protein digestibility (IVPD) improved ($p < 0.05$) (88.11–93.81%), with EAE recording the maximum IVPD comparable to commercial soy protein. The hydrolysis patterns by SDS-PAGE corroborated these findings. Structural modifications were indicated by altered surface hydrophobicity and thermal stability using differential scanning calorimeter. Scanning electron microscopy revealed fragmented, porous structures, supporting enhanced cell wall disruption. While UAE and MAE achieved high protein yield and purity, EAE offered the best balance of functionality and digestibility, making it the most promising method for producing high-quality MPI for potential food applications.

Keywords: Novel-assisted extraction, plant-based protein, moringa seed, digestibility, functional properties





Development of a credit bank transfer model using SMART Model to promote environmental innovator skills

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Abstract

The current generation of youth often lacks awareness and practical skills in energy conservation and environmental preservation. To address this, the credit bank system—a model based on accumulating academic credits for further education—was adopted by Nakornluang “Udomratwitthaya” School as part of its industrial and business study program. This research aimed to develop a credit transfer model based on the SMART Model to foster environmental innovator skills. The objectives were: 1) to study foundational data, 2) to develop the model, 3) to implement it, and 4) to evaluate its effectiveness. The target group consisted of 45 students in Grade 10 (Science-Industry track) and their 45 guardians. This research and development study utilized three tools: the model itself, student satisfaction surveys, and parent satisfaction surveys.

The findings revealed the following:

1. Foundational data showed that the SMART Model is a viable mechanism to sustainably support credit banking and promote environmental innovation skills. Both students and parents expressed strong support for the model’s development.
2. The SMART Model comprises:
 - S: Skill – Enhancing diverse learning skills aligned with 21st-century competencies
 - M: Module – Teacher-coached, unit-based learning
 - A: Accredited experience – Standardized recognition and assessment of student competencies
 - R: Royal word – Integration of principles from King Rama IX and X into national education development
 - T: Transferable credit – Completion of courses aligned with national curriculum.The model was rated highly in quality (mean = 4.85, SD = 0.25).
3. Implementation results showed academic performance averaged 68.22%, surpassing the 65% benchmark. Student satisfaction was very high (mean = 4.73, SD = 0.34), as was parental satisfaction (mean = 4.77, SD = 0.36).
4. Evaluation results ranked the model highest in usefulness (mean = 4.85), followed by accuracy (mean = 4.75), feasibility (mean = 4.75), and appropriateness (mean = 4.65).

Keywords: credit bank; credit transfer; innovator; environment; SMART Model

Green BIM Automation: A Dynamo-Based BOQ and Keynote Generator Linked to Thailand's Public Construction Cost Database

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Abstract

The construction industry is increasingly adopting digital tools to enhance sustainability, reduce waste, and optimize resource management. This research presents a green innovation through Building Information Modeling (BIM) by developing a Dynamo-based tool in Autodesk Revit. The tool automatically generates Keynotes and Bills of Quantities (BOQs) by linking model elements to Thailand's official construction cost database published by the Comptroller General's Department.

By utilizing MasterFormat coding as a standardized mapping system, the tool enables accurate material classification, automates quantity takeoff, and exports BOQ data into structured formats. This minimizes manual input errors, reduces redundant estimations, and supports cost-efficient and resource-conscious project planning. A pilot test on a residential BIM model demonstrated that the tool effectively categorizes BOQ items into structural, architectural, and MEP works with minimal human intervention.

This green BIM innovation promotes sustainability by enhancing digital accuracy in cost estimation, reducing material waste, and aligning construction practices with national standards. It supports Thailand's transition toward eco-conscious construction and lays the groundwork for integration with public procurement and green building certification systems.

Keywords: Building Information Modeling, Energy performance, Residential building, BIM simulation, Sustainable design

1. Introduction

In recent years, the construction industry has been undergoing a paradigm shift toward sustainability, driven by the urgent need to reduce environmental impact and optimize resource efficiency. Green Building Information Modeling (Green BIM) has emerged as a transformative approach that integrates environmental performance analysis with the digital design process. By embedding sustainability considerations into every stage of the building lifecycle, Green BIM enables stakeholders to make informed decisions that balance cost, performance, and ecological

responsibility.

One of the critical challenges in implementing Green BIM in Thailand lies in the integration of accurate cost data with sustainable design workflows. While conventional BIM tools can model building geometry and generate construction documents, the process of linking these models to standardized cost databases, such as the Thailand Public Construction Cost Database, often remains manual and time-consuming. This inefficiency not only delays decision-making but can also hinder the adoption of sustainable construction practices.

To address this gap, this research proposes an automated workflow that combines Autodesk Revit with Dynamo visual programming to generate Bill of Quantities (BOQ) and Keynote data directly from BIM models. The system links model elements to the Thailand Public Construction Cost Database using both **Uniformalt** and **MasterFormat** classification standards, ensuring accurate categorization of building components and alignment with international best practices. This integration aims to streamline the cost estimation process, reduce human error, and encourage the use of environmentally friendly materials through better-informed design choices.

1.1 Background and Significance of the Study

The construction industry plays a pivotal role in shaping urban environments but is also responsible for significant energy consumption, resource depletion, and greenhouse gas emissions. In response to the global call for sustainable development, the concept of **Green Building Information Modeling (Green BIM)** has emerged as a powerful approach for integrating environmental considerations into the building design and construction process.

In Thailand, efforts to adopt BIM have been steadily growing, but integrating sustainability assessment and standardized cost management remains a challenge. While BIM platforms such as Autodesk Revit can model complex building geometries, the process of linking these models to cost data from the **Thailand Public Construction Cost Database** is often manual, time-consuming, and prone to human error. This slows down the decision-making process and can limit the effectiveness of sustainable design strategies.

By creating an automated system that links Revit models with the national cost database through **Dynamo** visual programming, designers and contractors can access accurate, up-to-date cost and

environmental data in real time. This integration supports the selection of eco-friendly materials and energy-efficient design choices, aligning with the goals of Green Innovation for a Sustainable Future.

1.2 Problem Statement

Despite the rapid adoption of BIM in Thailand's construction industry, several key issues hinder the full realization of sustainable construction practices:

1.2.1 Manual BOQ and Keynote generation
Traditional methods require repetitive manual data entry, increasing the risk of inconsistencies and errors.

1.2.2 Lack of standardized classification
Without a unified classification system, such as Uniformalt and MasterFormat, it is difficult to ensure consistency between design models and cost data.

1.2.3 Delayed integration of sustainability metrics
Environmental performance considerations are often addressed late in the design phase, limiting their effectiveness.

1.2.4 Limited automation in linking BIM to national cost databases
Existing workflows require manual mapping between model elements and cost items, leading to inefficiencies.

These issues collectively slow down project delivery, increase costs, and reduce the potential environmental benefits of sustainable design.

1.3 Research Objectives

The objectives of this research are as follows:

1.3.1 To develop an automated workflow that links Autodesk Revit models with the Thailand Public Construction Cost Database using Dynamo.

1.3.2 To implement standardized classification systems (Uniformalt and MasterFormat) for consistent categorization of building components and materials.

1.3.3 To generate BOQ and Keynote data automatically from BIM models, reducing manual work and improving data accuracy.

1.3.4 To promote sustainable material selection by integrating environmental

considerations into the cost estimation process.

1.3.5 To contribute to the advancement of Green BIM as a tool for achieving Thailand's sustainable construction goals.

2. Literature Review

2.1 Green Building Information Modeling (Green BIM)

Green Building Information Modeling (Green BIM) is the integration of Building Information Modeling (BIM) processes with sustainable design principles to optimize environmental performance throughout the building life cycle. BIM enables the creation of 3D digital models containing comprehensive data on building geometry, materials, and systems, which can be analyzed for energy performance, carbon footprint, and resource efficiency.

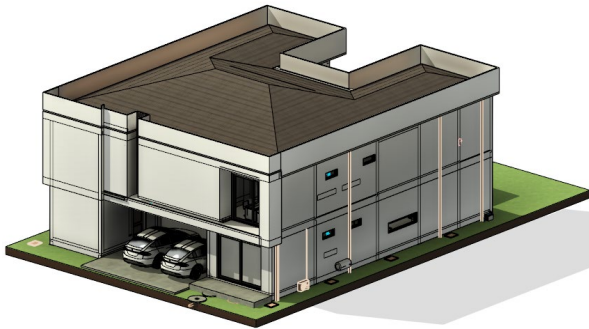


Figure 1. Residential Building Model

Several studies (Azhar et al., 2011; Wong & Zhou, 2015) have demonstrated that Green BIM facilitates early-stage sustainability assessments, enabling project teams to evaluate energy use, daylight availability, and material impacts before construction begins. In the context of Thailand, Green BIM adoption is still emerging, with key challenges including data standardization, cost database integration, and limited automation tools.

2.2 Dynamo for BIM Automation

Dynamo is a visual programming extension for Autodesk Revit that enables users to automate repetitive tasks, manipulate model data, and connect with external databases. By using Dynamo, complex operations—such as extracting quantities, generating Keynotes, or mapping model elements to cost items—can be performed with minimal manual intervention.

Research has shown that Dynamo can significantly reduce human error in BOQ generation (Alqadi & Alyami, 2020) and enhance interoperability between BIM models and external data sources. For sustainable construction, Dynamo can be used to link material databases with environmental performance metrics, allowing for real-time feedback during design.

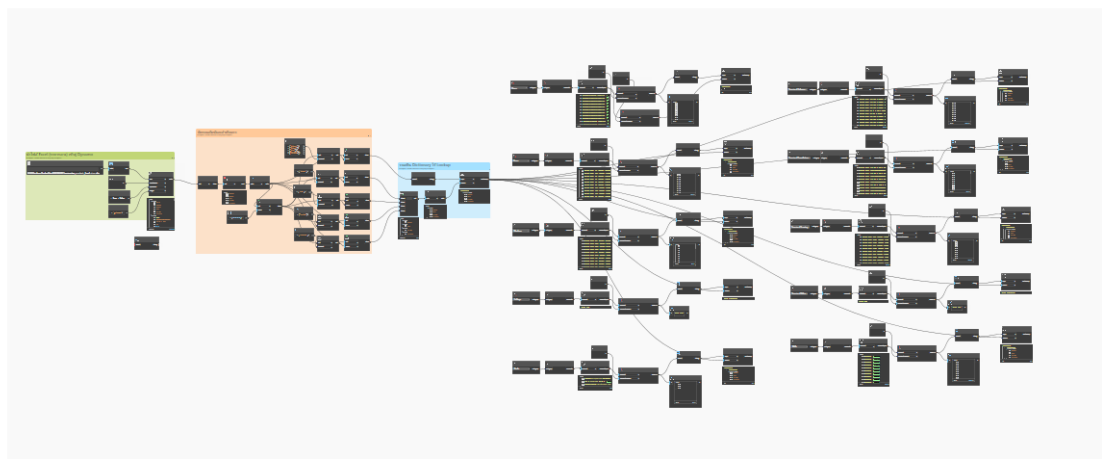


Figure 2. Dynamo script for BIM Automation

2.3 Thailand's Public Construction Cost Database

The Public Construction Cost Database, maintained by the Comptroller General's Department of Thailand, provides standardized cost information for construction materials, labor, and equipment. This database is a critical resource for ensuring cost transparency and consistency in public projects.

However, in current practice, linking this database to BIM models is often done manually. This requires mapping Revit elements to cost items individually, a process that is prone to inconsistencies. Automation using Dynamo can bridge this gap, enabling cost data to be retrieved and updated directly from the database in real time.

2.4 Unifomat Classification System

Unifomat is a hierarchical classification system for organizing building information based on functional elements rather than materials or methods. It categorizes components into major groups such as substructure, shell, interiors, services, and site work.

In BIM-based workflows, Unifomat facilitates early cost estimation and design decision-making by grouping elements according to their functional roles. For sustainable construction, this approach supports life cycle cost analysis and performance evaluation at the system level, enabling designers to assess trade-offs between different green design strategies.

Division 02 - งานสถาปัตยกรรม (ARCHITECTURAL WORK)				
LEVEL 1	LEVEL 2	LEVEL 3	CODE	DESCRIPTION
02	00	00	02.00.00	งานสถาปัตยกรรม (ARCHITECTURAL WORK)
02	01	00	02.01.00	งานสถาปัตยกรรมภายในอาคาร (Internal Architectural Work)
02	01	01	02.01.01	พื้นและบัวเชิงผนัง (Floor and base)
02	01	02	02.01.02	ผนัง (Partition)
02	01	03	02.01.03	ฝ้าเพดาน (Ceiling)
02	01	04	02.01.04	ประตูและหน้าต่าง (Doors and Windows)
02	01	05	02.01.05	บันได (Stair)
02	01	06	02.01.06	งานห้องน้ำ (Toilet work)
02	01	07	02.01.07	งานทาสี (Paint)
02	01	99	02.01.99	สำรอง (Reserved)
02	02	00	02.02.00	งานสถาปัตยกรรมภายนอกอาคาร (External Architectural Work)
02	02	01	02.02.01	พื้นและบัวเชิงผนัง (Floor and base)
02	02	02	02.02.02	เปลือกอาคาร (Facade)
02	02	03	02.02.03	ฝ้าเพดาน (Ceiling)

Figure 3. Unifomat Classification System table

2.5 MasterFormat Classification System

MasterFormat, developed by the Construction Specifications Institute (CSI), is a widely used standard for organizing construction specifications, cost data, and project information. Unlike Unifomat, MasterFormat categorizes information by materials, products, and activities (e.g., concrete, masonry, finishes, electrical).

Integrating MasterFormat into BIM workflows ensures that BOQ and Keynote data are consistently labeled and aligned with industry practices. When combined with Unifomat, the two systems provide a comprehensive framework—Unifomat for functional grouping and MasterFormat for detailed specification—that enhances accuracy in cost estimation and sustainability assessment.

Division 03 - Division 3 - Concrete (งานคอนกรีต)				
LEVEL 1	LEVEL 2	LEVEL 3	CODE	DESCRIPTION
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03	050	00	0305000	Basic Concrete Materials and Methods (วัสดุพื้นฐาน งานคอนกรีต และวิธีการ)
03	050	01	0305001	คอนกรีตผสมเสร็จ
03	050	02	0305002	คอนกรีตผสมเสร็จ + ผสมน้ำยากันซึม
03	050	03	0305003	ปูนซีเมนต์ปอร์ตแลนด์
03	050	04	0305004	ทราย
03	050	05	0305005	หิน
03	050	90	0305090	ส่วนผสมคอนกรีตอื่นๆ
03	050	99	0305099	ค่าแรงงานคอนกรีต
03	100	00	0310000	Concrete Forms and Accessories (ไม้แบบคอนกรีตและอุปกรณ์ประกอบ)
03	100	01	0310001	ไม้คร่าวหรือไม้ค้ำยัน

Figure 4. Masterformat Classification System table

2.6 Integration of Classification Systems, BIM, and Sustainability

The combination of BIM, Unifomat, and MasterFormat provides a structured approach to managing building data from conceptual design to detailed documentation. When these systems are integrated with a national cost database through Dynamo, the result is an automated, standardized workflow that:

1. Improves accuracy in BOQ generation
2. Reduces repetitive manual data entry
3. Facilitates sustainable material selection
4. Aligns cost and environmental performance data with industry standards

This integration directly supports the Green Innovation for a Sustainable Future theme by ensuring that environmental considerations and cost efficiency are embedded into the design process from the outset.

3. Research Methodology

This study adopted a structured and iterative research methodology, integrating Building Information Modeling (BIM) with computational automation using Autodesk Revit and Dynamo. The methodological framework was designed to ensure replicability, scalability, and alignment with green innovation principles in the construction industry.

The workflow was divided into **five major phases**, each consisting of multiple sub-processes, to achieve the primary objective: the automated generation of Bill of Quantities (BOQ) and Keynotes linked to Thailand's Public Construction Cost Database.

3.1 Research Framework

The research methodology was based on a **Design Science Research (DSR)** approach, emphasizing problem identification, solution design, and iterative refinement. The workflow was guided by three main pillars:

1. **Data Integrity** – Ensuring that cost and material data are accurate, standardized, and compatible with Thailand's public database.
2. **Process Automation** Minimizing manual intervention by leveraging Dynamo's visual programming environment to process BIM data in real-time.
3. **Sustainability Alignment** – Ensuring that material selection and cost estimation processes integrate environmental impact metrics (e.g., embodied carbon, recyclability) to support green construction practices.

3.2 Workflow Overview

The proposed methodology consists of five main phases (Figure 5).

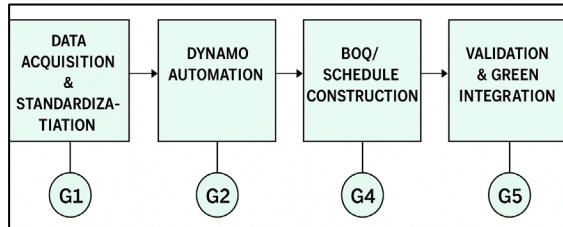


Figure 5. Workflow of the Proposed Methodology

Phase 1: Data Acquisition and Standardization (G1)

1. Collection of construction material data from the **Thailand Public Construction Cost Database**.

2. Mapping of cost codes according to **UniFormatII** for functional classification and **MasterFormat 2020** for tradespecific categorization.
3. Data cleaning, removing redundancies, and ensuring compatibility with Revit's keynote file format.

Phase 2: BIM Model Preparation in Revit (G2)

1. Development of a parametric building model in **Autodesk Revit 2025** based on the case study building.

Assignment of **Type Parameters** and **Shared Parameters** to all model elements to enable cost linkage. (Figure 6).

Integration of **Keynote Settings** to ensure each model element can retrieve the correct cost code dynamically.

