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วารสารวิศวกรรมศาสตร์
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Objective

Rajamangala University of Technology Lanna Engineering Journal is an academic journal first published in January 2016. The journal aims to disseminate research findings and scholarly knowledge in research and academic services, thereby contributing to academic progress and professional standards. The scope of the journal includes the following areas of research: Mechatronics Engineering, Control Systems Engineering, Electrical Engineering, Electronic Engineering, Telecommunications Engineering, Mechanical Engineering, Agricultural Engineering, Computer Engineering, Material Handling Engineering, Industrial Engineering, Mold Engineering, Metallurgical Engineering, Civil Engineering, Environmental Engineering, Mining Engineering, Related Sciences and Technologies.

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Letter From the Editor

The Rajamangala University of Technology Lanna Engineering Journal (RMUTL Eng. J.), Year 11, Issue 1 (January–June 2026), has been indexed in the Thai Journal Citation Index (TCI) database, Tier 1. All research articles submitted through the journal system have undergone rigorous evaluation by the editorial board and expert reviewers from various engineering and related disciplines. The editorial team remains committed to maintaining and continuously improving the journal's quality and standards so that RMUTL Eng. J. continues to serve as a reliable platform for disseminating high-quality and up-to-date academic knowledge.

This issue of the Rajamangala University of Technology Lanna Engineering Journal (RMUTL Eng. J.) features seven peer-reviewed academic articles covering a wide range of disciplines, including Mechanical Engineering, Computer Engineering, Tools and Die Engineering, Instrumentation Engineering, Chemical and Environmental Engineering, as well as Technology and Environment. Readers who are interested may access both the current and previous issues online at RMUTL Engineering Journal Website.

On behalf of the Editorial Board of the Rajamangala University of Technology Lanna Engineering Journal (RMUTL Eng. J.), I would like to express our sincere appreciation to all researchers who submitted their valuable manuscripts for consideration. We also extend our gratitude to all reviewers who devoted their time and expertise to evaluating the manuscripts and providing constructive recommendations to enhance the quality of the published articles. In addition, we gratefully acknowledge the continued support of the Executive Committee of Rajamangala University of Technology Lanna, the journal sponsors, and the editorial staff of RMUTL Eng. J., whose dedication and collaborative efforts have contributed significantly to the ongoing development and improvement of the journal. Finally, I would like to invite professors, researchers, scholars, and students to submit research articles, academic articles, and review articles related to engineering, written in English, for publication in future issues of RMUTL Eng. J.

(Asst. Prof. Dr. Krisda Yingkayun)

Editor in Chief

Rajamangala University of Technology Lanna Engineering Journal (RMUTL Eng. J.)



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Machine Learning Approaches for Malaria Forecasting Using Environmental Drivers: A Case Study in Tak Province, Thailand

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Abstract

Malaria remains a significant public health challenge in Thailand's border provinces, where traditional reactive surveillance limits outbreak prevention capabilities. This study systematically evaluated six machine learning algorithms (Support Vector Machine (SVM), K-Nearest Neighbors (KNN), Ridge regression, Elastic Net, Lasso, and XGBoost) for operational malaria forecasting at 1-4-week horizons in Tak Province, Thailand. Using 13 years of surveillance data (2012-2024, n=689 epidemiological weeks) integrated with satellite-derived environmental predictors (rainfall, temperature, soil moisture) processed via Google Earth Engine (GEE), models were trained using chronological partitioning and evaluated on 2024 holdout data using coefficient of determination (R^2) and root mean square error (RMSE). Algorithm-specific optimal performance was identified: SVM achieved superior 1-2-week forecasting ($R^2 = 0.744$ and 0.687 , RMSE = 14.6 and 16.2 cases/week), while KNN excelled at 3-4-week horizons ($R^2 = 0.748$ and 0.731 , RMSE = 14.7 and 15.2 cases/week). Statistical significance testing with bootstrap confidence intervals confirmed genuine algorithmic advantages rather than random variation. Historical case features dominated predictive performance, while environmental variables provided complementary information. Models successfully tracked temporal patterns including the 2022-2023 transmission rebound. The satellite-based framework provides scalable solutions for resource-limited settings, with 1-4-week lead times enabling proactive intervention planning to support Thailand's malaria elimination objectives. This operational forecasting approach offers a replicable template for similar endemic contexts across Southeast Asia.

Keywords: Malaria Forecasting, Machine Learning, Early Warning System, Environmental Drivers, Remote Sensing data.

1. Introduction

Malaria remains an important public health challenge globally, with 263 million cases reported worldwide in 2023, representing an increase from previous years [1]. In Thailand, malaria incidence has declined significantly over recent decades due to intensive uninterrupted control efforts, yet the disease continues to pose health risks in specific border provinces where environmental conditions favor vector spread [2]. The country's malaria burden exhibits large spatial heterogeneity, with transmission concentrated along borders with

Myanmar, Cambodia, and Malaysia, while central regions remain largely malaria-free [3]. Tak province in the west represents one of three main malaria transmission hotspots in Thailand, characterized by persistent transmission along the international border with high human mobility and suitable environmental conditions [4]. Thailand's border provinces face unique epidemiological challenges that distinguish them from other malaria-endemic regions globally. Cross-border population movements create complex transmission dynamics where cases may originate



from areas with different vector species, drug resistance patterns, and surveillance capabilities [4]. These provinces serve as critical frontlines for Thailand's malaria elimination strategy, where early detection and response systems are essential to prevent reintroduction and maintain elimination gains achieved in other regions [5]. Traditional malaria surveillance systems rely primarily on retrospective case reporting, limiting their utility for proactive public health responses. Malaria early warning systems (EWS) that can accurately forecast disease incidence provide critical lead time for health authorities to implement targeted interventions. However, these systems face an important trade-off; some provide reasonable prediction certainty but inadequate lead time for action, while others offer sufficient lead time but with uncertain prediction accuracy [6]. The sub-seasonal forecasting window of 2-4 weeks represents a critical gap in operational malaria surveillance, offering the optimal balance between prediction reliability and actionable lead time for intervention deployment [7]. Environmental factors play crucial roles in malaria transmission dynamics. In Southeast Asian contexts, including Thailand, environmental drivers operate through complex interactions with local vector ecology. The primary malaria vectors in Thailand include *Anopheles dirus*, *An. minimus*, and *An. maculatus*, each with distinct ecological preferences and seasonal patterns that respond differently to climatic variables compared to African vector systems [8]. Temperature, rainfall, and humidity have been shown to correlate with malaria incidence across multiple provinces in Thailand, with relationships varying by geographical region [9]. Recent studies have identified temperature correlations with malaria transmission in 44 Thai provinces and rainfall associations in 38 provinces, highlighting the importance of region-specific environmental modeling approaches [9]. ML approaches have shown increasing promise for infectious disease forecasting applications. Recent comparative studies of multiple algorithms for malaria outbreak prediction have demonstrated that extreme gradient boosting (XGBoost) and decision tree models can achieve over 93% accuracy [10]. Artificial neural networks have