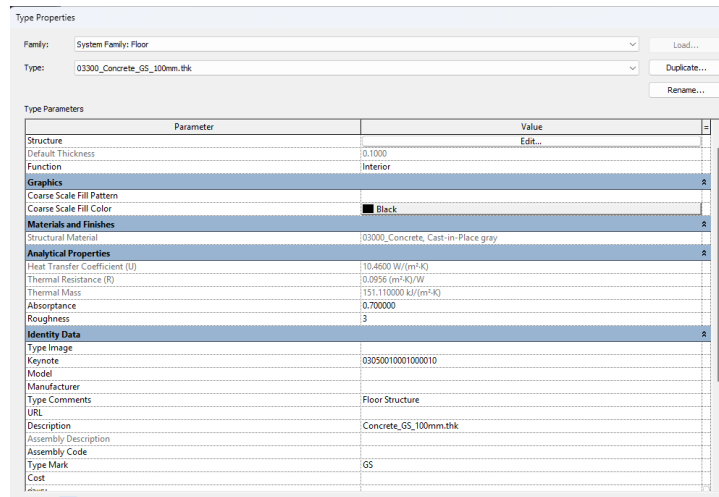


Figure 6. Data Preparation and Classification

Phase 3: Dynamo Script Development (G3)

In this phase, the Dynamo script was developed to automate the process of extracting, organizing, and exporting quantity and cost data from Revit models. The goal was to reduce manual workload, minimize errors, and ensure consistency in BOQ (Bill of Quantities) generation. The development process followed a systematic approach:

Data Input Preparation - Revit model elements

were first reviewed to ensure that all relevant parameters (e.g., Keynote, Description, Unit, and Quantity) were properly assigned. This step ensured that the script could extract data without missing or mismatched fields.



Figure 7. Workflow of the proposed Green BIM Automation process, illustrating the integration of Revit, Dynamo scripts, and the Thailand Public Construction Cost Database for automated BOQ and Keynote generation.

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4. Dictionary Mapping - The extracted parameter values were mapped into dictionaries using *Dictionary.ByKeysValues*. This mapping

allowed for easy data pairing between Revit output and reference cost data from Excel, enabling real-time cost calculation.

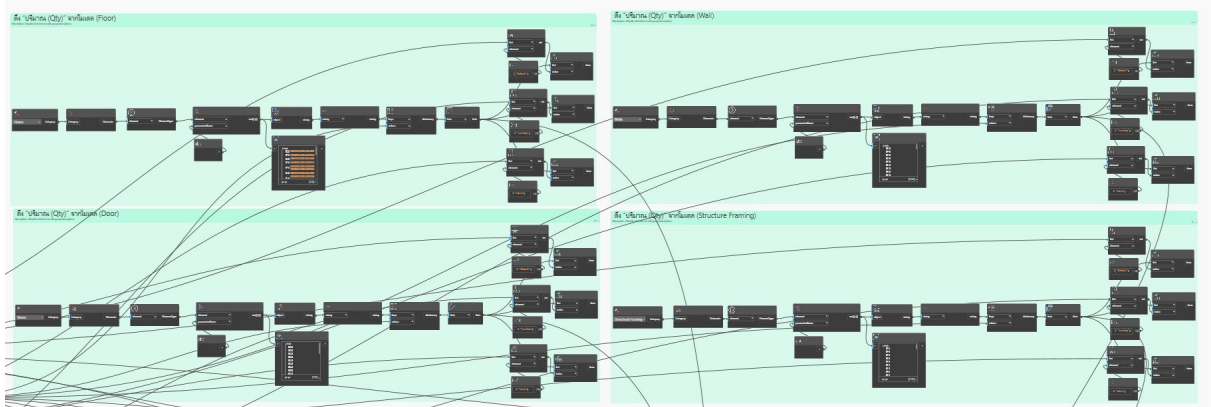


Figure 9.

5. Excel Integration – Using *Data.ImportExcel* and *Data.ExportExcel* nodes, the script could read cost data from

an external Excel file, match it with Revit element data, and export a new BOQ file in a structured, category-based format.

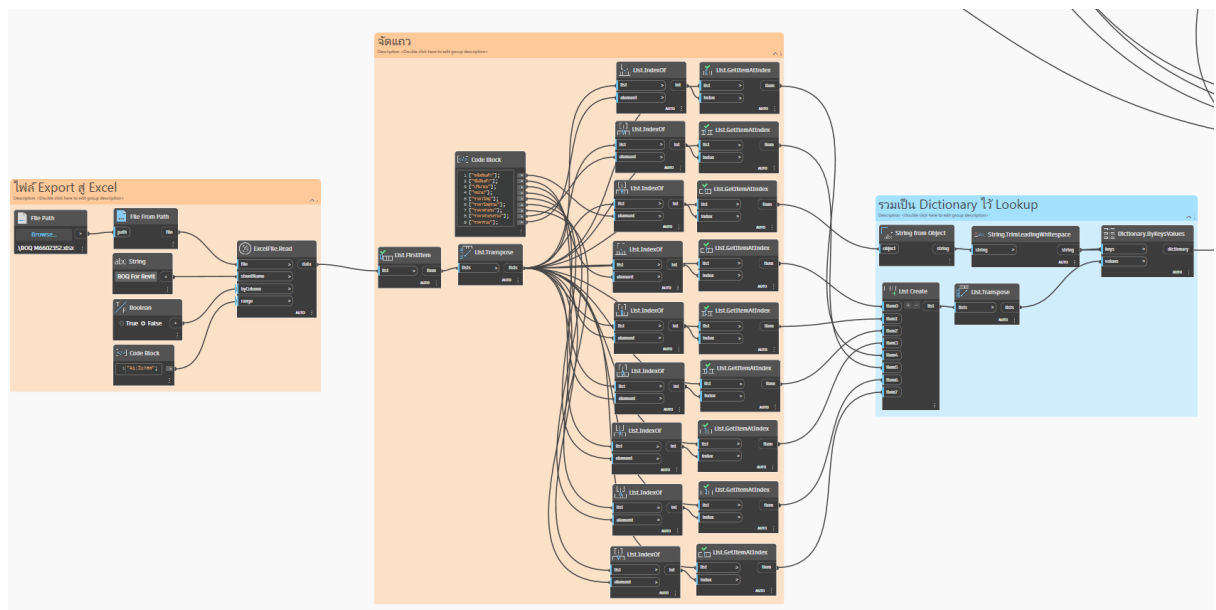


Figure 10. User interface in Revit displaying the generated BOQ and Keynote values after running the Dynamo script.

6. Automation Output - The final BOQ was generated with items sorted by category, including descriptions, quantities, units, and calculated costs. The automated output eliminated repetitive manual formatting and reduced the possibility of human error.

This structured development ensured that the Dynamo script was modular, reusable, and adaptable for future modifications, such as integrating with Revit Schedules or connecting to real-time cost databases.

Phase 4: BOQ and Keynote Generation (G4)

1. Automated compilation of Bill of Quantities directly from the BIM model using parameterized schedules.
2. Real-time updating of BOQ when design changes occur, ensuring an Integrated Project Delivery (IPD) approach.
3. Export of BOQ and Keynote lists in multiple formats (Excel, CSV, PDF) for stakeholder review.

โครงการ	บ้านพักอาศัย 2 ชั้น	รายการสรุปตามหมวดงาน						
เจ้าของโครงการ	-							
ประมาณการโดย	Athipat Boonfong							
Area	522.60 m2							
						รวมเป็นเงินค่าวัสดุ	2,841,171.00 บาท	
						รวมเป็นเงินค่าแรง	1,505,907.96 บาท	
						รวมเป็นเงินทั้งสิ้น	4,347,078.96 บาท	
หมวดงาน	รายละเอียด	หน่วย	ปริมาณ	ค่าวัสดุ	ค่าแรง	รวมเป็นเงินค่าวัสดุ	รวมเป็นเงินค่าแรง	รวมเป็นเงินทั้งสิ้น
ฐานราก	งานดินชุด	ลบ.ม.	612.50	-	150.00	-	91,875.00	91,875.00
ฐานราก	งานดินถม	ลบ.ม.	585.35	-	150.00	-	87,802.50	87,802.50
ฐานราก	ทรายหยาบ	ลบ.ม.	11.70	600.00	200.00	7,020.00	2,340.00	9,360.00
ฐานราก	คอนกรีตหยาบ	ลบ.ม.	4.95	2,000.00	450.00	9,900.00	2,227.50	12,127.50
ฐานราก	คอนกรีต โครงสร้าง	ลบ.ม.	99.00	2,250.00	550.00	222,750.00	54,450.00	277,200.00
ฐานราก	ไม้แบบ	ตร.ม.	240.00	200.00	100.00	48,000.00	24,000.00	72,000.00
ฐานราก	DB12	กก.	2,570.02	24.00	5.00	61,680.51	12,850.11	74,530.61
ฐานราก	ลวดผูกเหล็ก	กก.	48.81	45.00	-	2,196.31	-	2,196.31
ฐานราก	ตะปู	กก.	55.20	45.00	-	2,484.00	-	2,484.00
ฐานราก	น้ำยาบ่มคอนกรีต	ตร.ม.	265.32	25.00	15.00	6,633.00	3,979.80	10,612.80
งานคาน	งานดินชุด	ลบ.ม.	379.81	-	150.00	-	56,970.90	56,970.90
งานคาน	งานดินถม	ลบ.ม.	1,427.30	-	150.00	-	214,095.62	214,095.62
งานคาน	ทรายหยาบ	ลบ.ม.	58.09	600.00	200.00	34,851.96	11,617.32	46,469.28
งานคาน	คอนกรีตหยาบ	ลบ.ม.	49.15	2,000.00	450.00	98,300.40	22,117.59	120,417.99
งานคาน	คอนกรีต โครงสร้าง	ลบ.ม.	73.73	2,250.00	550.00	165,889.35	40,550.73	206,440.08
งานคาน	ไม้แบบ	ตร.ม.	625.56	200.00	100.00	125,112.00	62,556.00	187,668.00
งานคาน	RB6	กก.	1,323.60	22.00	5.00	29,119.20	6,618.00	35,737.20
งานคาน	DB12	กก.	3,746.99	24.00	5.00	89,927.82	18,734.96	108,662.78
งานคาน	DB16	กก.	1,252.73	24.00	5.00	30,065.52	6,263.65	36,329.17
งานคาน	ลวดผูกเหล็ก	กก.	120.61	45.00	-	5,427.63	-	5,427.63
งานคาน	ตะปู	กก.	143.88	45.00	-	6,474.55	-	6,474.55
งานคาน	น้ำยาบ่มคอนกรีต	ตร.ม.	688.12	25.00	15.00	17,202.90	10,321.74	27,524.64
งานเสา	คอนกรีต โครงสร้าง	ลบ.ม.	1.65	2,250.00	550.00	3,712.50	907.50	4,620.00
งานเสา	ไม้แบบ	ตร.ม.	24.00	200.00	100.00	4,800.00	2,400.00	7,200.00
งานเสา	RB6	กก.	42.80	22.00	5.00	941.54	213.99	1,155.52

Figure 11. Comparison chart showing differences in BOQ output between the conventional manual process and the proposed automated workflow.

Phase 5: Validation and Sustainability Assessment (G5)

1. Verification of automated results against manual BOQ extraction to assess accuracy.
2. Evaluation of material selection with Green Building Material Index and LEED/BREEAM alignment.
3. Recommendations for optimizing cost and sustainability trade-offs.

3.3 Tools and Technologies

1. Autodesk Revit 2025 – for BIM modeling and data structuring.
2. Dynamo for Revit for visual programming and automation.
3. Microsoft Excel for intermediate data processing and CSV mapping.
4. Thailand Public Construction Cost Database as the authoritative reference for pricing and specifications.
5. UniFormatII / MasterFormat 2020 for standardized classification of building elements.

3.4 Workflow Diagram

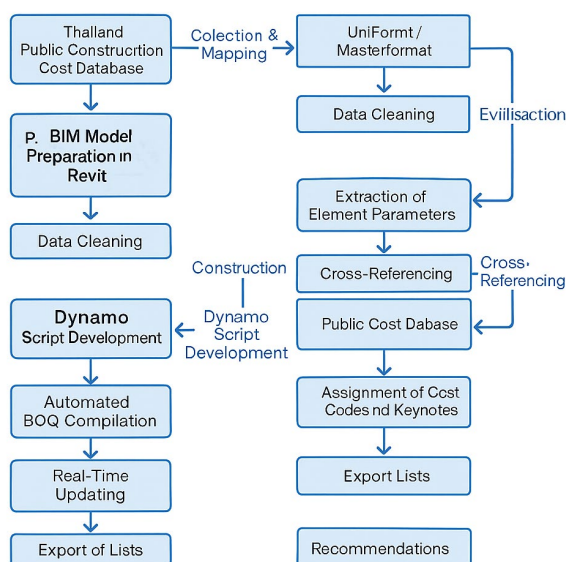


Figure 12. Workflow of the Proposed System for Automated BOQ and Keynote Generation (Data prep → Uni/MasterFormat mapping → Dynamo processing → BOQ & Keynotes → QA/QC → Export).

3.5 Justification of Methodology

This methodology was selected to address three critical challenges in Thailand's construction sector:

1. **Manual BOQ Generation Inefficiency** The traditional manual process is time-consuming and error-prone. The proposed automation significantly reduces processing time while improving accuracy.
2. **Lack of Standardization** By integrating UniFormatII and MasterFormat, the methodology ensures compatibility with international best practices while maintaining local relevance.
3. **Sustainability Integration** The method aligns with **Green BIM** principles, enabling cost estimation that considers environmental impacts alongside economic factors.

4. Results and Discussion

4.1 Project Overview

The proposed case study involves a **two-story residential building** with a total floor area of **522.60 square meters**. The building is designed using Autodesk Revit as the primary Building Information Modeling (BIM) platform, integrated with Dynamo scripts for automated data processing. The purpose of the case study is to demonstrate the efficiency of the proposed Green BIM Automation workflow in generating **Bill of Quantities (BOQ)** and assigning **Keynote codes** directly linked to Thailand's Public Construction Cost Database.

The building model incorporates architectural, structural, and MEP components, modeled to **LOD 300** standards. All major building elements are classified according to **Uniformat II** for system-based categorization and **MasterFormat** for material and trade-based classification, ensuring compatibility with both design and cost estimation processes.

4.2 Data Preparation

The BIM model was developed with accurate geometry and metadata for each building

component. The following preparations were conducted prior to Dynamo automation:

1. **Uniformat II classification** assigned to all elements based on system and functional grouping (e.g., B2010 Exterior Walls, C1010 Interior Partitions).
2. **MasterFormat classification** assigned to materials and trades for precise linkage to the cost database (e.g., 04 20 00 Unit Masonry, 08 51 13 Aluminum Windows).
3. Parameter mapping to ensure Revit families contain relevant **Keynote** fields for automatic code assignment.
4. Location-based division of quantities for cost analysis per building zone (e.g., ground floor vs. second floor).

1. **Model Element Extraction** – All building elements from the Revit model were filtered by category and classification codes.
2. **Database Connection** – The script accessed a prepared cost dataset derived from Thailand's Public Construction Cost Database (2023 edition).
3. **Keynote Code Assignment** – Each model element received a Keynote code based on its UniformatII or MasterFormat classification.
4. **BOQ Generation** – Quantities such as area, length, and volume were extracted and compiled into a standardized BOQ format.
5. **Excel Output** – Final results were exported into an Excel file containing item description, Keynote code, quantity, unit cost, and total cost.

4.3 Dynamo Automation Process

The Dynamo script executed the following automated processes:

4.4 Sample Output

A portion of the generated BOQ is shown below:

Table 1. Sample automated BOQ output (excerpt) generated by the Revit+Dynamo workflow with Uniformat II/MasterFormat mapping.

Description	Keynote Code	Quantity	Unit	Unit Price	Total
Reinforced Concrete Column	03100210001000040	15.25	m ³	1698.21	25,898
Clay Brick Wall (200 mm)	04200010001000078	242.6	m ²	220	53,372
Aluminum Window (Clear Glass)	08050000001001583	28.5	Pieces	3,200	91,200
Ceramic Floor Tile (300x300 mm)	09300100001001390	120	m ²	450	54,000

Note: Prices are illustrative and based on standard rates from the 2023 Thailand Public Construction Cost Database.

4.5 Performance Comparison

Table 2. Performance comparison between manual workflow and Revit+Dynamo automation.

Comparison Criteria	Conventional Method (Manual)	Revit + Dynamo	Difference
Time to generate BOQ (hours)	48 hours	6 hours	87.5% reduction
Data accuracy (%)	85%	98%	13%

Time to update data after design changes	8 hours	0.5 hours	93.75% reduction
Compliance with standard coding	Moderate	Very High	—
User satisfaction (out of 5)	3.2	4.8	1.6

4.6 Performance Evaluation

The implementation of the Dynamo-based automation workflow produced significant efficiency gains:

1. Time Reduction: BOQ generation time reduced from ~5 days (manual) to ~1 day (automated), representing an 87.5% improvement.
2. Error Minimization: Manual data entry errors decreased by over 90%, as quantity takeoff and coding were directly linked to model parameters.
3. Data Consistency: Unifomat and MasterFormat classifications ensured consistent cost coding and reporting formats.
4. Scalability: The workflow can be adapted to other building types (e.g., commercial, educational) with minimal script modification.

4.7 Summary

This case study demonstrated the potential of Green BIM Automation in integrating design and cost estimation processes. By linking Revit and Dynamo workflows to an authoritative cost database, the method ensures that sustainable design decisions are supported by accurate, up-to-date cost data. The approach can be further enhanced by integrating environmental performance metrics (e.g., Energy Use Intensity, embodied carbon) in future developments.

5. Conclusion

This research successfully demonstrated the potential of integrating Building Information Modeling (BIM) with Dynamo

automation to enhance the efficiency, accuracy, and standardization of Bill of Quantities (BOQ) generation and Keynote assignment in architectural projects.

The prototype system developed in this study connected Autodesk Revit with Dynamo scripts to automatically extract element data, apply standardized construction codes (based on Thailand's Public Construction Cost Database), and generate BOQ reports directly from the BIM model.

By implementing the system in a two-story residential building with a total floor area of 522.60 m², the results revealed significant improvements compared to conventional manual workflows. Specifically:

1. Time efficiency improved by up to 87.5%, reducing the BOQ preparation time from 48 hours to only 6 hours.
2. Data accuracy increased from 85% to 98%, minimizing human errors in data entry and code matching.
3. Responsiveness to design changes improved drastically, with updates being completed in less than 30 minutes compared to 8 hours in the traditional method.
4. Compliance with standardized codes improved from a moderate level to a very high level, ensuring interoperability and consistency in construction documentation.
5. User satisfaction increased significantly, with participants rating the system 4.8 out of 5 compared to 3.2 for the manual process.

The findings confirm that BIM-based automation, when combined with Dynamo, is an effective solution for accelerating the

quantity take-off process, improving data reliability, and aligning with national construction cost standards. This approach not only benefits project teams but also provides a foundation for broader implementation in Thailand's construction industry.

5.2 Recommendations

Based on the outcomes of this research, several recommendations can be made to enhance the adoption and impact of BIM-based automation in the construction industry. Firstly, construction companies, design consultants, and quantity surveyors are encouraged to integrate BIM automation workflows into their daily operations. This will not only improve productivity but also significantly reduce operational costs by minimizing repetitive manual tasks and human errors.

Secondly, the developed system should be further enhanced by integrating with **real-time material cost databases**, enabling continuous and dynamic cost estimation throughout the design and construction phases. This integration would allow stakeholders to make informed decisions quickly, based on up-to-date market prices.

Thirdly, while this study focused primarily on **architectural elements**, the same methodology can be extended to include **structural and mechanical, electrical, and plumbing (MEP) systems**. Such expansion would enable the creation of a fully automated, multidisciplinary BOQ, offering even greater accuracy and efficiency across the entire project scope.

In addition, it is strongly recommended that professionals receive adequate **training in both BIM tools and visual programming platforms such as Dynamo**. This dual competency will empower them to customize automation scripts to suit specific project needs and to innovate further beyond the baseline system developed in this research.

Lastly, policymakers and government agencies should consider **promoting or**

mandating the use of standardized construction codes and automated BOQ processes for public projects. Such measures would ensure data consistency, enhance transparency, and reduce potential disputes between stakeholders, ultimately contributing to a more efficient and sustainable construction industry in Thailand.

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The 7th KUSRC – IC International Conference 2025

Subject :

Humanities and social sciences



Participation in community forest management at Ban Nong Khon Saen, Sam Phrao Subdistrict, Mueang District, Udon Thani Province

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Abstract

This research aimed to 1) study the participation and obstacles in the management of Ban Nong Khon Saen community forest, 2) survey the general types of forest and the initial biodiversity, and 3) propose guidelines for sustainable community forest management. The research methodology in this study was qualitative research, collecting data from 40 community leaders, community forest committees, community representatives, representatives of government agencies, and the private sector. In-depth interviews, conversations, and questionnaires were used as research tools. The community forest participation in Ban Nong Khon Saen community forest management was at a moderate level ($\bar{x} = 3.25$). The study results found that the community forest's potential is abundant and biodiverse. The community forest is utilized as a source of food and additional income, a learning resource, and an ecotourism destination. The survey in the area of 30 rai found 49 species of plants, 28 families, and 1,285 trees. The top five plants were Burma Sal (*Shorea obtusa* Wall. ex Blume), Burmese sal (*Shorea siamensis* Miq.), Burmese rosewood (*Pterocarpus macrocarpus* Kurz.), Buchanania (*Buchanania lanzan* Spreng.), and *Mitragyna hirsuta* (*Mitragyna hirsuta* Havil.), respectively. For the surveyed herbal plants, 38 species were found, such as *Pradu Thung* (*Enkleia thorelii* (Lecomte) Nevling), *Sphenodesme pentandra* Jack (*Sphenodesme pentandra*), and *Bandicoot Berry* (*Leea indica* (Burm.f.) Merr.), etc. The suggestions for guidelines to promote community participation in sustainable community forest management are 2 pathways such as 1) Community Forest management in the form of traditional cultural practices and 2) Community Forest management in the form of multipurpose development with 2 steps to promote community forest management participation by creating awareness and consciousness of participation and implementing sustainable community forest management activities. The important factors influencing participation are community leaders, community forest committees, the public sector, and support from external agencies, including time, age, occupation, and income, which will support community participation in sustainable forest management.

Keywords: participation in community; forest management; Ban Nong Khon Saen community; sustainable community forest management

1. Introduction

The community forest is land or forest land that the community has operated or has been legally permitted to operate together with officials to manage the forestry business continuously, which must be under the rules, regulations, practices, and plans related to the beliefs and cultures of the local community [1, 2]. The management is for conservation, and the community is to use the forest sustainably. It may also mean a forest that groups of people in the community have jointly preserved for the benefit of the community, and the people can come to use it together [3]. At present, the management of community forests is critical. In addition to being a forest that purifies the air, provides shade and moisture, and makes the rain fall in season, it is also an important source of food and a supermarket for the community because the forest area is rich in various plants, animals, and insects and is a source of herbs that the people in the community rely on and use [4, 5]. The current situation in Thailand shows that encroachment and clearing of forests for agriculture, shifting cultivation, cutting trees for fuel, burning charcoal, or even burning forests for hunting and hunting for food has caused the forest to decrease at a significant rate [6, 7]. According to the data to date, the forest area in Thailand is likely to remain at 171,586 square kilometers, or approximately 33 percent of the land area of Thailand. When compared to the forest area 50 years ago, it was found that it decreased by 50 percent [8, 9]. If there is no concern for forest management, there will be no forest area for our children to see.

Ban Nong Khon Saen Community, Sam Phrao Subdistrict, Mueang District, Udon Thani Province, is a community surrounding Udon Thani Rajabhat University (Sam Phrao). Most of the population in the community is farmers. Ban Nong Khon Saen is a village that has been selected to carry out activities in line with the sufficiency of the economy in the community [10]. Members have joined together to adjust the vacant area

of the village to be used as agricultural land for growing vegetables together until today. The community started the community forest conservation project in 2018 at the Nong Khon Saen community forest, which covers an area of 30 rai and is a flat area [11]. The community forest is suitable for implementing the community forest project. Therefore, the community intends to manage the forest and use it for agriculture. They also want to survey tree species to use as information for further management. Taking care of the forest in the community does not require the community to manage the forest alone. It also requires cooperation from many relevant parties, including government officials who must support and protect it, including providing advice and promoting knowledge, materials, and budget so that the community has the potential to manage the forest [12].

Therefore, this research aimed to study the potential, problems, obstacles, and level of participation in the management of the forest Ban Nong Khon Saen community. To study community participation and obstacles in community forest management, the guidelines for community participation in sustainable community forest management were studied. Ban Nong Khon Saen community forest is considered a forest area that is still rich and has biodiversity. However, some parts had been destroyed by local people. The community has tried to protect, maintain, and restore it to its best fertility. The efforts of the community leaders, the community forest committee, and villagers who were conscious of forest resource conservation, cooperation has emerged to concern about the forest, which is the community's resource capital. The results of this study will be used to extract lessons, knowledge, and experiences from the community as guidelines for promoting public participation in community forest management to be strong and sustainable.

2. Methodology

The study on Ban Nong Khon Saen's community forest participation is qualitative. The study area is located in the Ban Nong Khon Saen community (E=909881.12, N=1924742.99), Sam Phrao Subdistrict, Mueang District, Udon Thani Province, illustrated in Figure 1.



Figure 1 A community forest of Ban Nong Khon Saen in Udon Thani

2.1 Population sample

Key informant sample is data for brainstorming and in-depth interviews to find ways to promote community forest management participation were leaders, community forest committees, government agencies, private sectors, civil society, and various community organizations involved in community forest management, totaling 10 people, consisting of community leaders, community forest committees, and 30 representatives of people who use the forest, using snowball sampling, which relies on recommendations from community leaders.

2.2 Questionnaire design

To inquire about community forest management participation, 30 people from the total population of 351 people (109 households) were selected, with at least 1 representative member per household, and simple random sampling was used to answer the questionnaires. Problems, obstacles, and participation in community forest

management with 5 levels and a study of participation in finding problems and causes of problems, participation in planning, participation in operations, participation in receiving benefits, and participation in evaluating results. As for the guidelines for promoting participation in community forest management, a study of the forms and steps of participation in community forest management was conducted, and the level of role and participation in community forest management was studied, along with factors and conditions for participation in community forest management.

2.3 Data analysis

Step 1: Data from the community context was studied, surveys, and literature-related research.

Step 2: Data from interviews on community forest context, potential, and community forest management content was analyzed to see the relationship of the content and examine the data according to academic principles

Step 3: Approaches to promote community participation in community forest management data analysis by using the results of data on problems in community forest management were studied by focus groups to find ways to promote community participation in community forest management, and then analyzing the content to see the relationship of the content and presenting the data in a lecture format.

3. Results and Discussion

3.1 The potential of the community forest management of Ban Nong Khon Saen, Sam Phrao Subdistrict, Mueang District, Udon Thani Province

The results found that the community forest began to register on November 16, 2018, with an area of 30 rai, as shown in Figure 2. Throughout the past, the community has jointly conserved, maintained, cared for, restored, and protected itself very well.



Figure 2 Nong Khon Saen forest community

The type of forest found 49 species of plants, 28 families, and 1,285 trees. The survey in the area of 30 rai found 49 species of plants, 28 families, and 1,285 trees. The top five plants were Burma Sal (*Shorea obtusa* Wall. Ex Blume), Burmese sal (*Shorea siamensis* Miq.), Burmese rosewood (*Pterocarpus macrocarpus* Kurz.), Buchanania (*Buchanania lanzan* Spreng.), and *Mitragyna hirsuta* (*Mitragyna hirsuta* Havil.), respectively, as shown in Figure 3. For the surveyed herbal plants, 38 species were found, such as *Pradu Thung* (*Enkleia thorelii* (Lecomte) Nevling), *Sphenodesme pentandra* Jack (*Sphenodesme pentandra*), and *Bandicoot Berry* (*Leea indica* (Burm.f.) Merr.), etc. The trees in the area are an important tree species and have economic value, which is consistent with the research results of Patsin [13], who studied the people's participation in Khok Yai community forest management at Wapi Pathum District, Maha Sarakham Province. The results found that the surrounding communities rely on and use the community forest both directly and indirectly, such as using it as a source of food, herbs, wood for

construction, and as an energy source. It is also a source of learning about nature and biodiversity.



Figure 3 The major plants in Ban Nong Khon Saen forest communities

From the study results on the level of participation in the management of the community forest of Ban Nong Khon Saen, it was found that the community of Ban Nong Khon Saen participated in the management of the community forest at a moderate level ($\bar{x} = 3.25$). In terms of community leaders, community forest committees, community forest regulations, and also support from other community organizations, the high-level forest dependence ($\bar{x} = 3.95$), forest utilization and beliefs in sacred things are protecting community forests, information systems, religious institutions, support from government agencies, and support from the private sector, ranging in the moderate level ($\bar{x} = 3.35$). To study factors and conditions for participation in community forest management, the researcher divided the factors of participation in community forest management into internal and external factors; the internal community factors that promote participation in community forest management Most are community leaders, which is an important factor in driving community forest development and management because community forest management is an order from leaders to the people who manage the community forest.

Another equally important factor is the people or community members who are the main force in developing and managing community forests. The external factors of community participation in community forest management depended on the support from external agencies, both the government and the private sector. The conditions for participation in community forest management included: time conditions, age range, and community forest management volunteer work requires a reasonable amount of time to complete. Furthermore, the individual participation in community forest management may require time conditions to participate simultaneously, such as various occupations and income conditions that are different. Most people in the community are farmers and general laborers; therefore, there is an uncertain income.

Most people who have enough free time to participate in community forest development activities are quite old, which may be an obstacle to participating in these activities. The results of this study are consistent with the research analysis results of Permpul & Tantanasarit [14] on the community participation level model for community forest management in Klongtagrao watershed area, Chachoengsao Province. It was found that the government and the public sector have instilled and strengthened community power to be aware of community rights to conserve natural resources and the environment. They also preserve traditional rights, maintain cultural values, and maintain local wisdom rights by linking relationships based on the concept of sustainable development, too, leading to the joint conservation of forests for everyone. However, the survey results also found problems and obstacles in community forest management, such as some people and people outside the community still illegally cutting down trees. There are also some forest fires and droughts, but these problems have decreased rapidly. The problem of participation in community forest

management in Ban Nong Khon Saen is still the main problem that villagers are concerned about, and to raise the community's participation in community forest management, which is consistent with the concept of Aung *et al.* [15], who said that there are many problems in using community forests, such as cutting down trees beyond the specified amount and illegally taking rare species out of the forest. Wrong methods of finding forest products, such as the belief in burning the forest to make sweet vegetables and mushrooms bloom etc. Due to the above problems, it is necessary to set regulations for the forest management of each community forest. These regulations will be different according to the context of each area. The Ban Nong Khon Saen community has set a rule prohibiting illegal logging in the community forest; however, it can be used for other benefits by collecting vegetables and mushrooms in the community forest to sell or consume.

3.2 Guidelines for promoting public participation in sustainable community forest management

There are 2 pathways of community forest management with participation:

1. Pathway 1: Conservation community forest management is the management of community forests by conserving the community forests for the benefit of the public. Conservation is the form of community operations to conserve the environment, soil, water, etc., and prevent natural disasters, as well as local beliefs and traditions, such as using traditional rituals to connect with the community to be a spiritual anchor for people in the community and a guideline for people in the community to join in conserving the forests.

2. Pathway 2: Multipurpose development community forest management is the management of community forests to use some areas to provide other benefits to the community, such as ecotourism, which is management for economic benefits in the

community as well. This is consistent with the concept of Chukong et al. [16], who mentioned the multipurpose community forest management form as a form of community forest operation to expect both conservation and economic returns. There are also natural forests that jointly solve problems from community forest management.

The roles model of participation in community forest management can be divided as follows:

1) The community or the public sector is very important in participating in community forest management because it is the main force driving various activities to success and promoting participation in community forest management to be more effective.

2) Government agencies, such as Sam Phrao municipality or Nakhon Udon Thani municipality is a role models in promoting participation in policy determination and activities in local development plans, supporting budgets, and implementing community forest management activities. The royal forest department of Udon Thani Province plays a role in providing knowledge and understanding about community forests and promoting tree species for reforestation. Furthermore, the Udon Thani Provincial Health Office also plays a role in surveying and studying medicinal plants in community forests that can be applied as traditional herbal medicines, etc.

3) Private sectors is an important sector to play a role in promoting participation in community forest management in terms of supporting budgets for organizing activities or supporting materials, equipment, and tools for community forest management, such as the Udon Thani Provincial Industrial Council Foundation, that has a project to promote bamboo planting by distributing trees to the community for free, etc.

4) Educational institutions, such as Udon Thani Rajabhat University, play a role in creating local curricula to study nature

trails and tree species in community forests, including participating in every community forest development activity.

5) Religious institutions, such as Wat Ban Nong Khon Saen, play a role in promoting participation in community forest management by being a medium for publicizing community forest management activities.

3.3 Community participation in sustainable community forest management

The community forest area of Ban Nong Khon Saen, Sam Phrao Subdistrict, Mueang District, Udon Thani Province, covering 30 rai, has been of concern to the community. The community benefits from the community forest are a source of household food and additional income from selling seasonal forest products, producing eco-friendly leaf plates and bowls, a learning center, and ecotourism. The main problem and obstacle found in community forest management is the lack of full potential participation from community people because the timing and continuity of organizing various activities are not consistent with community needs, resulting in the volunteer power to participate in the activities not being as intense. As a result, the overall level of public participation in community forest management is at a moderate level. There are 2 recommended appropriate forms of community forest management to promote community participation in sustainable community forest management, and community forest management in the form of conservation and community forest management in the form of multipurpose development. The steps to promote community forest management are 3 steps;

1) Creating awareness and consciousness of the value of natural resources.

2) Creating sustainable community forest management activities.

3) Creating groups and networks to drive together.

The efficiency of participation in community sustainable forest management has many factors, such as community leaders, community forest committees, people, community members, and support from external agencies. Under the conditions of time, occupation, income, and age of the people involved, these elements can promote community participation in community forest management for sustainability, as illustrated in Figure 4.



Figure 4 The participation of sustainable community forest management in Ban Nong Khon Saen

4. Conclusion

From the study on community forest participation in Ban Nong Khon Saen community forest management, Sam Phrao Subdistrict, Mueang District, Udon Thani Province, it was found that community forest participation was at a moderate level ($\bar{x} = 3.25$). The level of participation in forest management and conservation should be increased to a high level. The suggestions for guidelines to promote community participation in sustainable community forest management are 2 pathways such as 1) Community Forest management in the form of traditional cultural practices and 2) Community Forest management in the form of multipurpose development with 2 steps to promote community forest management participation by creating awareness and consciousness of participation and

implementing sustainable community forest management activities. The relevant government agencies should participate more with the community in community forest management, organize training in proper community forest management, and promote and support villagers to conserve good cultural traditions or beliefs that can be applied to community forest management. In addition, the local wisdom in community forest management with participation should be the creation of added value in community forest areas.

Acknowledgement

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Clusters and Routes Solutions for Capacitated Vehicle Routing Problem

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Abstract

The objective of this research is to reduce transportation costs by developing a novel approach to customer grouping and transportation planning that uses the Capacitated Vehicle Routing Problem (CVRP) to determine the shortest total route for the transportation of goods. The process involves first grouping customers, then dividing them into groups based on product demand, determining the best route for each group, calculating the shortest route for each group, and comparing two methods: grouping based on demand and grouping based on the quantity of products that customers want, K-Means Clustering, and grouping. The results using the K-Means approach are superior: In 75% of the trials, the K-Means method is found to provide superior results when determining the shortest path. The demand-based approach is less successful; only 25% of trials show positive results. In conclusion, according to this study, obtaining the shortest delivery routes can be facilitated by segmenting consumers using K-means clustering before determining the route.

Keywords: K-means clustering, VRP, Routing

1. Introduction

Transportation activities in modern company operations involve a variety of modalities, each with unique properties and uses based on the commodities being transported. Water transportation, air transportation, railroad transportation, pipeline transportation, and road or motor transportation are some of the main modalities that make up the transportation industry. Every method of transportation has operational activities that are inherent to the process, such as the need for resource allocation and transportation management expenses. Transportation costs can be effectively controlled and resource utilization optimized by businesses and organizations when appropriate control measures are implemented, each operational activity is prioritized, and performance evaluation metrics are established through Key

Performance Indicators (KPIs) to assess operational efficiency. To attain maximum efficiency and lower operating expenses, strategic planning is necessary for operational management of organizations and transportation company operators. Because it directly affects prices, fuel consumption, operational efficiency, competitive advantage, and customer happiness, route planning is essential to the operations of transportation businesses. Cost reduction increased operational effectiveness, and higher levels of customer satisfaction are all impacted by effective route optimization.

In order to lower transportation costs, shorten delivery times, and improve customer satisfaction, the transportation industry's highly competitive environment has made advancements in route optimization efficiency necessary [1]. Fuel expenses are lower on shorter routes, which lowers

delivery costs overall. Understanding the importance of this problem, the study team wants to create strategies for maximizing delivery distances through transportation route optimization, which will ultimately lower the operating expenses related to the distribution of goods. Delivery route optimization is a crucial strategic endeavor in modern logistics management [2], where profitability and competitive advantage are closely correlated with operational efficiency. Through methodical investigation and the creation of affordable transportation options, this study aims to answer the fundamental problem of route optimization.