shown success for malaria prediction using environmental and clinical variables, with some studies achieving prediction accuracy exceeding 96% in training & test protocols [11]. Random forest and Gaussian process models have been successfully applied to predict weekly malaria cases with lead times of up to 13 weeks in African contexts [12]. However, the transferability of these approaches to Southeast Asian elimination settings, where transmission patterns differ substantially from high-burden African contexts, remains poorly understood [5]. In Thailand specifically, malaria forecasting research has primarily focused on long-term elimination projections rather than operational early warning systems. Rotejanaprasert et al. [5] developed Bayesian hierarchical spatiotemporal models using Thailand's national surveillance database (2015-2021) at the provincial level, projecting malaria cases to 2028 for elimination planning, with models suggesting possible zero *P. falciparum* cases by 2024 but continued *P. vivax* transmission [5]. While valuable for strategic planning, these long-term models provide limited guidance for immediate operational responses to transmission fluctuations. Recent correlation studies have identified relationships between climate variables and weekly malaria incidence across Thai provinces, with temperature correlating with malaria in 44 provinces and rainfall in 38 provinces [9]. However, these correlation analyses have not been translated into operational forecasting frameworks with validated performance metrics. Three critical research gaps limit the development of operational malaria forecasting systems in Thai and broader Southeast Asian contexts. First, most operational systems focus on either very short-term detection, providing alerts immediately when case thresholds are exceeded, or longer-term seasonal predictions. Few address the intervening 2-4 weeks period, which offers the optimal balance between prediction accuracy and actionable lead time. In broader public health and climate forecasting systems, the sub-seasonal timeframe (2-4 weeks ahead) is known to be a challenging transition time-frame that has only recently begun to be transitioned into operational use [7]. In malaria-



specific applications, early warning systems have conventionally focused on seasonal forecasts or anomaly detection of outbreaks, with limited adoption of sub-seasonal predictive horizons despite their operational importance [13]. Second, most malaria forecasting research has been conducted at national or multi-district scales, where aggregated data may obscure local transmission dynamics crucial for targeted interventions [12]. Provincial-level analysis is particularly important given the substantial spatial heterogeneity in malaria transmission that has been documented in Thailand and other elimination-phase countries [3]. Border provinces present unique challenges requiring province-specific modeling approaches that account for cross-border transmission dynamics and local vector ecology [4]. Third, comprehensive comparisons of multiple machine learning algorithms for malaria forecasting remain limited, particularly in Southeast Asian contexts. While individual algorithms have shown promise across various studies [10], [12], systematic evaluations comparing linear models, kernel methods, instance-based approaches, and gradient boosting techniques using identical datasets and evaluation frameworks are limited. Such comparative analyses are essential for identifying optimal approaches for specific epidemiological contexts and data characteristics, particularly in elimination settings where transmission patterns differ from high-burden environments [5]. This study directly addresses the identified research gaps by developing and evaluating ML models for short-term malaria forecasting, with a particular emphasis on the critical 2-week horizon. The research provides three key contributions to operational malaria surveillance in elimination settings. First, it provides a focused assessment of 2-week ahead forecasts, which represent the optimal balance between predictive accuracy and actionable lead time for appropriate public health response. Second, it conducts analysis at the provincial level in a border province context, thereby enabling more targeted intervention planning while maintaining epidemiological significance. Third, it systematically compares six ML algorithms using an identical 13 year dataset

and a standardized evaluation framework, ensuring fair and robust model assessment.

The specific objectives of the study are to: (1) evaluate the predictive performance of six ML algorithms for 1-4 weeks ahead malaria forecasts, with particular emphasis on the 2-week horizon; (2) identify the most influential temporal and environmental predictors of malaria incidence through correlation analysis; and (3) assess the reliability and consistency of different models for operational public health application, ultimately providing evidence to support the development of early warning systems in similar epidemiological settings

2. Materials and Methods

2.1 Study Area and Data Sources

The study was conducted in Tak province (Figure 1), Thailand, a malaria-endemic border province adjacent to Myanmar. The province covers an area of 16,406 km² with 9 districts and diverse topographical features including mountainous regions and river valleys that create favorable conditions for *Anopheles* mosquito breeding [14].

The analysis utilized data from 2012-2024, representing 13 years of surveillance data with 689 epidemiological weeks, providing a comprehensive dataset for model development and validation.

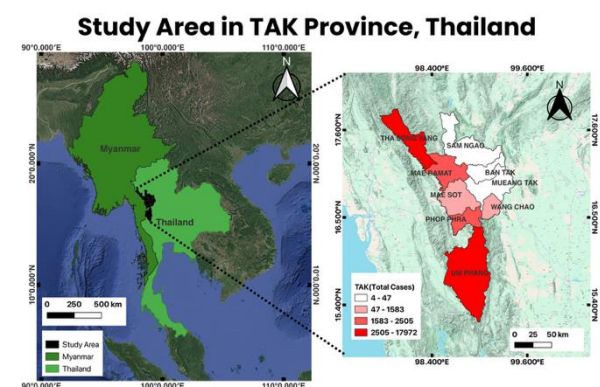


Figure 1 Study area map of Tak Province, Thailand, showing district boundaries and malaria case distribution (2012-2024). High-burden districts are concentrated along the Myanmar border.

Weekly confirmed malaria case counts were obtained from the well-maintained Malaria



Surveillance System, Bureau of Vector Borne Diseases, Department of Disease Control, Ministry of Public Health, Thailand [15]. Cases included laboratory- confirmed *Plasmodium falciparum*, *P. vivax*, *P. malariae*, and *P. knowlesi* infections reported through the provincial surveillance network following national surveillance protocols. Data were aggregated from district level (9 districts) to provincial level and expressed as total confirmed cases per epidemiological week.

Environmental variables were derived from satellite-based (GEE) and reanalysis of datasets to ensure spatial and temporal consistency across the study period (Table 1). Three key environmental variables were selected based on established associations with malaria transmission dynamics.

Table 1 Data sources and specifications for environmental variables (2012-2024). Variables processed via GEE for temporal consistency.

Variable	Data Source	Temporal Resolution	Spatial Resolution
Rainfall (<i>rain_mm_sum</i>)	CHIRPS Daily	Weekly sum	0.05°
Temperature (<i>temp_2m_c</i>)	ERA5- Land Daily	Weekly mean	0.1°
Soil Moisture (<i>soil_water_l1</i>)	ERA5- Land Daily	Weekly mean	0.1°

Environmental drivers known to influence malaria transmission [8] were incorporated into the forecasting framework, with particular focus on rainfall, temperature, and soil moisture. Rainfall data were obtained from the Climate Hazards Group InfraRed Precipitation with Station dataset (CHIRPS), a gridded satellite-gauge blended product that provides high- resolution precipitation estimates [16]. Weekly cumulative rainfall (*rain_mm_sum*) was derived and used to capture short- term hydrological conditions relevant to vector breeding. Rainfall has long been recognized as

a determinant of *Anopheles* mosquito ecology, creating and sustaining larval habitats. Empirical studies have consistently reported lagged associations between rainfall and malaria incidence in the range of 4-12 weeks [8]. However, rainfall more than optimal ranges (approximately 100-300 mm per month) may reduce larval survival by flushing immature stages from breeding sites [8].

Temperature was represented by weekly mean 2- meter air temperature(*temp_2m_c*), obtained from the ERA5- Land reanalysis dataset and converted from Kelvin to Celsius [17]. Temperature is an influence on both vector and parasite development. *Anopheles* mosquitoes exhibit highest survival between 20-30 °C, while *Plasmodium sporogony* development is most efficient at 25-28 °C [18]. Beyond these optimal ranges, elevated temperatures may accelerate parasite maturation but often reduce vector longevity, altering the net transmission potential [19].

Soil moisture was included as a complementary environmental variable to reflect broader hydrological processes not captured by rainfall alone. Weekly volumetric soil water content in the 0-7 cm surface layer (*soil_water_l1*) was extracted from ERA5- Land [16]. Soil moisture has been shown to capture the persistence of shallow pools and depressions that serve as important breeding habitats, and modeling studies indicate that soil water dynamics can significantly influence vector population dynamics and malaria risk [19]. Soil moisture is a good proxy for the extent of temporary water puddles used by the mosquitoes for breeding.