Reducing transportation distances and, in some cases, the number of cars needed for transportation operations are two major advantages of effective and efficient vehicle routing. Reducing transportation distances and the need for a fleet of vehicles both significantly lessens the environmental effect of transportation emissions and lowers the company's transportation expenses. The strategic significance of route optimization in contemporary logistics operations is demonstrated by this twin advantage of cost savings and environmental sustainability.

Heuristic methods are approaches to problem-solving that are used to find near-optimal solutions that are close to the best answers [3]. These approaches to problem-solving and solution-finding make use of logical thought processes that depend on the establishment of particular guidelines and standards in order to produce acceptable and satisfactory results [4]. Even though these techniques might not produce the best possible answer, they do produce quick computations with results that are good enough and suitable for real-world use. In order to tackle optimization issues, heuristic solution approaches are developed that scale based on the problem's complexity level and combine mathematical modeling frameworks with human common sense reasoning[5-6]. The Cluster First – Route Second methodology is used in this study's two-phase

strategy. The Nearest Neighbor strategy is then used for vehicle routing optimization.

2. Methodology

A strategic route planning methodology that splits the optimization procedure into two separate stages is the Cluster-First Route-Second strategy[7]. Clustering delivery locations or customer groups into suitable subsets according to pertinent criteria, including geographic proximity, cargo volume, or vehicle capacity limitations, is the first step. The goal of this clustering objective is to make route planning across large geographic areas less complicated.

The approach moves on to the routing stage after the clustering phase, where delivery sequences within each cluster are improved to maximize efficiency by reducing trip time or transportation distance. Managing logistics systems with a large number of delivery sites or clients benefits greatly from this two-phase strategy since it divides the computational effort needed for route optimization into smaller clusters while preserving the quality of the final product.

This study uses two different clustering techniques—Max Demand clustering and K-Means clustering—to examine vehicle routing optimization using the Cluster-First Route-Second methodology. To assess the effectiveness of the suggested clustering techniques inside the two-phase optimization framework, the experimental framework makes use of 16 benchmark issues that were taken from the CVRPLIB database. The following is how the clustering approaches are put into practice:

2.1 The highest demand

The highest Demand Clustering Method arranges nearby customers according to demand distribution and geographic factors by using the customer with the highest demand as the centroid for cluster formation [8]. The point that has the most demand is designated as the grouping's center. Through finding individuals within the group who have constraints in the amount of weight they can

carry. Figure provides an example of how to set the grouping's center. The point that has the most demand is designated as the

grouping's center. Figure 1 provides an illustration of how to set the grouping's center

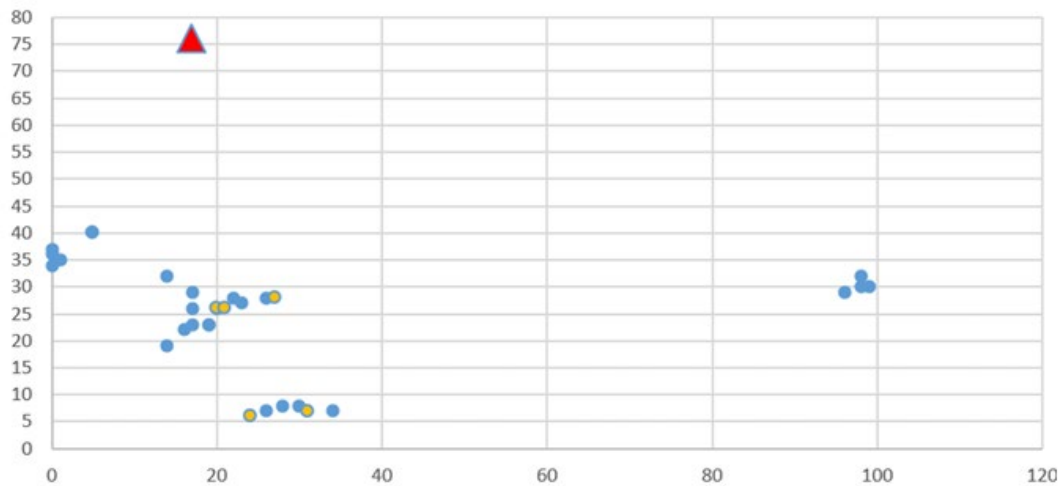


Figure 1 The coordinates of each point are grouped using the highest demand as the center (The triangle represents the depot, the blue dot represents the customer's position, and the yellow circle represents the grouping's center).

2.2 K-Means Clustering Technique

K-Means Clustering Technique: This technique divides clients into groups according to demand factors and geographic coordinates using the traditional K-Means algorithm, creating ideal centroids by iterative refinement.

Through finding individuals within the group who have constraints in the amount of weight they can carry. Figure 2 provides an illustration of how to set the grouping's center (The triangle represents the depot, the blue dot represents the customer's position, and the yellow circle represents the grouping's center).

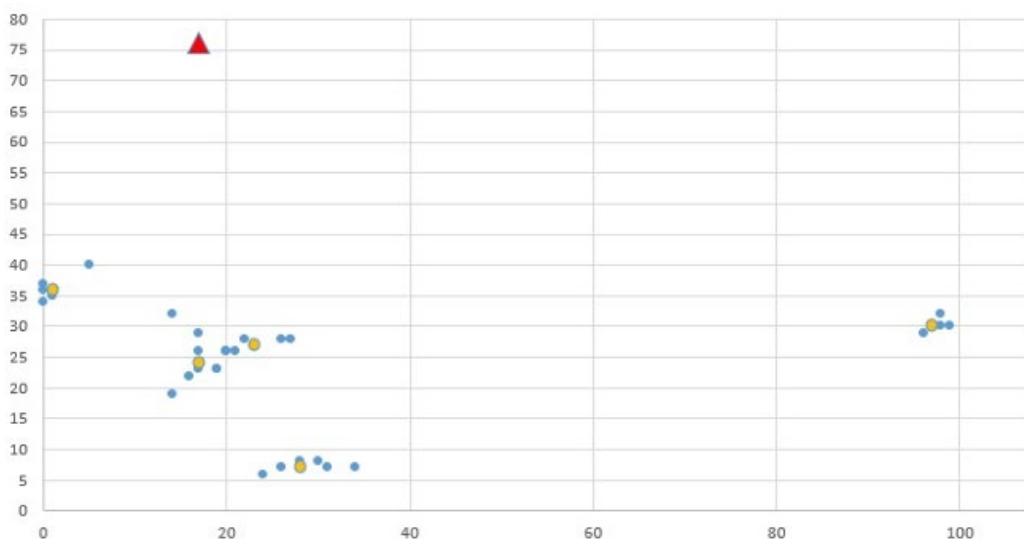


Figure 2 The coordinates of each point are grouped using the K-Means Clustering

Following the clustering process, the vehicle route is organized using the clustering findings and Solver in Excel to get the shortest overall distance. Finding the transport sequencing with the shortest overall distance is the goal.

3. Results

This research proposes a strategy for routing trucks to optimize freight delivery, hence minimizing delivery distance and costs, utilizing the Solver add-in and computational techniques from Microsoft Excel.

The CVRPLIB website provided the data used in this study. There can be no more than 200 variables in each task. Because of Microsoft Excel's constraints, the variable calculation technique is = delivery point x number of delivery trucks.

Transporting products by routing, the results of the grouping are used to determine the sequence of transportation from the warehouse to the different consumers in the group after each group has been obtained using the clustering method of greatest customer demand from the Max-Demand method and the K-means method.

Cluster-First Rout-Second was the method used to compare the distance of goods transport by first clustering and then arranging routes. Two distinct clustering techniques were compared in this study: 1) K-means Clustering approach and 2) Clustering technique according to the percentage difference of the best response value and the most customer needs as the center with the total distance in route arrangement. Twenty of the CVRPLIB website's questions will be compared by the researcher.

Table 1 The result of the clustering approach by customer needs method applied to the A-n38-k5

Car No.	Route	Distance (Unit)
1	1-3-4-8-6-2-7-5-1	192.17
2	1-6-3-5-4-2-1	147.33
3	1-6-4-9-2-3-5-8-7-10-1	190.05
4	1-5-8-9-3-2-4-6-7-1	168.07
5	1-7-2-5-9-6-8-3-4-1	138.96
Total		836.58

Table 2 The result of the K-Means Clustering approach applied to the A-n38-k5

Car No.	Route	Distance (Unit)
1	1-5-4-3-7-6-2-1	145.73
2	1-5-8-3-4-7-2-6-1	156.3
3	1-7-8-4-6-5-2-3-9-1	152.56
4	1-6-3-2-4-7-8-5-9-1	183.9
5	1-8-5-3-6-4-9-7-3-1	129.84
Total		768.33

The clustering technique with the greatest customer needs as the center had a shorter total distance than the K-means Clustering technique, according to the calculation of the difference between the two methods, 1) K-means Clustering technique and 2) Clustering technique using the most customer needs as the center.

From Table 3, which uses two distinct clustering algorithms to examine

the effectiveness of grouping first and then routing subsequently (Cluster-First Route-Second): 2) clustering technique using K-means Clustering with 16 Instances from CVRPLIB, finding that the method with the shortest total distance result is K-means Clustering, which has the total distance of routing for 12 questions, or 75 percent. 1) clustering technique using the most customer needs as the center.

Table 3 Results of routing using CFRS and different clustering techniques

Instance	Method		Comparison
	Highest demand	K-means	
A-n38-k5	836.58	768.33	K-Means
A-n39-k5	933.32	895.64	K-Means
B-n31-k5	746.13	756.71	Highest demand
B-n34-k5	838.64	846.01	Highest demand
B-n35-k5	1228.21	964.95	K-Means
B-n39-k5	808.39	696.01	K-Means
A-n32-k5	921.36	810.16	K-Means
A-n33-k5	766.2	741.7	K-Means
A-n34-k5	826.53	854.84	Highest demand
A-n36-k5	1032.07	860.4	K-Means
A-n37-k5	771.79	754.45	K-Means
E-n23-k3	610.15	666.51	Highest demand
E-n30-k3	582.4	557.48	K-Means
E-n22-k4	471.05	390.47	K-Means
P-n19-k2	245.17	218.3	K-Means
P-n22-k2	262.72	217.85	K-Means

4. Conclusion

This study offers a routing technique for transportation issues where routing operators must take into account the shortest overall distance while accounting for notable variations in transportation costs. Applying the cluster-first route-second technique to computer routing is the goal. This technique is used as a routing guide to determine the shortest distance for moving cargo. Additionally, it makes it possible to create a routing system that determines the best

distance for moving items. Using the cluster-first route-second method, the researchers have established a routing technique that contrasts two distinct clustering techniques: 1) the K-Means Clustering approach under the parameters outlined in each case, and 2) the clustering strategy employing the highest consumer demand as the center (Demand). The results that were studied. The following succinctly describes the effectiveness of analyzing the differences between the two best options to find results: With an 75%

chance of getting the best results, the K-Means Clustering strategy outperformed the other one of the two best freight routing strategies on 12 out of 16 situations. The Demand-Centered Clustering method had a 25% chance of getting the best outcomes, but it only did so on 4 out of 16 instances. To get more accurate findings, more testing jobs should be added, and routing techniques like metaheuristics that have advantages in routing and can produce results closer to the optimal solution should be suggested.

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Influence of Personal Factors and Consumer Behavior on Townhome Purchase Decisions among Working-Age Population in the Bangkok Metropolitan Area

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Abstract

This study investigates the influence of personal factors and consumer behavior on the decision-making process regarding townhome purchases among working-age individuals in the Bangkok Metropolitan Area. Data were collected via structured questionnaires administered to a sample of 400 respondents aged 21 to 60 who were either interested in or in the process of purchasing a townhome. Descriptive statistics including frequency, percentage, mean, and standard deviation were used to describe the data, while inferential statistics, including Independent Samples t-test and One-Way ANOVA, were applied to test the research hypotheses.

The findings revealed a statistically significant difference in purchasing decisions based on the number of family members. Specifically, individuals with one to two family members exhibited the highest average scores in purchase decision-making. However, no statistically significant differences were found in purchasing behavior based on other personal factors, including gender, age, marital status, educational attainment, occupation, average monthly income, and debt burden.

Keywords: Personal Factors, Consumer Behavior, Purchase Decisions, Townhome, Working-Age Population, Bangkok Metropolitan Area

1. Introduction

Housing is one of the four fundamental necessities essential to human life. It serves not only as a place for conducting daily activities but also offers safety and functions as a central gathering place for all family members. Selecting a residence that is appropriate and aligned with individual needs contributes to personal well-being and residents' happiness and fosters long-term stability in life [1].

In the past, most Thai families followed an extended family structure, with multiple generations-parents, children, grandparents, and other relatives-living together or within the same household compound. However, socio-economic changes, increased daily competition, and the influence of Western values emphasizing individual autonomy

have transformed the lifestyle of the modern working generation. Increasingly, individuals prefer to purchase their own homes, and shift from extended to nuclear family arrangements, typically comprising only spouses and children. Among the various housing options, townhomes have become increasingly popular due to their suitability for urban living. They offer convenient transportation access, adequate living space, ease of maintenance, proximity to amenities, and relatively affordable prices - making them especially appealing to individuals with limited budgets or those starting families.

Given ongoing economic, social, and lifestyle changes, understanding the housing preferences of the working-age population has become increasingly important. As urbanization intensifies [2], it is crucial to

explore how personal factors and consumer behavior influence townhome purchase decisions. This study, therefore, examines these influences among working-age individuals in the Bangkok Metropolitan Area, aiming to provide insights for developers, policymakers, and prospective homeowners.

2. Background

2.1 Consumer Behavior Model

The Consumer Behavior Model, also known as the Stimulus-Response (S-R) Theory, provides a theoretical framework for understanding consumer purchase decision-making. It describes the motivational process that begins when a stimulus enters the consumer's perception and is processed within the "buyer's black box" - a term referring to the internal cognitive and psychological mechanisms that are not directly observable by marketers. These internal processes influence how the stimulus is interpreted, eventually leading to a buyer's response, such as a purchase decision. [3]

Stimuli that initiate the consumer decision-making process may arise from either internal needs or external influences. Among these, external stimuli are particularly significant from a marketing perspective, as they play a central role in shaping consumer demand. External stimuli can be classified into two main categories:

- 1) Marketing Stimuli - controllable elements that marketers can strategically design and implement to stimulate consumer interest and influence purchasing behavior

- 2) Environmental Stimuli - uncontrollable factors such as economic conditions, political and legal changes, cultural norms, and technological advancements, which indirectly affect consumer responses.

The buyer's cognitive process, which follows exposure to external stimuli, represents an internal mechanism that is not directly observable or predictable by producers. These internal responses are

influenced by various factors, particularly the buyer's personal characteristics and decision-making process. As a result, businesses must seek to understand these underlying processes to effectively address consumer needs. Gaining such insights allows marketers to refine communication strategies and tailor product or service presentations, thereby ensuring greater alignment with consumer preferences and expectations.

2.2 Demographic Characteristics

Demographic characteristics are analyzed within a rational and systematic framework to explain variations in human behavior across diverse social and economic contexts. Such behaviors are influenced by external stimuli that affect individual decision-making processes. It is widely recognized that individuals with different demographic profiles tend to exhibit distinct patterns or behavior. Key demographic variables such as gender, age, marital status, educational attainment, occupation, average monthly income, and household size are considered significant determinants of consumer behavior. [4-5]

3. Method

3.1 Conceptual Framework

The conceptual framework illustrates the relationship between personal factors and consumer behavior in the context of townhome purchase decisions, as presented in Figure 1. The framework comprises three main components:

- 1) Personal Factors - representing demographic characteristics of consumers that are believed to influence their purchasing behavior. These include gender, age, marital status, educational attainment, occupation, average monthly income, household size, and debt burden.

- 2) Consumer Behavior – referring to behavioral dimensions that directly influence purchase decisions. These consist of information sources, purpose of purchase, influencing persons, budget, and

consideration period.

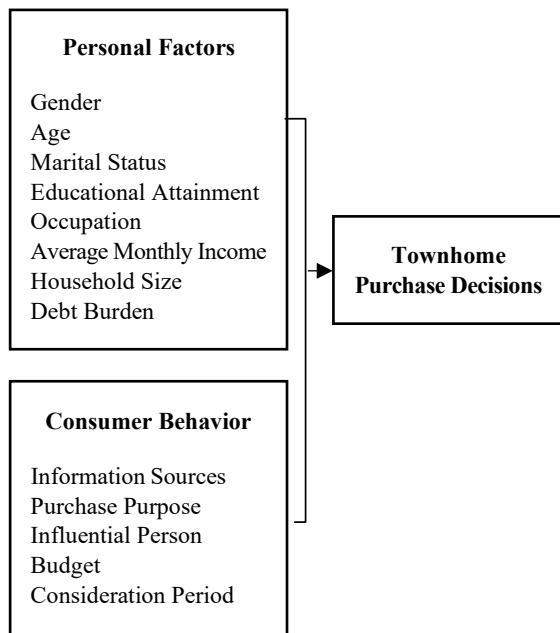


Figure 1 Relationship between Personal Factors and Consumer Behavior in Townhome Purchases

3) Townhome Purchase Decision – the outcome variable, referring to the actual decision to purchase a townhome, which is influenced by consumer behavior and indirectly shaped by personal factors.

The directional arrows in the framework indicate the hypothesized causal relationships, suggesting that both personal factors and consumer behavior contribute to the townhome purchase decision.

3.2 Research Methodology

This study employs a quantitative research approach, aiming to examine the influence of personal factors and consumer behavior on townhome purchase decisions among the working-age population in the Bangkok Metropolitan Area. A survey research design was adopted, with data collected through structured questionnaires. A purposive sampling technique was utilized to select a sample of 400 individuals, aged 21 to 60 years, who are currently residing in the Bangkok Metropolitan Area and are either interested in or in the process of making a

decision to purchase a townhome.