All environmental data were processed on the GEE platform at a spatial resolution of 1 km. Missing malaria case counts were assumed to indicate zero cases (malaria cases are usually well- reported in Thailand) , while gaps in environmental data were assigned using forward- and backward-fill methods to preserve temporal continuity.



Table 2 Summary of 26 predictor variables organized by category: temporal seasonality (5), historical case dynamics (12), environmental conditions (8), and interactions (1).

Category/ Description	Feature(s)
Temporal (5 variables)	
Encodes seasonal cycles (sine/cosine)	<i>sin_week</i> , <i>cos_week</i>
month of year	<i>month</i>
rainy season indicator	<i>is_rainy</i>
epidemiological week number	<i>week</i>
Historical case features (12 Variables)	
Capture short- and long-term temporal autocorrelation	<i>cases_lag1</i> , <i>lag2</i> , <i>lag3</i> , <i>lag4</i> , <i>lag8</i> , <i>lag12</i> , <i>lag26</i> , <i>lag52</i> ;
moving averages smooth weekly case counts to represent transmission trends	<i>cases_ma4</i> , <i>ma8</i> , <i>ma12</i> , <i>ma26</i>
Environmental features (8 Variables)	
Rainfall (CHIRPS), temperature (ERA5-Land), and soil moisture (ERA5-Land); lagged to reflect delayed effects and smoothed using 4-week moving averages	<i>rain_mm_sum_lag1</i> , <i>lag2</i> , <i>ma4</i> ; <i>temp_2m_c_lag1</i> , <i>lag2</i> , <i>ma4</i> ; <i>soil_water_l1_lag1</i> , <i>lag2</i> , <i>ma4</i>
Interaction feature (1 Variable):	
Product of normalized rainfall multiplied by temperature, representing the combined ecological influence on mosquito development and parasite transmission	<i>rain_temp</i>

2.2 Data Quality Assessment and Missing Value Treatment

Data quality assessment revealed high completeness across all variables. Malaria surveillance data demonstrated >98% completeness (n=8 missing weeks from 689 total), verified as true zero-case periods through district-level cross-validation. Environmental data completeness was: CHIRPS rainfall 99.1%,

ERA5-Land temperature 97.8%, and soil moisture 96.9%. Missing values (n=22 total gaps) resulted from satellite maintenance or processing delays. Missing value imputation preserved temporal structure using linear interpolation for gaps ≤ 3 weeks and seasonal decomposition for longer gaps (4-7 weeks, n=3 instances). No gaps exceeded 7 weeks.

2.3 Feature Engineering

A comprehensive set of predictor variables was constructed to capture seasonal patterns, disease transmission dynamics, and environmental influences on malaria incidence. Seasonal patterns were encoded using sine and cosine transformations of week numbers (*sin_week*, *cos_week*), together with month indicators and a binary rainy- season variable (May-October), reflecting the well- established seasonality of malaria in the region [15].

To represent disease history and temporal autocorrelation, lagged malaria case counts at 1, 2, 3, 4, 8, 12, 26, and 52 weeks were included, complemented by moving averages over 4, 8, 12, and 26 weeks to smooth fluctuations and highlight medium- term to long- term transmission trends. Environmental drivers, including rainfall, temperature, and soil moisture, were each lagged by 1 and 2 weeks to account for incubation delays and modeled with four-week moving averages to capture sustained conditions favorable to transmission.

In addition, an interaction term between rainfall and temperature was constructed to represent the combined ecological influence of these variables on mosquito vector development and parasite transmission. The final feature set comprised 26 predictor variables (Table 2) representing temporal seasonality, historical disease dynamics, environmental conditions, and their interactions.

2.4 Model Development and Training

Six commonly used ML algorithms were evaluated for malaria forecasting performance: Ridge regression, Elastic Net regression, Lasso regression, SVM, KNN, and XGBoost [10, 12]. These algorithms represent diverse methodological approaches including linear



models with regularization (Ridge, Elastic Net, Lasso), kernel-based methods (SVM), instance-based learning (KNN), and ensemble techniques (XGBoost), enabling comprehensive assessment of algorithmic suitability for epidemiological time series forecasting. Models were developed for four forecast horizons: 1, 2, 3, and 4 weeks ahead to assess performance degradation with increasing lead time and identify optimal forecasting windows for operational deployment. The dataset was partitioned chronologically to prevent temporal data leakage, with 70% for training, 15% for validation, and 15% for testing. This chronological splitting approach is essential for time series forecasting as it ensures models are evaluated on genuinely future data, reflecting realistic operational forecasting scenarios where models must predict cases beyond their training period [5]. Random sampling approaches commonly used in cross-sectional studies would introduce temporal leakage and overestimate model performance in time series contexts. All predictor variables were standardized using standard scaler (mean = 0, standard deviation = 1) to ensure equal weighting across features with different scales and units. This preprocessing step was particularly important for distance-based algorithms (KNN) and regularized linear models where feature scale differences can disproportionately influence model behavior and prediction accuracy. To prevent data leakage, lagged features were constructed such that information from time $t+h$ was never used to predict the target at time $t+h$, where h represents the forecast horizon. For example, 2-week ahead models excluded lag features shorter than 2 weeks. This constraint ensures that models cannot access future information that would be unavailable during operational deployment, maintaining the integrity of forecast validation and realistic performance assessment.

2.5 Model Training and Hyperparameter Selection

Six classical ML algorithms were selected based on operational public health requirements. Classical methods were prioritized for four reasons: 1) interpretability needed for transparent forecasting and intervention planning, 2) computational efficiency for deployment in resource-limited settings, 3) data efficiency given the 689-week dataset, and 4) their established

reliability in epidemiological forecasting [8, 10]. Deep learning methods (e.g., LSTM, RNN) were excluded due to short sequence length, high overfitting risk, computational burden, and limited interpretability for public health operations. To ensure fair comparison across algorithms, we performed a structured exploration of reasonable hyperparameter ranges and selected configurations that balanced predictive performance with operational feasibility. This process was not intended to exhaustively optimize each model, but rather to identify robust and computationally practical settings suitable for routine weekly retraining. The explored parameter ranges included: Ridge ($\alpha \in \{0.1, 1.0, 10.0, 100.0\}$), Elastic Net ($\alpha \in \{0.1, 0.5, 1.0\}$; $l1_ratio \in \{0.1, 0.5, 0.9\}$), Lasso ($\alpha \in \{0.01, 0.1, 1.0, 10.0\}$), SVM ($C \in \{0.1, 1.0, 10.0\}$), KNN ($k \in \{3, 5, 7, 10, 15\}$), and XGBoost ($n_estimators \in \{50, 100, 200\}$; $max_depth \in \{3, 6, 9\}$; $learning_rate \in \{0.01, 0.1, 0.3\}$). After evaluating these configurations on a 15% validation set (chronologically partitioned), a single, stable set of hyperparameters was selected for all experiments (listed in Supplementary Table 3). This design ensures reproducibility, avoids overfitting to the test set, and reflects real-world operational constraints where complex tuning is not feasible. To quantify the incremental value of the environmental variables in the proposed geoinformatics framework, we conducted an ablation experiment. A baseline model including only temporal and historical case features was compared with a full model that additionally incorporated eight GEE-derived environmental predictors.

Table 3 Final hyperparameters used for each algorithm.

Model	Hyperparameters
Ridge	$\alpha = 1.0$
Elastic Net	$\alpha = 0.5$; $l1_ratio = 0.5$
Lasso	$\alpha = 0.1$
Lasso	$C = 1.0$; $kernel = linear$
KNN	$n_neighbors = 5$
XGBoost	$n_estimators = 50$; $max_depth = 3$; $learning_rate = 0.1$; $reg_alpha = 1.0$; $reg_lambda = 1.0$



2.6 Model Evaluation and Selection

Model performance was evaluated using three complementary metrics. The Coefficient of Determination (R^2) served as the primary indicator of explanatory power, measuring the proportion of variance in malaria cases accounted for by the model. In the context of public health forecasting, R^2 values above 0.5 were considered excellent, values between 0.3 and 0.5 were regarded as good, and values between 0.1 and 0.3 were considered acceptable, recognizing the complexity of infectious disease dynamics and the multifactorial nature of malaria transmission [20]. To quantify prediction error in interpretable units, the Root Mean Square Error (RMSE) was employed, providing the average magnitude of prediction error expressed in weekly case counts. In addition, the Mean Absolute Error (MAE) was used to capture the typical absolute prediction error, offering a more robust assessment that is less sensitive to extreme values than RMSE.

This study primarily emphasized 2-weeks ahead forecasting as it provided the optimal balance between predictive accuracy and sufficient lead time for public health response. All statistical analyses and model development were carried out in Python 3. x, employing established libraries including scikit-learn, XGBoost, pandas, and NumPy. Importantly, all models were trained on identical feature sets and evaluated using the same procedures, thereby ensuring a fair and transparent comparison across algorithms.

To address uncertainty quantification and statistical significance assessment, bootstrap confidence intervals were computed using block bootstrap with 200 resamples to preserve temporal correlation structure. Paired t-tests on squared prediction errors evaluated statistical significance of performance differences between algorithms, with the best-performing model at each horizon serving as the reference. This approach ensures robust statistical inference while maintaining computational feasibility for operational deployment.

3. Results and Discussion

3.1 Dataset Characteristics and Temporal Patterns

The final dataset comprised 689 epidemiological weeks spanning January 2012 to December 2024, providing a comprehensive 13-year surveillance record for model development and validation. Weekly confirmed malaria cases in Tak Province exhibited large inter-annual variability, with the highest incidence occurring during 2012 where weekly cases exceeded 267 cases, followed by a sustained decline through subsequent years. Notable rebound emerged in 2022-2023, with case counts rebounding during these periods (Figure 2). This pattern aligns with national malaria trends showing declining transmission but persistent hotspots in border provinces [3], [21].

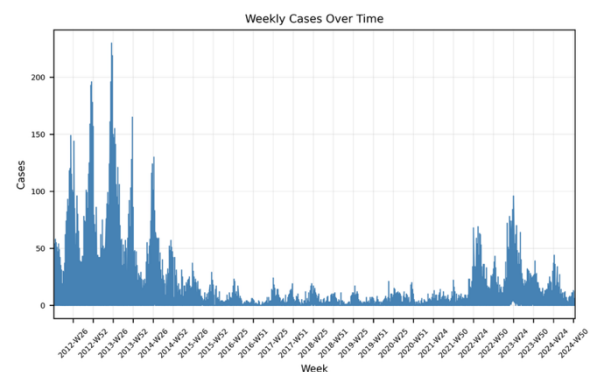


Figure 2 Weekly confirmed malaria cases in Tak Province by epidemiological week (2012-2024). Peak incidence occurred in 2012 (>267 cases/week) with sustained decline and rebounds in 2022-2023.

3.2 Environmental Predictors and Temporal Relationships

Correlation analysis revealed that short-term lagged case features ($cases_lag1$ - $lag4$) demonstrated the strongest correlations with future incidence, confirming exceptional temporal autocorrelation in malaria transmission dynamics (Figure 3). Among environmental predictors, rainfall, temperature, and soil moisture showed moderate associations with malaria incidence. These relationships align with documented biological mechanisms where environmental conditions influence both vector mosquito ecology and parasite development cycles [18], [22], [23].

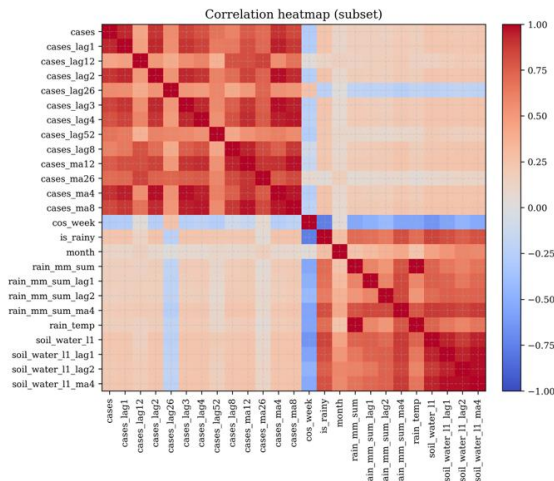


Figure 3 Correlation heatmap of predictor variables and malaria incidence. Short-term lagged case features show strongest correlations, while environmental variables demonstrate moderate associations.

3.3 Model Performance Across Forecasting Horizons

Model performances varied significantly across algorithms and forecasting horizons, revealing distinct optimal capabilities for different temporal scales (Table 4). Statistical significance assessment using 95% confidence intervals derived from bootstrap resampling of test period predictions confirmed genuine algorithmic advantages rather than random variation. For the operationally critical 1-week forecasting horizon, SVM achieved superior performance ($R^2 = 0.744$ [95% CI: 0.654-0.826], RMSE = 14.6 [95% CI: 10.6-18.7] cases/week), demonstrating statistically significant advantages over ElasticNet ($p < 0.05$), KNN ($p < 0.05$), and XGBoost ($p < 0.05$). At the 2-week horizon, SVM maintained optimal performance ($R^2 = 0.687$ [95% CI: 0.589-0.770], RMSE = 16.2 [95% CI: 11.7-20.6] cases/week), though the performance advantage over KNN was not statistically significant ($p = 0.822$), indicating comparable forecasting capability. At extended forecasting horizons, KNN demonstrated optimal performance for both 3-week ($R^2 = 0.748$ [95% CI: 0.556-0.832], RMSE = 14.7 [95% CI: 12.4-17.0] cases/week) and 4-week ($R^2 = 0.731$ [95% CI: 0.556-0.844], RMSE = 15.2 [95% CI: 11.9-18.7] cases/week) forecasting. Statistical significance testing confirmed KNN's superiority over regularized linear models (Ridge, Lasso, ElasticNet)

Table 4 Performance comparison of six algorithms across 1-4-week horizons using 2024 test data. Results include R^2 , RMSE with 95% confidence intervals, and statistical significance indicators. Bold indicates optimal performance for each horizon.