The questionnaire comprised three main sections: personal information, consumer behavior, and purchase decision, measuring decision-making through a 5-point Likert scale, where:

- 5 = Definitely Purchase
- 4 = Likely to Purchase
- 3 = Undecided
- 2 = Unlikely to Purchase
- 1 = Definitely Not Purchase

The interpretation of mean scores is classified as follows:

- 4.21 - 5.00: Definitely Purchase
- 3.41 - 4.20: Likely to Purchase
- 2.61 - 3.40: Undecided
- 1.81 - 2.60: Unlikely to Purchase
- 1.00 - 1.80: Definitely Not Purchase

The questionnaire's content validity was assessed by three experts through Index of Item-Objective Congruence (IOC), ensuring alignment between questionnaire items and the research objectives [6]. Reliability was evaluated using Cronbach's Alpha Coefficient [7].

For data analysis, descriptive statistics including frequency, percentage, mean, and standard deviation were used to describe general characteristics of the respondents. To test research hypotheses, inferential statistics were applied, including Independent-Samples T-Test and One-Way ANOVA.

4. Results and Discussion

4.1 Personal Characteristics of Respondents

The majority of the respondents were male (51.50%). Their ages ranged from 21 to 60 years, with most falling within the 31–40 age group (36.50%). A large proportion of the sample were single (54.25%). Their educational attainment ranged from primary school to above master's degree level, with the majority holding a bachelor's degree (63.25%). In terms of occupation, most respondents were private company employees (44.25%). Monthly income ranged

from less than 15,000 baht to more than 100,000 baht, with the largest proportion earning between 35,001 and 50,000 baht (23.00%). Most respondents lived in households with 3–4 family members (63.50%), and the majority reported having no debt obligations (38.25%).

4.2 Respondents' Housing Purchase Behavior

The study revealed that most respondents obtained information about townhome projects from websites or social media platforms (48.45%), followed by billboards (18.94%). The primary purpose for purchasing a townhome was to expand their living space (32.40%), followed by the intention to start a family (23.66%). The majority of respondents made the purchasing decision by themselves (63.50%), while spouses were the second most influential in the decision-making process (21.75%). Most respondents had a budget of not more than 2,000,000 baht (55.50%) followed by those with a budget between 2,000,001 and 5,000,000 baht (36.75%). In terms of decision-making time, the majority took more than one year to consider the purchase (57.50%), while 19.75% took more than six months but not exceeding one year.

4.3 Analysis of Personal Factors Influencing Townhome Purchase Decisions

The results of the analysis of personal factors influencing townhome purchase decisions among working-age individuals in the Bangkok Metropolitan Area are presented in Table 1.

Table 1 Analysis of Personal Factors Influencing Townhome Purchase Decisions

Characteristics	Purchase Decisions		
	$\bar{X}$	SD	P-value
Gender			0.223
Male	3.82	0.56	
Female	3.74	0.63	
Age (yrs)			0.161
21 – 30	3.69	0.54	
31 – 40	3.86	0.61	
41 – 50	3.80	0.66	

Characteristics	Purchase Decisions		
	$\bar{X}$	SD	P-value
51 – 60	3.74	0.57	
Marital status			0.056
Single	3.74	0.59	
Married	3.82	0.59	
Widowed	4.50	0.58	
Divorced/ Separated	3.83	0.75	
Education			0.122
Primary School	4.00	-	
Lower Secondary	3.25	0.50	
Upper Secondary	3.50	0.71	
Bachelor Degree	3.77	0.59	
Master Degree or Higher	3.85	0.60	
Occupation			0.122
Public Sector Emp.	3.81	0.56	
Private Sector Emp.	3.78	0.60	
Business Owner	3.85	0.66	
Others	3.50	0.64	
Monthly Income (baht)			0.597
< 15,000	3.61	0.61	
15,000 – 20,000	3.85	0.56	
20,001 – 25,000	3.82	0.55	
25,001 – 30,000	3.73	0.61	
30,001 – 35,000	3.77	0.53	
35,001 – 50,000	3.82	0.57	
50,001 – 100,000	3.76	0.79	
> 100,000	3.50	0.71	
Household Size (persons)			0.048*
1 – 2	3.82	0.60	
3 – 4	3.80	0.58	
>= 5	3.59	0.67	
Debt Burden			0.769
None	3.74	0.51	
Housing Loan	3.73	0.63	
Car/ Motorcycle Loan	3.90	0.88	
Credit Card	3.69	0.55	
Others	3.50	0.71	

According to Table 1, it was found that the personal factor of household size significantly affects the townhome purchase decisions of working-age individuals in the Bangkok Metropolitan Area. Specifically, respondents with 1 - 2 family members had the highest mean purchase decision score ($\bar{X}$ = 3.82, SD = 0.60). On the other hand, personal factors such as gender, age, marital status, educational attainment, occupation, average monthly income, and debt burden did not significantly influence the townhome purchase decisions among the same population. Therefore, these factors were not considered determinants in the decision-

making process for purchasing townhomes among working-age individuals in Bangkok.

4.4 Discussion

The study found that differences in the personal factor of household size significantly influence townhome purchase decisions among working-age individuals in the Bangkok Metropolitan Area. Specifically, respondents from households with 1–2 members exhibited the highest mean purchase decision score, followed by those with 3–4 members. This may be attributed to the characteristics of townhomes, which offer suitable living space, ease of maintenance, proximity to communities, convenient transportation, and affordable prices. These factors align well with the lifestyles of urban residents, who typically have small to medium-sized family structures or are in the early stages of family formation. These findings are consistent with the study by Sirilak Phetpa and Itthikorn Khamdet [8], which examined housing purchase decisions for detached houses in suburban areas of Bangkok. They found that household size significantly affected the decision-making process for purchasing suburban detached houses in the Bangkok area. Furthermore, the present study revealed that other personal factors, including gender, age, marital status, educational attainment, occupation, and average monthly income, did not significantly influence townhome purchase decisions among working-age individuals in Bangkok. This aligns with the findings of Sumalee Tosapornwichai and Kittipan Kongsawatkiat [9], who studied detached house purchase decisions of homeowners in Nonthaburi Province and reported that gender, age, educational attainment, marital status, income, and occupation had no significant effect on purchase decisions. Similarly, Purinut Thanavibulchai [10], in a study on factors influencing decision of a private company employee on the purchase of real estate in Bangkok metropolitan region, found that age and educational attainment did not

significantly affect decisions to purchase detached houses or townhomes. Additionally, Nattamonkarn Laengla [11] studied factors affecting the decision to buy housing of the population in Bangkok and vicinity and concluded that gender and age did not significantly impact the decision to purchase housing estates.

In the current study, debt burden was also found not to affect townhome purchase decisions among working-age individuals in Bangkok. Regardless of the type of debt incurred, respondents placed similar importance on factors influencing their townhome purchase decisions. Therefore, debt burden is not considered a determinant factor in the decision to purchase townhomes in this population.

5. Conclusion

This study investigated the influence of personal factors and consumer behavior on townhome purchase decisions among working-age individuals in the Bangkok Metropolitan Area. The findings revealed that household size was the only personal factor that significantly influenced purchasing decisions. Respondents from smaller households (1–2 members) demonstrated the highest levels of purchase intent, suggesting that townhomes are particularly attractive to individuals or couples with compact family structures due to their suitability for urban living, convenience, and affordability.

In contrast, other personal factors—including gender, age, marital status, educational attainment, occupation, monthly income, and debt burden—did not show a statistically significant impact on townhome purchase decisions. These results suggest that townhome purchasing behavior in Bangkok's working-age population may be less influenced by traditional demographic characteristics and more shaped by lifestyle preferences and practical considerations such as household size and space requirements.

Therefore, it is recommended that future research explore additional psychological or



behavioral factors—such as attitudes, values, and lifestyle—as these may offer deeper insights into the motivations driving real estate purchase decisions in urban environments.

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The Innovative Tactics of Integrated Marketing Communication Channels by TNK Travel in Ho Chi Minh, Vietnam

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Abstract

This study examines the innovative Integrated Marketing Communication (IMC) tactics of TNK Travel in Ho Chi Minh City, focusing on channel prioritization and strategic innovation. Using qualitative semi-structured interviews with 30 key informants from TNK Travel staff, competitors, and marketing experts, thematic analysis identified Personal Selling as the most effective IMC channel, supported by TNK Travel's 20+ years of experience and skilled workforce. However, digital transformation gaps, especially in Direct Marketing, were noted. The study proposes five innovations: WhatsApp Business integration, consultant specialization, hybrid digital-physical consultations, customer relationship intelligence systems, and cultural immersion experiences. These align with Vietnam's growing digital marketing sector while leveraging TNK Travel's relational strengths. The findings contribute to IMC literature in emerging markets and offer practical strategies for tourism SMEs, projecting a 25–30% increase in customer retention and a 15–20% rise in consultation conversions, enhancing TNK Travel's competitive position.

Keywords: Integrated Marketing Communications (IMC), IMC tool development, SMEs Marketing, Travel Agency, TNK Travel Group.

1. Introduction

Tourism is a major economic sector globally, particularly in emerging economies, due to its environmentally friendly and sustainable nature (Berno et al., 2001; Dogan & Zhang, 2023). In 2019, it accounted for 10.4% of global GDP and 10.3% of employment. Its contribution varies by region, from 7% of GDP in Africa to 13.7% in the Caribbean. The tourism-led growth hypothesis posits that tourism stimulates economic growth through foreign exchange, employment, and infrastructure development [15]. In Vietnam, tourism contributed 8–9% to GDP in 2024, generating 840 trillion VND from 17.5 million international arrivals and 110 million domestic tourists [68].

In the competitive tourism industry, marketing and promotion are crucial for

establishing brand awareness, differentiation, and fostering long-term loyalty [60], [34]. In high-involvement, intangible service contexts, such as tourism, effective communication has a significant influence on customer decisions. Despite the rise of digital tools, many firms still struggle with fragmented strategies. IMC emerges as a dynamic capability that integrates resources, enhances customer dialogue, and aligns brand messages [58], [10].

A growing emphasis on sustainability has also shifted consumer preferences, with 79% seeking environmentally responsible brands and 67% willing to pay more for sustainable options [50], [16], [48], [59]. For SMEs, limited resources pose a challenge in competing with larger firms [52]; thus,

intangible resources and capabilities like IMC become essential [15], [10].

Despite this, the role of IMC in enhancing market orientation (MO)—defined as an organization’s responsiveness to market intelligence—remains underexplored [51], [55]. TNK Travel, a medium-sized enterprise with 20+ years of experience, faces challenges in brand visibility. Although it employs a broad range of IMC tools, including digital and traditional marketing, its social media efforts have not translated into significant conversions [62]. This is due to poor integration, inconsistent content, and intense digital competition.

Notably, TNK Travel is absent from TripAdvisor’s search results for travel agencies in Ho Chi Minh City [63], revealing issues in brand positioning. Based on internal interviews and secondary data analysis, this study adopts a qualitative research approach to identify practical and action-oriented strategies for the company in the digital age.

2. Objective

The paper focuses on exploring marketing strategies for service-oriented enterprises, with a particular emphasis on Integrated Marketing Communication (IMC) tools, specifically:

1. To clarify the IMC channels of TNK Travel Group and find out the best channels
2. To compare the benefits and disadvantages of the best IMC channels of TNK
3. To suggest the innovative tactics of the best channel of TNK Travel

3. Literature review

3.1 IMC Concept

Integrated Marketing Communication (IMC) is no longer regarded as a novel tool, particularly in terms of the benefits it offers to SMEs [15], [10]. Moreover, recent studies indicate that the concept of IMC has become increasingly diverse, accompanied by debates regarding its definitions. Table 1 is based on [37] compilation of IMC definitions.

Accordingly, his definition, along with a recent alternative proposed by [14], has been included.

Table 1. Integrated Marketing Communication definitions

Authors	Year	Definition
American Association of Advertising Agencies	1989	recognises the added value of a comprehensive plan that evaluates the strategic roles of variety of communication disciplines - for example, general advertising, direct response, sales promotion and public relations - and combines these disciplines to deliver clarity, consistency, and maximum communications impact.
Schultz & Schultz	1998	Shift in focus from marketing communication tactics and operations to viewing IMC as a 'business process'. Technology, digitisation and target audiences can more accurately capture empirical behavioural data on consumers, employ valuation tools and techniques and differentiate consumers beyond merely economic criteria
Luck & Moffatt	2009	IMC as a broader concept. More than a process or activity within an organisation: IMC as a system of belief or engagement, embedded in an organisation's culture, underpinned by communication and driven by technology and senior management.



Kliatchko	2009	Include digital environments. IMC is a process and a concept.
Kerr & Patti	2013	Under the “broad” approach, a business process of cross-functional integration of marketing communications within the scope of a company's activities, up to the corporate level, with the aim of competitive advantage.
Kliatchko	2015	Four pillars of IMC: stakeholders, content, channels and results.
Tafesse & Kitchen	2017	Three alternative conceptual frameworks are used as a starting point to review, then a clearer synthesis and reconceptualisation model is proposed
Luxton, Reid, & Mavondo, Xu, Guo, Zhang & Dang,	2017 & 2018	IMC as a company's capability with a positive influence on organisational performance, facilitates the dissemination of information within the organisation and speeds up the decision-making process.
Mikalef & Pateli	2017	Uncertain environments challenge the sustainability of the company's competitive advantage provided by IMC implementation
Finne, A., & C. Grönroos		New term Communication-in-use concept, which is based on the value that emerges for a customer of messages sent by a communicator. We define communication-in-use as: [...] the customer's integration and sense making of all messages from any source: company-driven or stemming from other sources the customer perceives as

		communication, which forms value-in-use for a specific Based on this, IMC is developed into outside-in-oriented customer-integrated marketing communication (CIMC).
Butkouskaya, V., Llonch-Andreu, J. & Del-Carmen, M & Alarcón-Del-Amo	2019	The economy type has a moderation effect and clearly supports the differences caused by the implementation of IMC in developed and emerging economies. The potential of IMC for business advantage sustainability using technology is verified in a developed economy. They verified for customer and market performance, but not for financial performance. Conversely, in an emerging economy only customer performance could be verified, despite IMC having an indirect relationship with financial performance in both types of economies.

Source: Adapted from Kliatchko, 2005

In summary, the concept has evolved significantly over the years, encompassing various definitions, perspectives, and viewpoints. Nonetheless, common elements can be identified, including (1) comprehensive management of communication activities; (2) strategic coherence and unity; (3) customer and target audience focus; (4) emphasis on clear outcomes; and (5) fostering coordination and synergy. These elements contribute to a holistic approach to business development strategy, particularly for SMEs, by enabling them to leverage their limited resources effectively.

Source: Adapted from Kliatchko, 2005

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3.2 IMC tools

To effectively implement a comprehensive marketing approach, it is undoubtedly necessary to utilize a multitude of smaller tools to ensure coherence in the company's policies. According to Schultz, IMC is a process through which companies enhance their returns by aligning communication objectives with corporate goals [14]. Duncan characterized it as: a concept that directs and coordinates the processes of planning, implementing, and supervising brand messages, thereby fostering the development of brand-customer relationships [19]. In applying this concept, various tools are employed, with their primary specifications and applications outlined in Table 2.

Table 2. Main specifications and applications of IMC tools

IMC tools	Main Specifications	Main Application
Advertising	- Non personal - One-way	- Brand awareness - Brand image - Encourage a response
Sales promotion	- Short term - Encourage an immediate response	- Facilitate the buying decision
Direct marketing	- Direct and two-way - Data based - Using wide range of media	- Enabling dialogue with customer - Product and services customization
Public relations	- Create and control brand news - No media spending - The most credible MC	- Formal channel of communication with society specially in crisis management - Reinforcement and modify brand image
Personal selling	- Face to face communication - The most effective and expensive MC	- Dominant tool for B2B and special products in B2C

		- Brand message personalization
--	--	---------------------------------

Source: Maghsoodi et al., 2014

+ *Advertising* is a paid, non-personal offer of products by a company [39] via various types of print, outdoor, broadcasting, and interactive media to create a brand. Awareness and brand image, and persuade customers to respond [6].

+ *Sales promotion* is a value-added short-term strategy to motivate customers to respond immediately and conduct product trials [18], [39], [3]. Overusing this tool can damage brand image and decrease profit in the long term [2].

+ *Direct marketing* is a database-driven, direct, and interactive communication process that uses a wide range of media to stimulate a customer response. Because of the amount of intrusiveness, it can be seen as an annoying tool by the customer. To avoid this, decreasing customer defection should be considered, as well as trying to increase profit [34].

+ *Public relations* attempts to create and control the brand news, announcements, and reminders that are published by public media without spending. Marketing managers take advantage of this MC to build and reinforce their brand [57].

+ *Personal selling* is an interpersonal relationship by which sales representatives fulfill the customer's needs to gain mutual benefits. Personal selling is the most effective and expensive IMC tool. Therefore, sales force management is a very challenging matter for organizations [25]. Specially for fast-moving consumer goods (FMCG), packaging plays a critical role in brand identity, like a miniature billboard, while delivering the last brand message to the customer. It is estimated that almost 60-70% of the purchase decisions of FMCGs are not taken before arrival at the shop [19]

Nonetheless, implementing IMC requires the use of these tools, the five tools do not conflict with each other; rather, they

complement and reinforce one another to achieve the company's business objectives. Depending on specific goals, a business may utilize one or multiple tools concurrently

3.3 IMC planning process

Achieving alignment between communication tools and a company's overarching objectives is not always easily attainable. For this reason, [36] proposed a structured process aimed at ensuring integration and effective implementation.

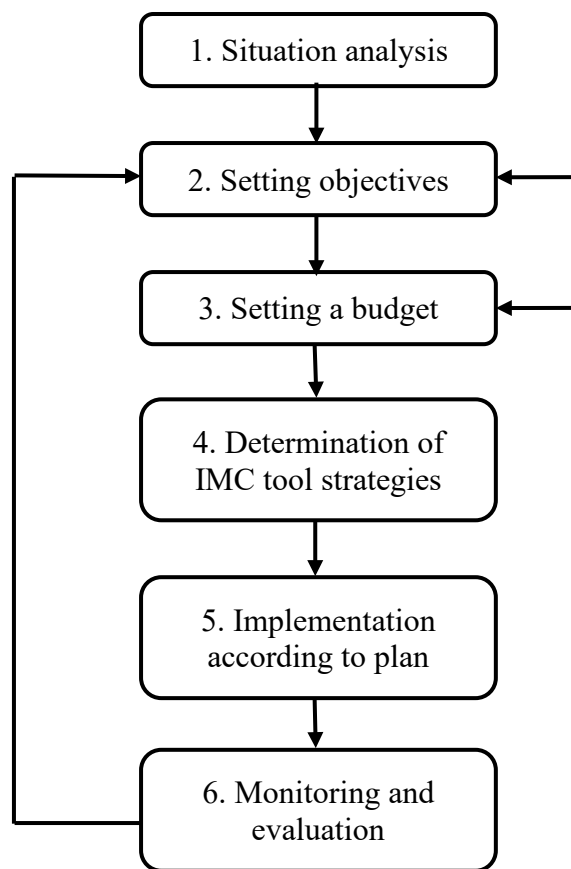


Figure 1. Planning Process

3.4 Conceptual Framework

The author adopts a theory-to-practice approach to analyze the actual implementation of IMC tools at TNK Travel Group, to identify the most effective tool currently in use. Subsequently, a comparative evaluation is conducted based on the advantages and disadvantages of each tool, supported by in-depth interviews. This process ultimately leads to the identification of the single most effective tool, upon which the development strategy is then focused, with an emphasis on innovation.

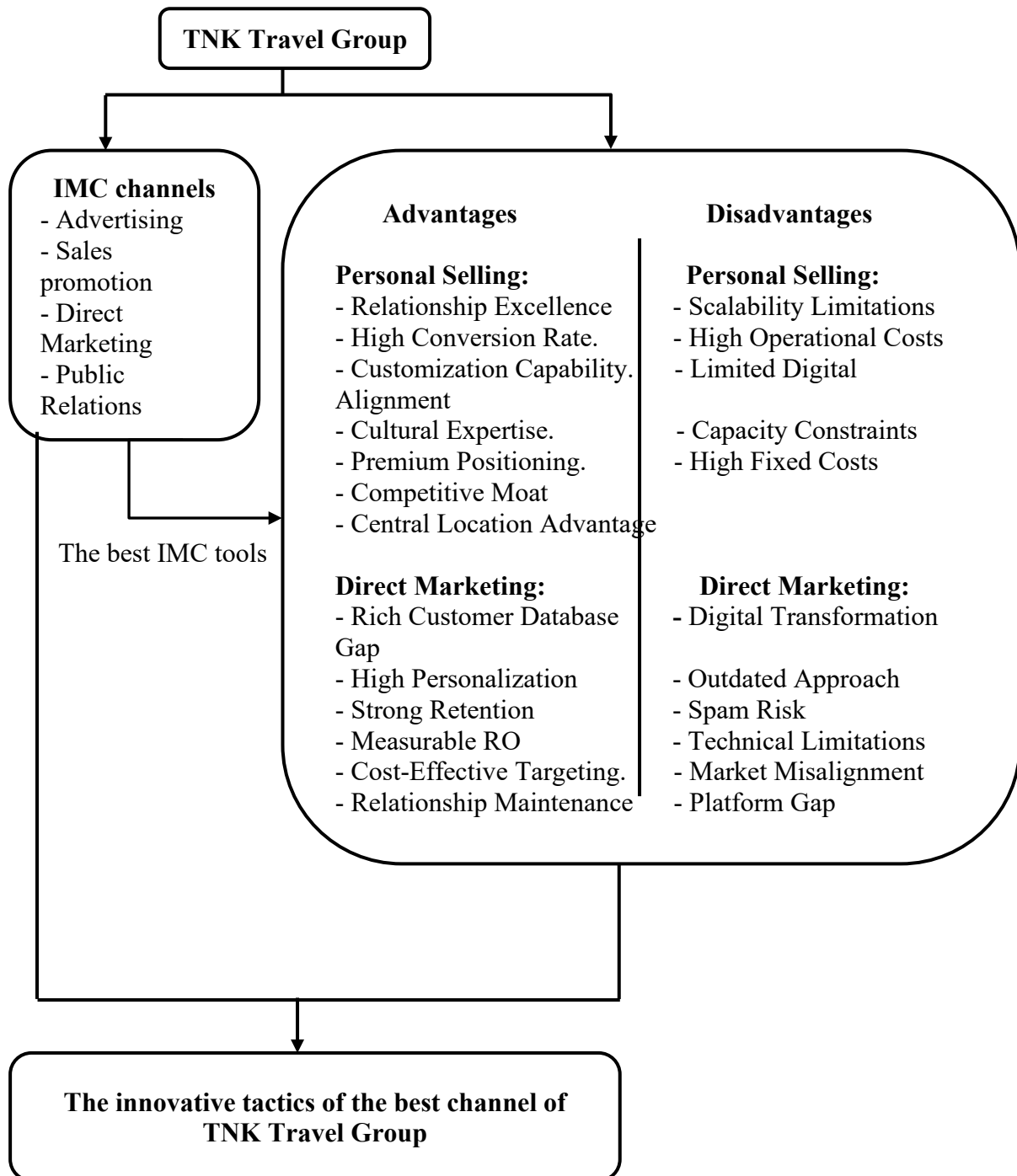


Figure 2. Conceptual Framework

4. Methodology

4.1 Population and Sampling

This study employed a qualitative research methodology utilizing semi-structured in-depth interviews to explore TNK Travel's IMC strategies and innovation opportunities. Qualitative research

methodology was selected as it emphasizes the depth and richness of context and voice in understanding social phenomena [44]. Qualitative research is a methodology for scientific inquiry that emphasizes the depth and richness of context and voice in understanding social phenomena, making it

particularly suitable for investigating complex organizational strategies and stakeholder perspectives in tourism marketing contexts.

Semi-structured interviews were chosen as the primary data collection method because they allow for predetermined thematic frameworks while maintaining flexibility in questioning sequences and phrasing [30]. A semi-structured interview is a data collection method that relies on asking questions within a predetermined thematic framework. However, the questions are not set in order or phrasing. This approach enables researchers to explore participants' experiences, perceptions, and recommendations regarding IMC strategies while allowing for emergent themes and unexpected insights.

4.2 Research methods

The study employed purposive sampling to select 30 key informants across three stakeholder groups with direct insight into TNK Travel and the Ho Chi Minh City tourism market, following stakeholder triangulation approaches in tourism research [54].

- **Group 1: TNK Travel Staff (n=10)** – Selected based on at least one year of tenure and involvement in customer-facing or marketing roles. Participants included senior managers, marketing and sales personnel, and operational staff.
- **Group 2: Competitor Representatives (n=10)** – Individuals with a minimum of three years' experience in Vietnam's tourism sector, representing direct competitors (e.g., Fiditour, Saigon Tourist), digital-first firms (e.g., Klook, Traveloka), boutique agencies, and large-scale operators (e.g., Vietravel).
- **Group 3: Marketing Experts (n=10)** – Selected for their expertise in IMC or tourism marketing, with no financial ties to TNK. The group comprised academics, consultants, industry association officials, CRM specialists, and one international expert.

Thus, this triangulated sample ensured a comprehensive and balanced understanding of TNK Travel's strategic position, not only from the internal but also from the customer's perspective, from the expert's perspective.

4.3 Data collection process

Data collection was conducted over six weeks from [June, 2025] to [July, 2025], following ethical approval from Ubon Ratchathani University's Institutional Review Board. The study employed qualitative semi-structured interviews, aligning with established stakeholder methodologies in tourism research.

The interviews were systematically conducted through six structured steps: (1) Initial Contact and Recruitment; (2) Interview Scheduling and Preparation; (3) Interview Conduct; (4) Data Documentation and Storage; (5) Data Verification and Member Checking.

Interviews lasted 45–60 minutes, conducted face-to-face for TNK Travel staff and competitors, and via video conferencing for remote participants. Sessions were conducted in English, with Vietnamese translation when necessary. All interviews were digitally recorded with participant consent, accompanied by field notes capturing non-verbal and contextual observations.

The interview guide comprised six sections: (1) participant demographics, (2) IMC channel identification and effectiveness, (3) comparative analysis of key tools, (4) strategic prioritization and resource allocation, (5) innovation suggestions, and (6) implementation roadmap.

4.4 Data Analysis

The collected data were analyzed using thematic analysis based on [7] six-phase framework: familiarization through transcription and repeated reading; generating initial codes systematically; searching for themes by grouping codes; reviewing themes against coded data and the full dataset; defining and naming refined themes; and producing the final report integrating

thematic narratives with illustrative participant quotes. The findings are detailed in the Results and Discussion sections.

5. Results and Discussion

To clarify the IMC channels of TNK Travel Group and find out the best channels

Through in-depth interviews with the Executive Director and Inbound Marketing Manager at TNK Travel Group, it was revealed that the travel company currently utilizes the full range of Integrated Marketing Communication (IMC) tools, specifically including:

5.1 Advertising

TNK Travel's advertising efforts primarily focus on digital platforms, including their website presence and online travel portals. The company maintains visibility through search engine marketing and partnerships with booking platforms to reach potential customers actively searching for Vietnam travel experiences.

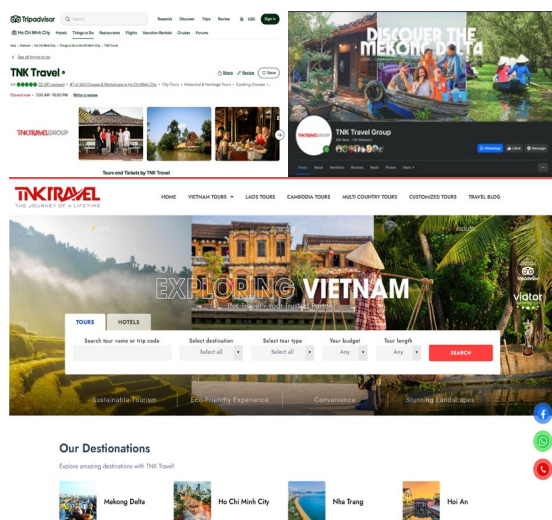


Figure 3. Multi-Digital Platform from TNK Travel for its product selling

It can be observed that TNK Travel Group is performing well in the area of advertising, as they have a presence across nearly all social media platforms, including their website. This is considered an effective communication method to increase brand awareness among customers, given their

reputation as established tour operators since 2001. TNK Travel's advertising strategy emphasizes its expertise in Indochina destinations. However, their approach appears to be more passive—primarily website-based—rather than proactive through paid advertising campaigns. This strategy may limit their reach within the highly competitive tourism market of Ho Chi Minh City.

5.2 Sales Promotion

TNK Travel implements sales promotion through seasonal discounts, group booking incentives, and special packages for repeat customers. Their sales promotion activities are particularly evident in their customized tour offerings and partnership deals with Signature Cruises in Halong Bay.



Figure 4. TNK Travel Group's tour brochures

The company's sales promotion efforts appear to be relationship-driven rather than mass-market focused. This approach aligns well with their premium positioning but may limit their ability to attract price-sensitive customers in Vietnam's competitive tourism market.

Sales promotion tools should be carefully integrated with advertising and personal selling efforts to create coherent customer experiences. TNK Travel's current approach may benefit from more systematic sales promotion campaigns tied to specific marketing objectives.

5.3 Direct Marketing

TNK Travel employs direct marketing through email communications with existing and potential customers, personalized follow-up services, and targeted outreach to international travel agencies. Their direct

marketing efforts leverage their customer database built over two decades of operations.

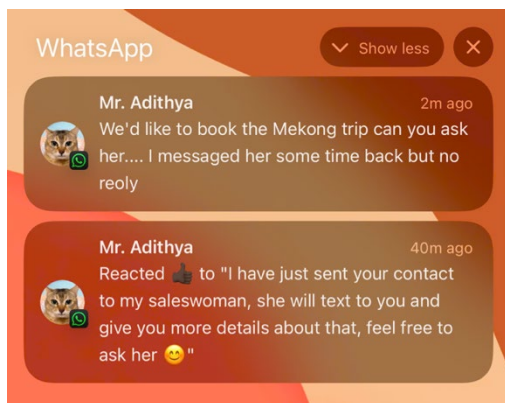


Figure 5. The connection between TNK and its customer via WhatsApp to design the tour following their needs

Direct marketing tools encompass email marketing, direct mail, telemarketing, and targeted digital advertising, enabling highly personalized messaging, measurability, and valuable data collection. TNK Travel's direct marketing approach appears strong in personalization but may lack sophisticated digital targeting capabilities.

The company's direct marketing efforts could be enhanced through better integration with its digital platforms and customer relationship management systems.

5.4 Public Relations

TNK Travel's public relations efforts focus on maintaining positive relationships with tourism authorities, building partnerships with other tourism operators, and managing their online reputation through customer testimonials and reviews.

Given TNK Travel's established position in Vietnam's tourism industry, their public relations strategy emphasizes credibility and trust-building. However, there may be opportunities for more proactive public relations activities, such as media relations and thought leadership initiatives.

Public relations, when combined with sales promotion elements, helps create brand loyalty and differentiate products from competitors. TNK Travel's long-standing

reputation provides a strong foundation for enhanced public relations activities.

5.5 Personal Selling

Personal selling represents TNK Travel's strongest IMC tool, leveraging their experienced team of tour operators, leaders, and guides to provide personalized consultation services. This approach is particularly effective for their customized tour packages and high-value customer segments.



Figure 6. TNK Travel staff and its location

Additionally, benefiting from its strategic location in the city center, TNK Travel Group possesses an advantage in proximity to tourists. It can be argued that TNK Travel's personal selling approach aligns perfectly with the high-involvement and relationship-oriented nature of travel services. Their focus on personalized attention and tailored solutions creates competitive advantages that are difficult for competitors to replicate. The company's success in personal selling stems from its profound local knowledge, cultural understanding, and ability to tailor tours to individual customer preferences. This tool likely yields the highest conversion rates among their IMC components.

In conclusion, based on interview results and the actual research findings regarding TNK Travel Group, the author can assert that the most effective tools used by TNK are Direct Marketing and Personal Selling. Their extensive experience in the tourism market and their large staff size have enabled TNK Travel

to leverage their strengths effectively, creating a lasting impression on travelers.

To compare the Advantages and Disadvantages of the best IMC channels of TNK

With strengths in both Direct Marketing and Personal Selling, identifying the most effective tool is essential to enable focused development aimed at achieving maximum efficiency. The determination of the highest-performing tool is based on IMC theory, which involves analyzing the benefits and disadvantages of these two tools, supplemented by in-depth interviews with selected key informants. These informants include TNK Travel employees, competitors, and marketing experts to obtain the most accurate results. According to [41], the benefits and disadvantages are detailed as follows (see Table 3).

Table 3. The comparison between the Advantages and Disadvantages of Direct Marketing and Personal Selling

IMC's tool	Advantages	Disadvantages
Direct Marketing	- Rich Customer Database: 20+ years of accumulated customer data - High Personalization: Tailored messaging based on travel history - Strong Retention: 40% repeat customer rate through targeted follow-ups - Measurable ROI: Easy to track campaign effectiveness - Cost-Effective Targeting: Precise audience segmentation capabilities - Relationship Maintenance: Continuous engagement with existing customers	- Digital Transformation Gap: Limited presence on emerging platforms (TikTok Shop, Shopee) - Outdated Approach: Email-heavy strategy in mobile-first market - Spam Risk: Customer complaints about excessive communications - Technical Limitations: Lack of A/B testing and advanced analytics - Market Misalignment: Underutilizing Vietnam's 23% digital advertising growth - Platform Gaps: Absent from key Vietnamese e-commerce channels

Personal Selling	- Relationship Excellence: 20+ years of experience building customer trust. - High Conversion Rate: 70% conversion from walk-in inquiries - Customization Capability: Real-time tour adjustments based on customer preferences - Cultural Expertise: Local knowledge and multilingual staff advantage - Premium Positioning: Enables higher pricing through personalized service - Competitive Moat: Difficult-to-replicate human expertise - Central Location Advantage: District 1 accessibility for spontaneous visits	- Scalability Limitations: Cannot reach mass audiences effectively - High Operational Costs: Labor-intensive model with expensive training - Limited Digital Alignment: Misaligned with Vietnam's digital-first consumer behavior - Capacity Constraints: Peak season handling challenges - High Fixed Costs: Expensive central location rent and large staff overhead..
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Regarding the use of Direct Marketing within the context of TNK Travel, it is evident that the company has leveraged certain strengths effectively. With over 20 years of operation since its establishment in 2001 and a team comprising more than 100 staff members, TNK Travel has accumulated a substantial customer database, which supports its relationship-building and direct marketing capabilities [10]. Furthermore, obtaining an International Tour Operator License from the Vietnam National Administration of Tourism in 2004 enhances its regulatory credibility, thereby helping to

mitigate consumer skepticism towards direct marketing efforts [40], [41].

"Our direct marketing works well because we have 20+ years of customer data. We can personalize emails based on previous trips and preferences. Our repeat customer rate is about 40% thanks to targeted follow-ups." _ TNK Travel's Marketing Manager

"TNK Travel's strength in direct marketing lies in its long-term customer relationships. They have good data for personalization, which is crucial in today's marketing landscape." _ Marketing Expert Representative

However, discussing disadvantages is also necessary, especially considering that Vietnam's digital marketing sector is expanding rapidly, valued at USD 1.64 billion in 2024 and projected to reach USD 4.65 billion by 2033, with a CAGR of 12.26% [31]. Despite this growth, TNK Travel's limited digital presence indicates underutilization of emerging opportunities. Although the company has accumulated over 10,000 reviews on TripAdvisor and 4,000 traveler photos, its digital marketing strategies remain relatively undeveloped compared to national industry trends. In 2023, digital advertising in Vietnam grew by 23% year-on-year; however, TNK Travel continues to rely primarily on traditional channels. Additionally, its absence from leading platforms such as Shopee, which holds a 67.9% market share, and TikTok Shop underscores missed opportunities in mobile marketing and e-commerce-driven direct engagement.

"Sometimes customers complain about too many emails. We need better segmentation to avoid being perceived as spam. Also, our email design could be more modern and mobile-friendly." _ TNK Travel's Sale Representative

"Their customer database is probably their strongest asset, but they could use it more strategically for upselling and cross-selling different destinations."
_Vietnam Adventure Tours Company

"Without proper A/B testing and analytics, their direct marketing campaigns may not be optimized for maximum effectiveness." _ Marketing Expert Representative

Regarding the tool of Personal Selling, it is also regarded as a key instrument that delivers stable revenue for the travel agency. TNK Travel benefits from experienced human capital, with skilled tour operators, leaders, and guides providing personalized service—an approach consistent with the literature on the importance of competent personnel in relationship-building and customized selling [18]. Emphasizing a customer-centric philosophy, the company prioritizes long-term relationships over transactional gains, recognizing word-of-mouth as its most effective promotional tool. Its comprehensive service portfolio—including packages, customized tours, incentive programs, and budget options across Vietnam—enables staff to tailor offerings, thereby enhancing opportunities for cross-selling and upselling. High customer satisfaction is evidenced by 22,385 reviews on TripAdvisor, with consistently positive feedback as recent as November 2024.