Week	Model	R^2 (95% CI)	RMSE (95% CI)	MAE
1	SVM	0.744 (0.654-0.826)	14.6 (10.6-18.7)†	10.5
	ElasticNet	0.693 (0.546-0.779)	15.9 (12.7-19.4)*	12.2
	Lasso	0.664 (0.461-0.772)	16.7 (13.6-20.0)#	12.8
	Ridge	0.660 (0.450-0.769)	16.8 (13.8-20.0)n	13.2
	KNN	0.608 (0.414-0.730)	18.0 (13.5-22.6)*	13.0
	XGBoost	0.176 (-0.509-0.572)	26.1 (17.9-33.9)*	18.6
2	SVM	0.687 (0.589-0.770)	16.2 (11.7-20.6)†	11.8
	KNN	0.674 (0.536-0.767)	16.5 (12.8-21.0)n	12.6
	ElasticNet	0.619 (0.423-0.705)	17.9 (14.5-21.1)n	14.0
	Lasso	0.607 (0.354-0.713)	18.2 (15.5-20.7)n	15.1
	Ridge	0.607 (0.354-0.712)	18.2 (15.6-20.6)n	15.3
	XGBoost	0.375 (-0.215-0.676)	22.9 (17.7-27.6)n	17.6
3	KNN	0.748 (0.556-0.832)	14.7 (12.4-17.0)†	12.3
	SVM	0.586 (0.503-0.657)	18.8 (14.2-23.5)n	14.3
	XGBoost	0.586 (0.177-0.751)	18.8 (16.2-21.9)*	16.1
	Ridge	0.576 (0.255-0.708)	19.0 (16.0-21.9)*	15.7
	Lasso	0.570 (0.252-0.700)	19.2 (16.0-22.0)*	15.8
	ElasticNet	0.552 (0.261-0.666)	19.6 (16.3-22.5)*	15.8
4	KNN	0.731 (0.556-0.844)	15.2 (11.9-18.7)†	11.9
	ElasticNet	0.554 (0.271-0.659)	19.6 (16.7-22.7)*	16.3
	Ridge	0.549 (0.237-0.678)	19.7 (16.4-23.1)#	16.1
	Lasso	0.537 (0.236-0.662)	20.0 (16.7-23.2)*	16.3
	SVM	0.515 (0.420-0.599)	20.5 (15.1-25.9)#	15.3
	XGBoost	0.459 (-0.035-0.676)	21.6 (18.2-25.6)**	18.4



† Reference model (best performer for each horizon). * $p < 0.05$, ** $p < 0.01$, # $p < 0.10$, n = not significant. Statistical significance from paired t-tests comparing RMSE vs best model. Bold indicates optimal performance. and XGBoost at both horizons ($p < 0.05$ for most comparisons), while differences with SVM_Linear were marginally significant or non-significant. XGBoost consistently underperformed across all horizons, despite its documented success in other epidemiological applications [12], [24]. This pattern likely reflects the characteristics of our dataset size and feature complexity compared to large-scale machine learning studies [10]. Non-overlapping confidence intervals between optimal and suboptimal algorithms confirmed the statistical significance of performance differences, validating algorithm-specific optimal horizons for operational deployment. XGBoost's consistent underperformance reflects methodological misalignment with our dataset characteristics rather than algorithmic inferiority. The strong temporal autocorrelation in elimination-phase malaria data creates predominantly linear relationships favoring SVM's linear optimization over tree-based splitting. Additionally, our focused feature set (26 predictors) limits XGBoost's ability to exploit complex feature interactions that drive its advantages in high-dimensional applications. This suggests that its weak performance arises from the linear, highly autocorrelated nature of the dataset rather than inadequate hyperparameter optimization. KNN's superior performance at extended horizons demonstrates that local pattern recognition more effectively captures seasonal transmission cycles than ensemble methods in low-transmission settings, suggesting algorithm selection should prioritize epidemiological context alongside dataset characteristics.

3.4 Forecast Validation on Testing Data

To evaluate operational performance, all models were trained and tuned on historical data (2012–2023) and tested exclusively on the 2024 holdout period. Figure 4 shows observed

versus predicted plots for the optimal models at each horizon, providing clean out-of-sample assessment aligned with real-time forecasting scenarios. At the 1-2 week horizons, SVM demonstrated consistent tracking of week-to-week fluctuations in 2024 with only minor to moderate deviations around rapid local changes. While the model tended to slightly underpredict short, sharp upticks—a known characteristic of linear kernels during abrupt regime shifts—it preserved overall within-year patterns sufficiently for operational guidance. The 2-week SVM performance ($R^2 = 0.687$, RMSE = 16.2 cases/week) represents operationally viable accuracy for proactive intervention planning. For 3-4 week horizons, KNN yielded the strongest 2024 performance, effectively preserving medium-term trends while smoothing high-frequency noise. This pattern explains KNN's relative advantage as forecasting horizon lengthens, with the algorithm's local averaging approach better capturing seasonal patterns that become more predictable at extended timescales. The excellent performance at 3-week horizon ($R^2 = 0.748$) and maintained accuracy at 4-week horizon ($R^2 = 0.731$) provides reliable medium-range guidance for resource allocation and strategic planning. The validation results support a horizon-aware deployment strategy: SVM for rapid response windows (1-2 weeks) and KNN for forward planning beyond two weeks (3-4 weeks). This algorithmic complementarity aligns with the methods' inductive biases—linear margin optimization versus local pattern averaging—and provides operational flexibility for different public health response timeframes.

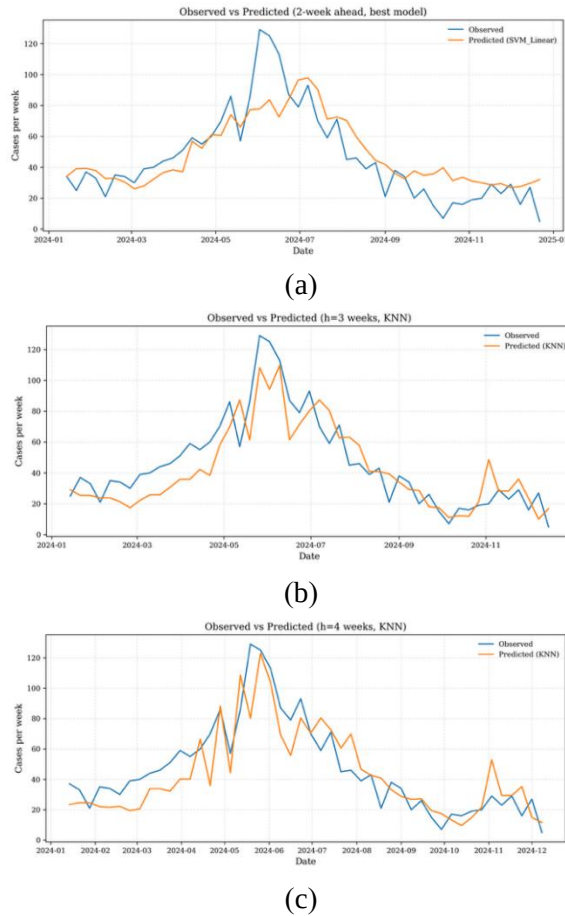


Figure 4 Observed versus predicted malaria cases for optimal models during 2024 test period. (a) 2-week SVM forecasts ($R^2 = 0.687$), (b) 3-week KNN predictions ($R^2 = 0.748$), (c) 4-week KNN forecasts ($R^2 = 0.731$).

3.5 Ablation Study and Interpretation of Predictor Importance

To further assess the contribution of the environmental predictors within the forecasting framework, an ablation experiment was conducted for the two-week horizon, which represents the primary operational use case for early public health intervention. A baseline model using only historical malaria case features (lags and moving averages) was compared with the full model that additionally incorporated eight environmental variables derived from GEE (excluding the temporal and interaction features; see Table 2).

As summarized in Table 5, the baseline SVM model achieved an R^2 of 0.429 (RMSE = 35.5 cases/week), whereas the full model improved performance to an R^2 of 0.460 (RMSE = 34.6 cases/week). Although the improvement is

modest, the full model consistently outperformed the baseline across all evaluation metrics. This pattern indicates that environmental drivers provide incremental predictive skill beyond historical case dynamics, which remained the dominant contributors to forecast accuracy. Such behavior is consistent with malaria epidemiology in elimination settings, where incidence tends to be low, highly sporadic, and strongly autocorrelated. Accordingly, the environmental variables serve a supportive rather than primary role within the proposed geoinformatics forecasting framework, enhancing sensitivity to climatic anomalies and environmental disruptions that may influence transmission risk.