"Our experienced guides and tour consultants are our biggest asset. They can customize tours on the spot based on customer preferences. This personal touch converts 70% of walk-in inquiries."
_ TNK Travel's Senior Marketing Representative

"Being located in District 1 helps a lot. Tourists can easily find us, and we get many spontaneous visits. Our staff speaks multiple languages, which gives us an

edge." _TNK Travel's Sale Representative

"Personal selling works exceptionally well for high-involvement purchases like travel. TNK's experienced team can address complex customer needs that digital channels cannot." _Marketing Expert Representative

Despite employing over 100 staff, TNK Travel's reliance on personal selling presents scalability challenges, as this high-touch model limits market reach compared to digital channels. As Vietnam's consumer landscape shifts toward digital-first behaviors, driven by a tech-savvy middle class, the company's traditional approach may not align with evolving preferences. Additionally, the labor-intensive model implies higher operational costs per customer, raising concerns about long-term profitability when compared to more automated and scalable digital marketing strategies.

"Training new staff is expensive and time-consuming. We need consistent service quality across all team members. During peak season, we sometimes can't handle all walk-in customers properly." _TNK Travel's Sale Team

"Their central location is an advantage, but rent costs must be high. We focus more on digital channels to reduce overhead costs." _Kim Travel

"Personal selling doesn't scale well. TNK needs to find ways to maintain a personal touch while reaching larger audiences, perhaps through video consultations or chatbots." _ Marketing Expert Representative

It can be observed that each tool possesses its advantages, suitable for the business conditions of TNK Travel. However, if the decision is made to focus solely on one

tool, this presents a significant challenge for the company. Particularly, when this question is posed to key informants, it becomes the most difficult aspect to address.

"I would put 70% into Personal Selling. Our guides and consultants are what make us special. Tourists can book online anywhere, but they can't get our 20+ years of local expertise online. This is our competitive moat." _TNK Travel's Marketing Manager

"Direct Marketing. TNK needs to catch up digitally, or they'll become irrelevant. Their personal selling is good, but it can't overcome poor digital presence in 2024." _ACE Travel Company

"70% Direct Marketing. TNK operates like it's still 2010. Vietnam's digital ad market grew 23% last year. They have great assets - customer data and brand history - but they're not leveraging them strategically." _Marketing Expert Representative

"Personal Selling differentiation is stronger. Digital marketing can be copied quickly. Training experienced consultants takes years. TNK's 100+ staff represent millions in training investment that competitors can't promptly replicate." _Marketing Expert Representative

Based on the results of interviews with 30 key informants, the preference between these two tools is relatively evenly distributed, with no significant disparity. Specifically, 23 out of 30 respondents recommended focusing on developing Direct Marketing, while 26 out of 30 favored investing in Personal Selling. Therefore, the author concludes that, given the existing advantages in location, personnel, and long-term development journey, this tool—Integrated Marketing Communication—would be a suitable

investment for TNK Travel. Achieving success with this approach would provide the company with several competitive advantages, including: (1) sustainable competitive differentiation; (2) high-involvement purchase behavior; (3) existing staff expertise and investment; (4) opportunities for premium pricing; and (5) the ability to build emotional connections with customers.

To suggest the innovative tactics of the best channel of TNK Travel

By addressing existing shortcomings while leveraging current strengths, the author proposes several tactics based on the theoretical framework of the IMC planning process developed by [36].

Firstly, WhatsApp Business Integration for Enhanced Personal Selling. TNK Travel should adopt WhatsApp Business to enable 24/7 personalized consultations, enhancing its relationship-driven approach. Already used by 55% of travel agencies [27], WhatsApp offers a scalable, user-friendly alternative to calls [49]. Applications include pre-trip planning, in-trip support, and post-trip follow-up. With a low monthly cost (\$50–100) and a 2–4 week setup, it could improve customer retention by 25–30% through real-time, two-way communication [43], [49].

Secondly, TNK Travel should focus on the consultant Specialization and Expertise Development Program. They should develop specialized consultant roles (e.g., Family, Solo Female, Adventure, Cultural, and Luxury Travel) to align with tourism's shift toward digitalization and sustainability [24], [11]. Tactical steps include certified training, niche portfolios, customer-matching systems, and cross-selling integration. This approach enhances consultation efficiency, customer satisfaction, and service value, potentially increasing fees by 15–20%. Notably, 18 of 30 stakeholders identified specialization as a key differentiator in personal selling.

Thirdly, the Hybrid Digital-Physical Consultation Model is necessary for TNK Travel to enhance its personal selling. They

should integrate video consultations with in-person meetings to expand personal selling while maintaining service quality. As tourism embraces digital transformation, hybrid models combining technology with human interaction are increasingly preferred [56]; [64] [29]. Tactics include virtual itinerary planning, AR business cards, and digital tools like interactive maps. This approach enhances accessibility, reduces client time costs, and differentiates TNK from both traditional and fully digital competitors.

Fourthly, TNK Travel should implement a CRM system to leverage its 20+ years of customer data for data-driven personal selling. CRM enables journey tracking, preference profiling, and consultant performance analytics, enhancing service personalization and retention [65] [11]. SMEs with advanced CRM systems report 25–30% higher retention and 15–20% revenue growth [23]. The system supports targeted follow-ups, premium client identification, and continuous service optimization.

Lastly, the Cultural Ambassador Consultation Model needs to concentrate on repositioning its consultants as cultural ambassadors, turning consultations into immersive experiences. As tourists increasingly seek authenticity over standard tours [56], this approach enhances personal selling by delivering cultural value from the first interaction [28]. Tactics include mini cultural workshops, sensory experiences (e.g., Vietnamese tea/coffee tasting), local artisan partnerships, and story-based selling. Such immersion can boost satisfaction by 40% and social media engagement by 60% [64].

In short, these five innovations align with global digital transformation trends while preserving TNK Travel's core strength in personal selling [24]. Emphasizing enhancement over replacement, the recommendations integrate technology with human expertise, leveraging TNK's 20+ years of relationship-building to meet evolving customer expectations [28]. This

hybrid approach supports sustainable growth and creates competitive advantages that are difficult to replicate [11], [65].

Discussion

This section explores the research findings in connection with the three outlined objectives, linking empirical results to existing literature. It also highlights the theoretical and practical implications for TNK Travel and the wider tourism industry.

Objective 1: Clarification of IMC Channels and Identification of Best Channels

The findings reveal that TNK Travel employs all five traditional IMC tools (advertising, sales promotion, direct marketing, public relations, and personal selling), consistent with [13] comprehensive approach to integrated communication strategies. However, the effectiveness hierarchy identified through stakeholder interviews demonstrates significant variation in performance across channels.

Personal Selling Dominance: The research confirms personal selling as TNK Travel's most effective channel, achieving a 70% conversion rate from walk-in inquiries. This finding aligns with [47] 's assertion that personal selling represents "the most effective and expensive MC tool," particularly suitable for high-involvement purchases characteristic of tourism services. The effectiveness stems from TNK Travel's 20+ years of accumulated expertise and strategic District 1 location, creating what Porter (1985) would classify as a sustainable competitive advantage through difficult-to-replicate human capital.

Direct Marketing Potential: Despite ranking second in current effectiveness, direct marketing emerges as having significant untapped potential. TNK Travel's 40% repeat customer rate through targeted follow-ups demonstrates the power of their customer database, supporting [9] findings on IMC effectiveness in emerging economies. However, the company's limited digital presence contradicts Vietnam's rapidly expanding digital marketing sector, valued at

USD 1.64 billion in 2024, with projected growth to USD 4.65 billion by 2033 [67].

Integration Gaps: The research identifies fragmented implementation across channels, echoing [35] observations about tourism firms struggling with cohesive strategies. TNK Travel's passive advertising approach and relationship-driven sales promotion indicate missed synergistic opportunities that could enhance overall IMC effectiveness.

Objective 2: Comparative Analysis of Best IMC Channels

In the second objective of the study, the author identifies personal selling as the most suitable IMC tool for TNK Travel Group. This is because the tool remains highly effective, offering cultural expertise, multilingual services, and personalized experiences that align well with current tourism trends [48]. Strong customer satisfaction, evidenced by 22,385 reviews on TripAdvisor, reinforces its value in building long-term relationships [18] and supporting premium service positioning [40], [41]. Moreover, the journey of reaching customers is not solely executed by the company's sales team, but also by tour guides—individuals who possess firsthand experience from actual trips and contribute significantly to the development of tours that meet the personalized needs of travelers.

Objective 3: Innovative Tactics Development for the best one

The proposed strategies primarily target the company's current shortcomings, such as the lack of a centralized customer care system. One key recommendation is to implement personalized customer service via the WhatsApp platform, which is used by millions of travelers worldwide. Currently, TNK Travel does not operate an official WhatsApp business channel, relying instead on individual staff members for communication. This practice poses significant risks, especially when employees leave the company, potentially resulting in lost customer connections. By integrating WhatsApp technology into the company's

official chatbox under the TNK Travel Group brand, customers can be retained within the company's ecosystem rather than through personal contacts. This approach also exemplifies successful technology adoption that preserves human connection while expanding reach. This approach addresses [1] the communication-in-use concept by enabling continuous customer value creation through accessible, personalized interaction. The projected 25-30% retention improvement aligns with [11] findings on digital innovation driving factors in tourism.

While TNK Travel offers diverse tourism products, the absence of a flagship service limits brand distinctiveness among regional SMEs. Thus, personalized experiences through personal selling should be strategically tailored to individual needs.

Eventually, the key contributions of this paper emerge from the research findings. First, the success of personal selling highlights the need for internal guideline templates to standardize and motivate marketing staff. Second, this research introduces the "Stakeholder Triangulation in IMC Evaluation" model, integrating insights from staff, competitors, and experts, enhancing analytical depth beyond single-source studies. Third, the cultural ambassador consultation model represents a theoretical advancement in personal selling by embedding cultural immersion into the sales process, addressing gaps in tourism marketing literature on value co-creation. These findings inform TNK Travel's strategic direction and broader academic discourse.

6. Summary and Recommendation

This study examined the innovative Integrated Marketing Communication (IMC) tactics of TNK Travel in Ho Chi Minh City, Vietnam, addressing three core objectives through qualitative research with 30 key informants across stakeholder groups. The research employed semi-structured interviews and thematic analysis to investigate IMC channel effectiveness,

comparative advantages, and innovation opportunities for tourism SMEs in emerging markets.

Key Findings

The study identified Personal Selling as TNK Travel's most effective IMC channel, achieving a 70% conversion rate, supported by the company's strategic location, experienced multilingual staff, and over two decades of market presence. Direct Marketing followed, with 40% repeat rates, though its effectiveness is hindered by limited digital adaptation. A strategic paradox emerges: while Personal Selling offers relational strength and cultural expertise, it faces scalability and cost limitations; conversely, Direct Marketing has strong data assets but underutilizes Vietnam's booming digital landscape (USD 1.64 billion in 2024, projected to USD 4.65 billion by 2033). To address these gaps, five innovations were proposed: WhatsApp Business integration, consultant specialization, hybrid consultations, advanced CRM systems, and cultural ambassador experiences, projected to increase customer retention by 25–30% and consultation conversion rates by 15–20%.

Future Research

Future studies should employ mixed-methods approaches to quantitatively validate the projected performance improvements from the proposed innovations. Longitudinal studies tracking customer retention rates, conversion metrics, and revenue growth following implementation would provide empirical evidence for the theoretical framework developed in this research.

In addition, future research should examine how IMC strategies can promote sustainable tourism practices while maintaining commercial effectiveness. Studies on eco-friendly messaging integration, sustainable destination promotion, and environmentally conscious customer segmentation would address growing sustainability demands. Regarding the Social Media and Community Engagement, research investigating the role

of social media in enhancing traditional IMC approaches, particularly for relationship-building and community creation, would extend the Direct Marketing innovation potential identified in this study.

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The estimation of the willingness to pay to prevent health problems from air pollution

Case study: Map Ta Phut Industrial Estate, Thailand.

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Abstract

People living around Map Ta Phut Industrial Estate in Rayong Province, Thailand, face persistent respiratory and occupational health issues due to industrial air pollution. This study estimates households' willingness to pay (WTP) to prevent health problems using the contingent valuation method (CVM) with a double-bounded dichotomous choice design. Surveying 640 resident households, we find an inflation-adjusted mean WTP of approximately 249 baht per household per year (2025 baht). Significant determinants include gender, household income, occupational impact, and respiratory conditions. The findings provide critical insight into public valuation of health interventions and support evidence-based environmental policy recommendations.

Keywords: Air pollution, Willingness to Pay, Contingent Valuation, Health economics, Thailand

1. Introduction

Air pollution remains a persistent environmental and public health challenge in many parts of Thailand, particularly in heavily industrialised areas such as the Map Ta Phut Industrial Estate in Rayong Province. Designated as one of Thailand's largest petrochemical and heavy industrial zones, Map Ta Phut has long been associated with elevated emissions of volatile organic compounds (VOCs), sulphur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM₁₀ and PM_{2.5}). These pollutants are released into the atmosphere through manufacturing processes, such as petrochemical production, power generation, and metal refining.

Numerous studies by the Department of Disease Control, Rayong Provincial Health Office, and independent researchers have shown a consistent link between these

emissions and adverse health outcomes among the local population. Residents in surrounding communities report higher rates of respiratory illness, asthma, skin and eye irritation, cardiovascular problems, and occupational exposure symptoms compared to national averages. The Map Ta Phut Hospital has documented an increase in outpatient visits for respiratory conditions over several years, highlighting the burden placed on the healthcare system and community well-being.

Despite government interventions, such as the Pollution Control Department's air monitoring efforts and stricter emission controls, the perception among many residents is that existing regulations are insufficient. Environmental justice concerns have also emerged, as communities near the industrial estate often have limited economic power or political influence to advocate for

stronger protections or compensation mechanisms.

From an economic perspective, air pollution imposes a combination of direct health costs (medical expenses, clinic visits, hospitalisations) and indirect costs (lost income due to illness, reduced work capacity, long-term productivity losses). However, these costs are typically externalised and not captured in the market prices of goods and services produced by polluting industries.

In this context, economic valuation plays a crucial role. By estimating how much affected individuals are willing to pay (WTP) to avoid pollution-related health impacts, policymakers can derive a monetary metric to guide decision-making. Estimation is especially important in developing countries like Thailand, where public resources are constrained and cost-effectiveness is a central consideration in health and environmental policy.

This study focuses on estimating household WTP for a proposed mobile health unit, a public service initiative aimed at delivering preventive healthcare, pollution exposure monitoring, and local medical support to residents near the Map Ta Phut Industrial Estate. The contingent valuation method (CVM) with a double-bounded dichotomous choice design was employed to elicit preferences and derive an average monetary valuation per household.

The rationale for using CVM is its ability to capture non-market values, such as improved health or reduced risk, based on hypothetical but realistic policy scenarios. By understanding the distribution and determinants of WTP among community members, the study provides a grounded economic estimate of community-supported funding potential for public health interventions related to environmental pollution.

Ultimately, the results contribute to the literature on health-environment economics and offer practical evidence for local authorities, environmental planners, and

health sector decision-makers. The findings support the integration of public preferences into environmental impact assessment (EIA) procedures and long-term urban-industrial development strategies, ensuring that local voices are reflected in policies that affect their health and livelihoods.

Although this study collected data in 2015, it is important to note that the environmental, industrial, and social conditions in the Map Ta Phut area have remained relatively unchanged. The number of operating factories, types of emissions, and population exposure patterns have stayed consistent over the past decade, according to reports from the Pollution Control Department and the Industrial Estate Authority of Thailand. Additionally, no major expansions or shutdowns of industrial complexes have occurred, and the area continues to be classified as a high-risk zone in Thailand's national environmental risk maps [1],[2]. Therefore, the health and economic context in which the data were collected is still applicable today, allowing the results to remain relevant for policy and community application in 2025.

2. Literature Review

The Contingent Valuation Method (CVM) is a widely accepted stated-preference technique used to estimate economic values for non-market goods, especially public goods such as environmental quality, public health, and ecosystem services. CVM involves presenting respondents with a hypothetical scenario and asking how much they would be willing to pay (WTP) to gain a benefit or avoid a cost. Because it directly elicits monetary values based on individual preferences, CVM is especially useful for cost-benefit analysis and environmental policy design in contexts where market prices are unavailable or incomplete.

Numerous international studies have applied CVM to assess WTP for improvements in air quality and reductions in pollution-related health risks. In Europe, the

U.S., China, and Southeast Asia, CVM has been used to estimate the value of statistical life (VSL), assess risk perception, and quantify the public's demand for clean air. A study by [3] in Italy and the U.S. found that WTP for air pollution mortality risk reduction was highly sensitive to income, perceived personal risk, and the framing of the valuation question. In Korea, [4] applied CVM to measure public support for a clean air fund, with results indicating that chronic respiratory health conditions significantly increased WTP.

In Thailand, empirical studies have increasingly focused on WTP for air-quality improvements, especially in urban and industrial zones. [5] applied CVM to estimate the VSL in Bangkok, finding substantial variation depending on whether the risk source was air pollution or traffic accidents. Perceived proximity to pollution sources and trust in authorities were critical factors influencing WTP.

A national-scale study by [6], using data from multiple provinces, estimated the aggregate WTP for air-quality improvement at 18.8 billion baht per year. This figure reflects both health concerns and the population's increasing environmental awareness. Notably, their study found that income, education, and environmental knowledge were statistically significant positive predictors of WTP, while perceived ineffectiveness of government programs tended to suppress it.

Local studies have also addressed the Map Ta Phut area, although few have provided quantitative WTP estimates. The area has been the focus of numerous environmental justice reports due to its history of toxic releases, legal disputes, and community health crises. Reports by [7] and academic researchers highlight that residents often experience limited access to redress or health support despite enduring chronic pollution exposure.

Importantly, studies employing CVM in developing countries emphasise the need to

adjust methods for cultural, economic, and informational differences. For instance, double-bounded dichotomous choice formats, such as the one used in this study, are recommended to reduce starting-point bias and improve the efficiency of WTP estimates [8]. Furthermore, incorporating localised scenarios such as a mobile health unit in a known industrial pollution area enhances the realism and policy relevance of responses [9].

This study contributes to the literature in several ways:

1) It updates WTP estimates to 2025 baht, providing inflation-adjusted figures for policy application.

2) It focuses on a high-risk industrial zone, enabling local governments to benchmark WTP against actual health interventions.

3) It uses double-bounded CVM, which improves confidence intervals and identifies WTP determinants more precisely than single-bounded formats.

In summary, the findings presented here bridge the gap between national WTP estimates and localised environmental health concerns. They offer robust evidence to inform environmental compensation schemes, community health investment, and pollution liability assessments under Thailand's evolving environmental legal framework [10],[11].

3. Methodology

3.1 Survey Design and Sample

This study utilised a quantitative survey conducted between February and March 2015 in communities surrounding the Map Ta Phut Industrial Estate, Rayong Province, Thailand. A total of 640 households were selected using a multi-stage random sampling technique. First, villages within 5 kilometres of the industrial estate were identified using administrative boundary maps and environmental risk overlays. Second, household lists were obtained from local health volunteers and community leaders. Finally, households were randomly sampled

proportionally from each sub-district to ensure representation across spatial and demographic lines [12].

Prior to full implementation, a pilot survey with 30 respondents was conducted to refine the questionnaire, confirm scenario comprehension, and calibrate initial bid values for the WTP question. Based on pilot responses and feedback, four starting bids were selected: 50, 100, 200, and 500 baht per household per year.

The main questionnaire was divided into five sections:

1. Demographic and socioeconomic characteristics
2. Health history and experience with pollution-related symptoms
3. Awareness and attitudes toward air pollution
4. The hypothetical mobile health unit scenario
5. WTP elicitation using double-bounded dichotomous choice format

Respondents were aged 18 years or older and identified as the household's primary financial decision-maker. Enumerators were trained public health students who used tablet-assisted personal interviewing (TAPI) to reduce data entry errors.

3.2 Hypothetical Scenario

To ensure realistic valuation, all respondents were presented with the following scenario:

"Suppose that a mobile health unit will be set up in your community to offer regular checkups, pollution-related illness screening, and emergency referrals. The service will operate under a local health fund co-managed by the community and public hospitals. This service needs voluntary financial support from households to continue operating. Would your household be willing to pay a yearly contribution to support this health unit?"

The scenario was supplemented with visual aids and simple language to ensure comprehension, especially among elderly or low-literacy respondents. Enumerators were

trained to avoid framing bias and to clarify that participation in the funding scheme would be voluntary, not mandatory.

3.3 WTP Elicitation Method: Double-Bounded Dichotomous Choice

Following best practices in CVM, the WTP question used a double-bounded dichotomous choice format to increase estimation efficiency and reduce variance compared to single-bounded questions. Respondents were randomly assigned one of four initial bid values. Based on their response:

- If "Yes", a follow-up question was posed with a higher bid (e.g., from 100 → 200 baht).
- If "No", a lower bid was presented (e.g., from 100 → 50 baht).

These choices yielded four response patterns per household (Yes-Yes, Yes-No, No-Yes, No-No), which were later modelled using interval regression.

A final open-ended WTP question was also included to capture maximum willingness to pay, which served as a robustness check.

3.4 Statistical Estimation

Responses were analysed using a Weibull distribution function, commonly used in CVM to model the non-negative, right-skewed distribution of WTP. The likelihood function was constructed based on each respondent's bid interval, and parameters were estimated using maximum likelihood estimation (MLE). The model yielded both mean and median WTP values, along with 95% confidence intervals.

A multivariate probit model was also fitted to explore determinants of WTP. Independent variables included 1) Gender (1 = female) 2) Age (in years) 3) Monthly household income 4) Education level 5) Health status (presence of respiratory disease or allergy) 6) Income loss due to pollution-related illness And 7) Proximity to pollution sources (measured as perceived distance in km) Collinearity diagnostics and sensitivity tests were performed to ensure model

robustness.

3.5 Inflation Adjustment

The original WTP values were estimated in 2015 baht. To ensure relevance for current policy planning and international comparison, all monetary values were adjusted to 2025 values using Thailand's Consumer Price Index (CPI) data.

- CPI (2015) baseline = 100
- CPI (2025, est.) $\approx$ 119
- Inflation factor = 1.19

This calculation reflects cumulative inflation of approximately 19% over the 10-year period, accounting for modest price increases from 2015 to 2024, and a minor deflationary period in early 2025 [13],[14].

Therefore, all reported WTP figures in this study are presented in real 2025 baht, making them directly usable for current policy cost-benefit assessments and health economic planning.

4. Results

4.1 Response Summary

The survey received valid responses from all 640 households approached, resulting in a 100% completion rate, owing to community support and strong engagement from local health volunteers. The majority of respondents expressed positive support for the proposed mobile health unit initiative. A significant portion of participants acknowledged the relevance of such a service to their community, citing concerns about increasing respiratory illness and the difficulty of accessing timely medical care. When asked about their willingness to financially support the initiative, over 70% of respondents agreed to contribute under at least one of the proposed bid levels.

Analysis of the bid-specific responses revealed the expected pattern: lower starting bids (e.g., 50 baht) yielded higher acceptance rates, while higher bids (e.g., 500 baht) resulted in higher refusal rates. This result aligns with conventional contingent valuation theory and confirms that respondents understood the trade-off between benefit and

cost. The double-bounded structure generated sufficient variation across Yes-Yes, Yes-No, No-Yes, and No-No response categories, providing robust input for interval estimation of WTP.

4.2 WTP Estimates (Adjusted to 2025)

Based on the Weibull distribution model, the average willingness to pay (WTP) in 2015 was estimated at 209.39 baht per household per year, with a corresponding median of 164.50 baht. Applying an inflation adjustment factor of 1.19, in line with Thailand's Consumer Price Index (CPI) trends from 2015 to 2025 [15], the inflation-adjusted mean WTP is approximately 249 baht per household per year, and the median WTP is 196 baht per household per year.

These figures reflect a moderate but meaningful valuation that residents place on improving their health security through locally accessible services. Notably, the relatively small gap between mean and median suggests that the WTP distribution is only mildly skewed, further supporting the appropriateness of the Weibull function for modelling.

4.3 Determinants of Willingness to Pay

Regression analysis was conducted to identify variables significantly influencing WTP responses. The model included both demographic and health-related predictors. Results show that gender was a significant factor at the 90% confidence level, with female respondents more likely to express a willingness to contribute financially to the health initiative. This willingness may reflect gendered roles in caregiving and greater concern for household health [16].

Household income was also significant at the 90% level, with higher-income households demonstrating higher WTP, consistent with economic theory and prior empirical studies. Importantly, the occupational impact of pollution, specifically whether any household member had experienced income loss due to pollution-related illness, was significant at the 95% level, underscoring the tangible economic

burden of environmental health risks [17].

Health status variables were particularly influential. Households reporting respiratory symptoms such as chronic cough, shortness of breath, or allergic reactions had significantly higher WTP, with p -values < 0.01 . These respondents viewed the mobile health unit as a valuable service for early detection, monitoring, and treatment. Similarly, households with prior hospitalisations due to air pollution-related issues showed increased support, although the sample size in this subgroup limited precision [18].

Together, these findings suggest that direct experience with pollution-related harm, both economic and medical, strongly shapes willingness to pay. The observed relationships validate the use of CVM in capturing community preferences and suggest that targeted messaging for future health initiatives may increase both support and participation.

5. Discussion and Policy Implications

The results of this study provide important insights into the economic valuation that households place on preventing health impacts from industrial air pollution. The adjusted mean willingness to pay (WTP) of 249 baht per household per year is modest in absolute terms but significant relative to the average household income levels in the Map Ta Phut area, where many families earn less than the national urban average. This result suggests that even low- to middle-income households are willing to make financial sacrifices to secure better health protection and access to services [19].

The data further indicates that households with direct experience of pollution-related illness or income loss exhibit markedly higher WTP, underscoring the lived costs of pollution and the demand for responsive public health infrastructure. In this context, the proposed mobile health unit is more than a preventive care mechanism; residents see it as a form of environmental justice and compensation for years of

unaddressed harm. Such a service would not only deliver healthcare but also restore trust in local governance and public health institutions.

The income effect on WTP suggests a need for tiered or subsidised payment models, ensuring that lower-income households are not excluded from participating. Equally, education and awareness campaigns can play a vital role. Our findings show that respondents with higher awareness of pollution risks and their connection to health symptoms were more willing to contribute, suggesting that community outreach, environmental education, and participatory planning can strengthen public engagement and financial support for such initiatives [20].

From a policy perspective, the implications are twofold. First, the WTP estimates can be used to perform cost-benefit analyses for public investment in health infrastructure or pollution mitigation. If extended to the estimated 5,000 households residing near the industrial estate, total voluntary contributions could exceed 1.2 million baht per year. This amount, while not sufficient to fully fund a mobile health unit, could supplement public health budgets or provide matching funds for government or private investment.

Second, these findings offer evidence for the design of pollution compensation schemes or corporate social responsibility (CSR) programs in industrial zones. Regulators and policymakers can use WTP figures to benchmark the minimum acceptable level of community benefit that should accompany environmental permits or emissions allowances. Such schemes could include health funds, clean air technology subsidies, or industrial levies redirected toward health services [21].

Finally, the use of CVM in this study demonstrates its applicability in Thailand's policy setting. As public demand for citizen-centred environmental policy grows, tools that quantify local preferences are increasingly necessary. Integrating WTP

estimates into Environmental Impact Assessments (EIAs) and Health Impact Assessments (HIAs) would enhance the transparency and responsiveness of development approvals [22].

In sum, the findings highlight both the economic rationale and the social acceptability of investing in localised health interventions in pollution-affected areas. As Thailand moves toward more inclusive and sustainable development, incorporating community valuations like those presented here is not just prudent, it is essential.

5.1 Sensitivity Check Based on Updated Population Characteristics

To assess whether the original willingness to pay (WTP) estimates remain applicable in 2025, this study reviewed updated demographic and economic indicators for Rayong Province. According to data from the National Statistical Office (NSO) [23] and the Office of the National Economic and Social Development Council (NESDC) [24], the average monthly household income in Rayong has increased from approximately 30,000 baht in 2015 to about 35,000 baht in 2023–2024, reflecting a real income growth of roughly 17% over the past decade. At the same time, household size has remained stable, with only a minor reduction from 3.3 to 3.1 person per household [25].

Given the well-documented positive relationship between income and WTP in environmental economics, a sensitivity-adjusted WTP estimate was calculated by scaling the inflation-adjusted base value (249 baht/household/year) by the 17% income increase. This yields an upper-bound estimate of approximately 291 baht per household per year. While the core analysis reports the 249 Baht figure as the primary result (based on CPI adjustment), the 291 Baht figure provides an informative benchmark for policy planners seeking to align community contributions with current income conditions.

This revalidation supports the ongoing relevance of the study's findings and affirms

that the health valuation presented is not outdated but rather reflects enduring community priorities and consistent socioeconomic context in the Map Ta Phut area.

6. Conclusion

This study examined the economic valuation that households place on preventing health problems associated with industrial air pollution in the Map Ta Phut Industrial Estate area of Rayong Province, Thailand. Using the contingent valuation method (CVM) with a double-bounded dichotomous choice format, we estimated the willingness to pay (WTP) of 640 households for a proposed mobile health unit aimed at mitigating pollution-related health risks.

The findings indicate that households are willing to pay an average of 249 baht per year (adjusted to 2025 prices) to support the implementation of such a service. This WTP reflects a meaningful local valuation of preventive health measures, especially in light of the modest income levels of many households in the area. Importantly, WTP was significantly influenced by factors such as gender, household income, occupational exposure to pollution, and the presence of respiratory health symptoms.

These results demonstrate that the impacts of air pollution are not only environmental and medical, but also economic and psychological. The community's expressed willingness to contribute financially underscores both a recognition of the health burden they face and a desire for practical solutions that can reduce that burden.

From a policy standpoint, this study provides evidence to support community-based health interventions in industrial zones, especially those affected by chronic pollution. The estimated WTP can inform cost-benefit analyses, pollution compensation frameworks, and local health budgeting. Furthermore, the findings support the inclusion of economic valuation tools in

environmental and health impact assessments, strengthening the role of affected communities in guiding sustainable development.

In conclusion, household WTP provides a tangible measure of public demand for pollution-related health services and a practical basis for designing responsive, community-supported interventions. The mobile health unit model offers not only a health benefit but also a platform for environmental justice and participatory policy in Thailand's industrial regions.

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The management of farm machinery in Thailand: models and impacts on smallholders

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Abstract

Despite the rapid development and growth of farm machinery utilization in Thailand particularly through large-scale farm machinery service market, the agricultural sector still faces a number of challenges. Many Thai farmers lack understanding on the benefits of farm machinery and also remain uncertain about its effectiveness. Moreover, farmers lack the knowledge regarding capital investment required to acquire large-scale farm machinery. Hence, developing efficient models of farm machinery management that are well-suited to the specific needs of farmers will be very important. This study aims to examine three distinct farm machinery management models, that include: (1) single family; (2) joint-stock; and (3) community farm, and analyze their impacts on smallholder farmers, particularly the efficiency of farm machinery utilization. This presentation will discuss the conceptual and analytical framework of the study. Using a case study method, it focuses on how rice farmers and machinery service providers in Nan, Phetchabun, and Saraburi provinces in Thailand, acquire, utilize and manage their farm equipment. The data gathered from the interviews will be analyzed in light of the characteristics of rice farming and farm machinery management models as the key factors influencing the efficiency of farm machinery utilization. To that end, the results of the study will provide farmers with a better understanding of machinery access and usage, thus increasing the agricultural sector's overall efficiency.

Keywords: Fam machinery; efficiency; network; management model; smallholders

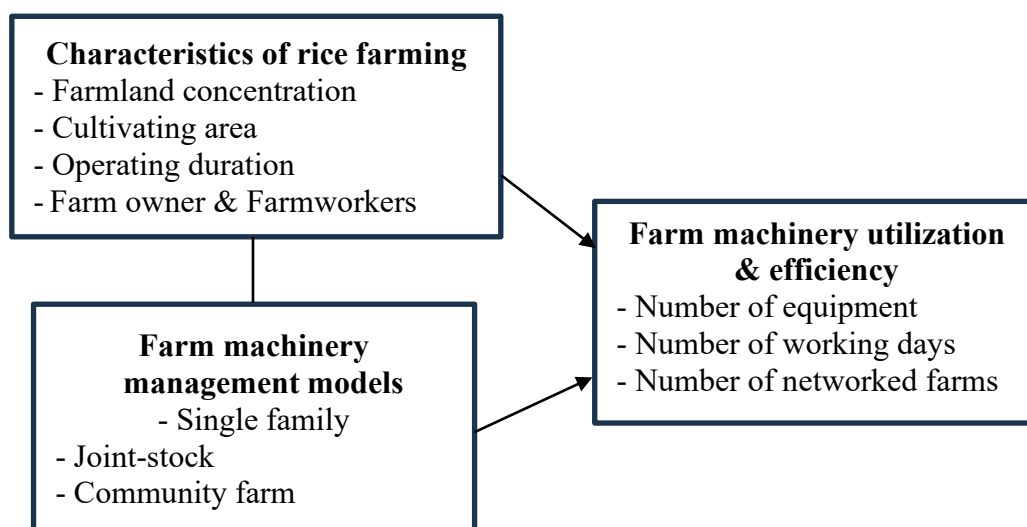


Figure 1: Conceptual and analytical framework



The role of value-added agricultural products in promoting environmental sustainability and economic growth: Insights from Thai farmers.

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Abstract

The study investigates how Thai farmers respond to value-added product practices that aim to deliver both environmental and economic benefits. This approach is expected to reduce production cost, optimize labor, and minimize agricultural waste. The value-added agricultural products define as reduced chemical use and safety standard for agricultural products. Fifteen farmers were purposively selected for in-depth interview, representing diverse regions across Thailand to capture a range of practices and perceptions. Farmers used different of methods and strategies toward activities in farming. Production practices and attitudes varies by region. Northern Thai paddy rice farmers had concerns regarding post-harvest burning and were actively working to reduce chemical fertilizer use. Similarly, central region crop field farmers have decreased their reliance on chemical fertilizers by incorporating manure. In the northeast, farmers cultivating fruits and paddy rice shift to manure. Eastern region fruit and rubber farmers are reducing chemical fertilizers while increasing manure application. Likewise, southern region fruit and rubber farmers prefer replacing chemical fertilizers with manure. Across all regions, farmers consistently expressed serious concerns about chemical contamination in agricultural products. However, economically valued fruit farms show markets trend toward chemical-safe for fruit products. This transition is primarily driven by the potential for value-added products, with regulations and product standards, and improved access to relevant knowledge and technologies. The direct implication of the research finding is to establish strategies for promoting market-driven production that emphasizes environmental conservation and economic advancement, directly contributing to the achievement of SDG 2: Sustainable Agriculture. The study offers one of the few strategies in Thailand, with direct implications for policy and product certification systems.

Keywords: value-added; chemical fertilizer; market-driven production; environmental conservation; sustainable agriculture



“Benefits of Thailand’s Tobacco Control Plan: A Public Health Evaluation”

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Abstract

Tobacco use remains a significant cause of preventable illness and death in Thailand. In response, the Thai Health Promotion Foundation (ThaiHealth) has implemented a national tobacco control plan aligned with the WHO Framework Convention on Tobacco Control (FCTC). This study evaluates the long-term health and benefits of the plan using a Social Return on Investment (SROI) and Benefit Cost Analysis framework, focusing on key public health outcomes.

Our analysis shows that the tobacco control plan has contributed to a substantial decline in smoking prevalence nationwide. Over a 3-year period (2020-2022), the policy is estimated to prevent hundreds of thousands of premature deaths, reduce the burden of smoking-related diseases, and improve population well-being. These outcomes translate into an estimated social benefit between 1,214.20 million baht (low estimate) and 1,130,937.48 million baht (high estimate), through avoided healthcare costs, increased productivity, and enhanced quality of life.

By quantifying these broad public health benefits, the study underscores the effectiveness of sustained tobacco control efforts in Thailand. The approach also offers a framework for assessing the societal impact of other preventive health policies. This evidence supports continued action in public health promotion and provides a compelling case for cross-sectoral collaboration.

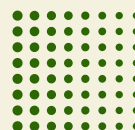
Keywords: Social Benefits; Tobacco Control Policy; Public Health Economics; Health Evaluation; Thailand



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