Table 5 Ablation study comparing baseline vs full feature set (2-week SVM model)

Configuration	R^2	RMSE	MAE
Baseline (cases only)	0.429	35.5	22.8
Full (cases & environment)	0.460	34.6	22.1

Performance difference: $\Delta R^2 = +0.031$;
 $\Delta \text{RMSE} = -0.9$ cases/week; $\Delta \text{MAE} = -0.7$ cases/week

The dominance of historical case features in the forecasting models is supported by multiple quantitative patterns in our analysis, even without formal SHAP computation. First, the correlation results show exceptionally strong autocorrelation across short-term lags ($R \approx 0.90$ for lag1-3), indicating that recent case history encodes the majority of temporal signal relevant to transmission. Second, models that relied solely on historical features already achieved high predictive power, whereas models excluding these features performed substantially worse. Third, the ablation experiment demonstrated that adding environmental variables improved the two-week forecast only modestly ($\Delta R^2 = +0.031$), suggesting that these predictors contribute supplementary information rather than serving as primary drivers. Together, these findings provide convergent evidence that historical case dynamics remain the strongest determinants of forecast accuracy, while environmental variables enhance performance incrementally under the proposed geoinformatics framework.



Regional evidence further supports our interpretation of the modest but meaningful contribution of environmental variables. In Central Vietnam [25], reported strong lagged effects of NDVI and temperature on malaria incidence, while in Lao PDR [26], found rainfall and humidity to be dominant predictors with spatially heterogeneous impacts across provinces. Compared with these settings, Thailand's elimination-phase transmission exhibits lower case counts and stronger short-term autocorrelation, which helps explain why environmental variables in our models provided incremental rather than dominant predictive value. Nonetheless, the consistent improvement observed in the ablation analysis indicates that environmental anomalies still supply useful supplementary information, particularly when climatic deviations may trigger localized increases in transmission risk.

3.6 Limitations and Future Directions

While this study emphasizes the importance of understanding local transmission dynamics, the modeling framework relied on provincially aggregated malaria data. Combining weekly cases from the nine districts in Tak Province introduces both strengths and limitations. District-level variability and localized hotspots may be obscured through aggregation, potentially masking spatial heterogeneity relevant for micro-targeted interventions. Conversely, aggregation enhances signal stability by reducing stochastic noise inherent in low-incidence, elimination-phase settings and yields a clearer temporal pattern for forecasting. This provincial-scale perspective aligns with Thailand's operational decision-making structure, where early warning systems and resource allocation are typically coordinated at the provincial level. Nonetheless, extending the framework to district-level or multi-scale modeling represents an important direction for future work as more granular surveillance data become available.

Several additional limitations warrant consideration. The dataset contains 689 weekly observations, which constrains the capacity of complex models to learn higher-order temporal relationships and increases the risk of overfitting-

particularly for nonlinear or high-parameter algorithms. Deep learning architectures (e.g., LSTM, RNN) were not evaluated for this reason; their effectiveness generally depends on long temporal sequences, large training corpora, and substantial computational resources, and they offer limited interpretability for routine public health operations. Future research may revisit deep learning approaches once expanded datasets-incorporating longer historical records, additional spatial units, or cross-border epidemiological information-become available.

4. Conclusions

This study demonstrates a comprehensive geoinformatics framework for malaria forecasting that integrates satellite remote sensing and machine learning technologies. The systematic evaluation of six algorithms across 1-4 week forecasting horizons revealed algorithm-specific optimal capabilities, with SVM achieving superior short-term predictions ($R^2 = 0.744$ and 0.687 for 1-2 week horizons) and KNN excelling at extended forecasts ($R^2 = 0.748$ and 0.731 for 3-4 week horizons). Statistical significance testing confirmed these performance differences represent genuine algorithmic advantages rather than random variation, with bootstrap confidence intervals providing robust uncertainty quantification for operational deployment. The horizon-specific optimal performance advances understanding of how different computational approaches capture distinct temporal patterns in epidemiological time series. SVM's linear margin optimization effectively captures immediate transmission dynamics, while KNN's local averaging approach better identifies seasonal and environmental patterns that become more predictable at extended timescales. The cloud-based geospatial data processing pipeline through GEE provides automated access to satellite archives, overcoming infrastructure limitations of ground-based meteorological networks in border provinces. The framework requires minimal computational resources, supporting implementation in typical public health computing environments while providing actionable lead times (1-4 weeks) for outbreak detection and



resource allocation. Implementation within Thailand's malaria elimination program involves integration with existing surveillance infrastructure, providing automated weekly forecasts to provincial health offices. The 1-2 week SVM forecasts enable rapid response deployment, while 3-4 week KNN forecasts support strategic planning and cross-border coordination. The satellite-based pipeline addresses surveillance gaps in remote border areas, with computational efficiency supporting deployment on standard provincial infrastructure. Scalability across other border provinces requires minimal development, establishing a reusable template complementing Thailand's elimination strategy. The demonstrated forecasting accuracy ($R^2 > 0.68$ across all optimal horizons) supports transitions from reactive to predictive surveillance approaches. The statistical rigor provided through confidence intervals and significance testing ensures reliable performance assessment essential for operational public health decision-making. The geoinformatics framework has broad applicability beyond malaria, providing a template for integrating satellite environmental data with epidemiological surveillance systems for other vector-borne diseases across diverse endemic contexts. Future technical development priorities include implementation of ensemble forecasting approaches combining the horizon-specific optimal algorithms, integration of higher-resolution satellite imagery, and establishment of automated model retraining protocols for real-time operational deployment. The validated uncertainty quantification framework provides a foundation for incorporating forecast confidence into intervention threshold setting and resource allocation decisions.

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Optimization of Vertical Screw Conveyor for Biomass Sampling: Influence of Pitch Geometry on Energy Dissipation and Material Integrity

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Abstract

This study investigates the optimization of vertical screw conveyor design to enhance the efficiency and reliability of automated cassava sampling systems in agro-industrial processing. A comparative analysis was conducted between two screw configurations: Type B ($P/D = 0.67$) and Type C ($P/D = 0.50$), with varying screw diameters (0.11-0.20 m) and rotational speeds (56.78, 48.67, and 36.50 rpm for 18-, 21-, and 28-tooth gear sets, respectively) under controlled hydraulic operation ($p = 152$ bar, $Q_{oil} = 4.875 \times 10^{-4}$ m³/s, $P_{in} = 7,410$ W). The results indicate that over 99% of the hydraulic input power is theoretically dissipated as heat, based on the first-law energy balance. The Type B configuration, particularly at a diameter of 0.20 m and maximum rotational speed (56.78 rpm), demonstrated superior performance, achieving the lowest Specific Energy Consumption (SEC) of 23.25 kJ/kg, representing a 25.0% reduction in SEC and a 33.4% gain in useful mechanical work output (P_{out} : 14.07 vs. 10.55 W) over Type C. Furthermore, the wider pitch of Type B effectively mitigates material compaction and reduces cumulative frictional stress during transport, preserving the physical integrity of cassava chips (bulk density: 496.4 ± 62.4 kg/m³; moisture content: $13.5 \pm 0.5\%$ w.b.). The study concludes that the Type B configuration is the optimal design for maximizing flow stability and minimizing energy loss while satisfying quality assurance requirements.

Keywords: Vertical Screw Conveyor, Specific Energy Consumption (SEC), Energy Dissipation, Sampling Integrity, Cassava sampling

1. Introduction

In agro-industrial cassava processing, bulk solids handling is a critical unit operation directly influencing process efficiency and product quality. Cassava chips exhibit high physical property variability, requiring a robust sampling system to ensure quality assurance (QA) accuracy under the Process Analytical Technology (PAT) framework; any sampling bias leads to significant errors in moisture content and starch yield estimation [1].

The core engineering challenge in vertical screw-based sampling units is the complex momentum transfer and hydrodynamics of non-uniform biomass. As material is conveyed vertically against gravity, internal and wall friction generate resistance, causing momentum loss, slippage, and unstable mass flux. According to Roberts [2] and Bridgwater [3], volumetric efficiency is highly sensitive to pitch-to-diameter ratio; inefficient geometry induces flow discontinuities that are a

primary source of sampling bias in automated industrial systems [4],[5].

Process safety presents an additional engineering challenge. Frictional heat dissipation - governed by transport phenomena principles [6] - can cause hazardous heat accumulation in short-pitch configurations. Recurrent clogging represents states of zero momentum transfer where all input energy converts to thermal energy, creating localized ignition sources. Combined with combustible fines generated through particle attrition, this significantly elevates the risk of dust explosions under the Dust Explosion Pentagon framework [7],[8].

Despite extensive theoretical and computational work - including the granular rheology framework of Roberts [2], DEM-based conveying models of Owen and Cleary [9], biomass-specific feeding studies by Rackl and Günthner [10], and recent DEM and CFD studies [11-13] - a critical gap remains: no experimental data simultaneously characterizes energy partitioning and material integrity as a direct function of P/D ratio for fragile agricultural feedstocks under vertical hydraulic conveying. This study addresses that gap directly by optimizing the vertical sampling unit for cassava chips through analysis of screw geometry, flow stability, and energy dissipation - identifying an optimal configuration that preserves sampling integrity, minimizes biochemical degradation risk, and supports scale-up of automated sampling in large-scale biorefineries.

2. Materials and Methods

2.1 Feedstock Characterization

The feedstock utilized in this study was commercial-grade cassava chips (Figure 1a), characterized by high morphological heterogeneity and an irregular, fibrous structure (Figure 1b). From a process engineering standpoint, these physical attributes govern the interparticle momentum transfer and the resulting flowability of the bulk solid [1], [3].

The average bulk density (ρ_b) was determined to be $496.4 \pm 62.4 \text{ kg/m}^3$ ($0.4964 \pm 0.0624 \text{ g/cm}^3$). The moisture content (MC) was strictly maintained at $13.5 \pm 0.5\%$ (wet basis) to simulate

standard industrial conditions. This parameter is critical as it influences the interfacial friction and cohesive forces, which directly affect the internal shear stress (τ) distribution and the potential for mechanical interlocking within the screw flight [2], [14].

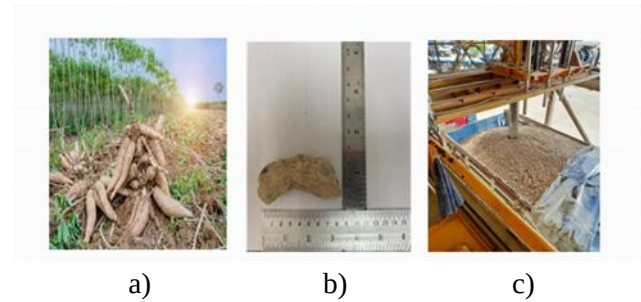


Figure 1 Physical Properties and Conveying Behavior of Cassava Chips

- a) Harvested cassava roots from the field.
- b) A representative cassava chip (length: 70-100 mm) with a 20 mm scale bar (approximate, based on chip reference dimensions).
- c) The screw conveyor-based automatic sampling system operating during

2.2 Experimental Setup and Geometric Boundary Conditions

The automated sampling unit (Figure 1c) serves as the control volume for this investigation. The boundary conditions and operational constraints were defined by the interaction between the screw geometry and the drive system. The experimental design focused on two distinct screw configurations, as summarized in the design matrix in Table 1.

Table 1 Experimental Design Matrix and Geometric Boundary Conditions of the Vertical Screw Sampling System

Screw Configuration Type	Pitch-to-Diameter Ratio (P/D)	Drive Ratio (Gear Teeth Count, n_2)	Screw Diameter Range (D), [m]
Type B	2/3	18, 21, 28	0.11 – 0.20
Type C	1/2	18, 21, 28	0.11 – 0.20

The selection of Type B (P/D = 0.67) and Type C (P/D = 0.50) geometries (Figures 2 and 3) enables evaluation of how pitch compression ratio and gear-regulated rotational speed affect transport

phenomena and energy dissipation. These P/D values represent the practical manufacturing extremes within $D = 0.11\text{--}0.20\text{ m}$ using standard CNC fabrication, establishing the performance envelope within which intermediate configurations (e.g., $0.55\text{--}0.65$) must operate; their investigation is identified as a priority for future work.

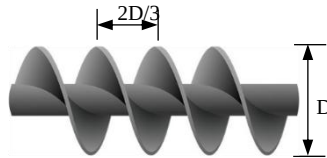


Figure 2 Full-pitch screw with $2D/3$ pitch length.

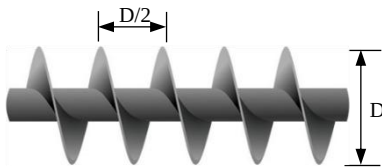


Figure 3 Full-pitch screw with $D/2$ pitch length.

The experimental configuration replicates the hydraulic drive setup at the Betagro cassava processing facility (Lopburi Province, Thailand), ensuring direct industrial applicability without system redesign. Alternative technologies were excluded on technical grounds: belt conveyors cannot achieve the required vertical transport angle under cassava chip bulk density and moisture conditions [1], and pneumatic conveying induces particle fragmentation and moisture loss

that compromise sampling integrity [3]. The hydraulic screw conveyor therefore uniquely satisfies all operational constraints - vertical transport, chip morphology preservation, and process infrastructure compatibility. Screw diameters (D) ranged from $0.11\text{ to }0.20\text{ m}$, and the instrumentation setup (Figure 4) enabled real-time acquisition of hydraulic pressure (p), oil flow rate (Q_{oil}), and mass flow rate ($\dot{m}$) for comprehensive transport analysis [5].

Both Type B and Type C flights were fabricated from the same mild steel batch under identical CNC specifications; flight thickness and surface roughness (R_a) therefore constitute controlled constants, and any difference in η_v or SEC is attributable exclusively to P/D ratio. Profilometer measurement of R_a is recommended as a standard protocol when comparing flights of different materials in future studies.

The screw shaft speed (N) was set by a chain-and-sprocket drive governed by Equation (1):

$$N = N_{\text{motor}} \times (n_1 / n_2) \quad (1)$$

where $N_{\text{motor}} = 73\text{ rpm}$ (hydraulic motor output speed), $n_1 = 14\text{ teeth}$ (fixed driving sprocket), $n_2 =$ interchangeable driven sprocket (18, 21, or 28 teeth). The calculated shaft speeds ($N_{\text{motor}} \times n_1/n_2 = 73 \times 14/18 = 56.78, 73 \times 14/21 = 48.67, 73 \times 14/28 = 36.50\text{ rpm}$) match the directly measured shaft speeds to within $\pm 0.01\text{ rpm}$ ($CV < 0.004\%$), confirming stable hydraulic drive output across all gear settings.

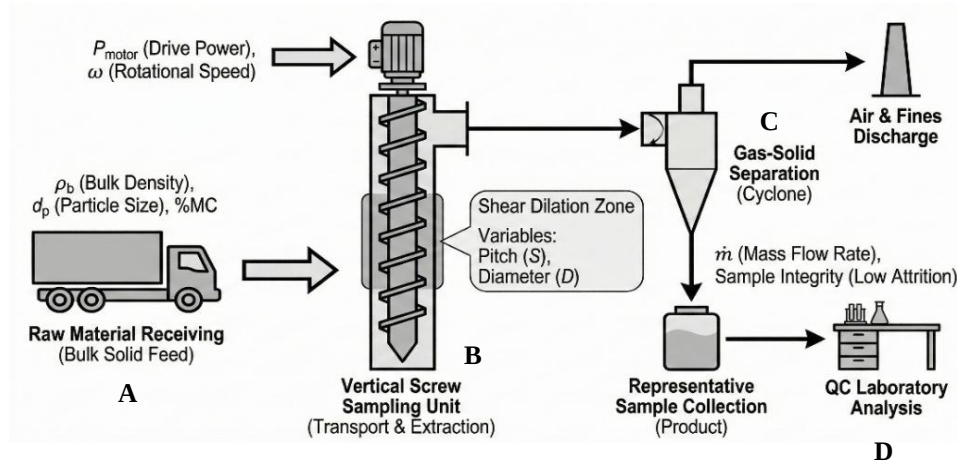


Figure 4 Process Flow Diagram of Cassava Chip Sampling Unit Operation.



2.3 Theoretical Framework and Governing Equations

To ensure scientific rigor, the unit operation was analyzed through the lens of conservation laws and dimensionless transport parameters.

2.3.1 Momentum Transport and Mass Flux Stability

The efficiency of mass transport was quantified via the Volumetric Efficiency (η_v) shown in Equations (2) and (3), which serves as a dimensionless indicator of the stability of the Mass Flux and the degree of momentum loss due to material slippage [15]:

$$\eta_v = \frac{\dot{m}_{\text{actual}}}{\dot{m}_{\text{theoretical}}} \quad (2)$$

$$\eta_v = \frac{\dot{m}_{\text{actual}}}{\rho_b \times A \times P \times N} \quad (3)$$

where A is the effective cross-sectional area, P is the screw pitch, and N is the rotational speed. A significant deviation of η_v from unity indicates inefficient momentum coupling between the screw flight and the material bed, often caused by internal shear losses [2], [10].

2.3.2 Conservation of Energy and Dissipative Heat Generation

Applying the first law of thermodynamics to the sampling unit, the total hydraulic power input (P_{in} or P_{total}) is partitioned into productive potential energy and dissipative losses. The fundamental energy balance for this vertical transport operation is defined as Equation (4):

$$P_{\text{total}} = P_{\text{potential}} + Q_{\text{gen}} \quad (4)$$

Where $P_{\text{potential}}$ represents the energy rate required for the vertical displacement of the material ($\dot{m}gh$), and Q_{gen} represents the rate of dissipative heat generation primarily arising from inter-particle and wall friction. The heat generation rate is further derived as Equation (5).

$$Q_{\text{gen}} = (p \times Q_{\text{oil}}) - (\dot{m}gh) \quad (5)$$

Where

p = The hydraulic pressure (Pa or kg-m/s²)

Q_{oil} = The oil flow rate (m³/s)

$\dot{m}$ = Mass flow rate (kg/s)

g = The gravitational acceleration (m/s²)

h = The vertical transport height (m)

Evaluating Q_{gen} is a critical step in assessing Process Safety, as excessive heat accumulation can lead to Thermal Degradation of the starch or serve as a potential Ignition Source in dust-prone environments [7], [8].

To evaluate the process efficiency independent of throughput capacity, the specific energy consumption (SEC) was determined. SEC serves as a standardized metric to compare the energy cost per unit mass of material transport as Equation (6):

$$\text{SEC (kJ/kg)} = \frac{P_{\text{total}}}{\dot{m}} \quad (6)$$

where P_{total} is the total power input (kW) and $\dot{m}$ is the mass flow rate (kg/s). A surge in SEC values indicates a transition from efficient conveying to a high-friction regime, where energy is wasted on mechanical grinding rather than transport [7].

2.4 Evaluation of Sampling Integrity and Attrition Kinetics

The preservation of the feedstock's physicochemical properties, defined as sampling integrity, was evaluated through particle attrition analysis. According to the principle of mass conservation, mechanical stress induces size degradation, leading to fines generation, which is quantified as a source of sampling bias [1], [16]. The interaction between energy dissipation (Q_{gen}) and mechanical interlocking was analyzed to establish the operational limits, ensuring that the extracted samples accurately reflect the feedstock quality without induced thermal or mechanical degradation.

2.5 Statistical Analysis

One-way analysis of variance (ANOVA) was performed to compare mass flow rate, volumetric efficiency (η_v), and SEC between Type B and Type C configurations across the three gear speed conditions (18-, 21-, and 28-tooth gear). Post-hoc pairwise comparisons were conducted using Tukey's HSD test. All analyses were performed at $\alpha = 0.05$. Statistically significant differences between Type B and Type C were confirmed for all primary performance variables ($p < 0.05$).



3. Results and Discussions

3.1 Operational Baseline and Process Failure Analysis

A longitudinal retrospective analysis covering the operational period from May to April was conducted to diagnose the baseline performance of the existing screw conveyor-based sampling system. The empirical data revealed a consistent pattern of mechanical failure, characterized by an average of three clogging incidents per month, which resulted in a cumulative downtime of approximately 126 minutes per month. Notably, the peak operational instability was recorded in September, when the downtime escalated to nearly 240 minutes.

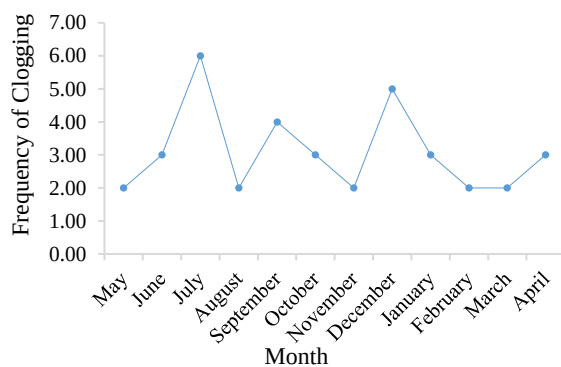


Figure 5 Monthly frequency of clogging in the cassava chip screw sampling system.

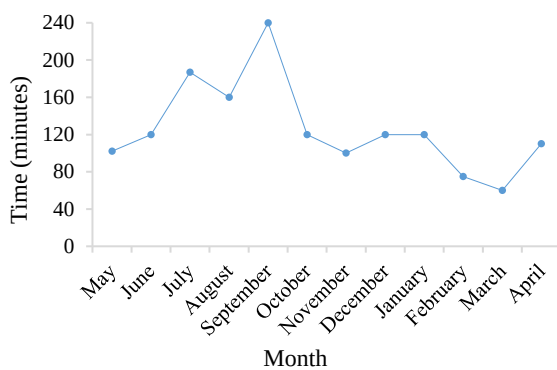


Figure 6 Comparison of monthly repair time required to resolve clogging issues in the cassava chip screw sampling system.

These blockage episodes, as illustrated in Figure 5, are not merely operational disruptions but critical indicators of momentum stagnation. In the context of granular rheology, these recurring stoppages signify a transition from a dynamic flow regime to a static "jamming state," where the motive torque of the drive system is overwhelmed

by the internal shear stress of the cassava chips. This phenomenon aligns with the mechanical interlocking hypotheses for fibrous bulk solids described by Roberts [2].

Furthermore, Figure 6 quantifies the repair duration associated with these failures. From a process safety perspective, these extended downtimes represent periods of dangerous thermal accumulation. When the screw jams, the input kinetic energy is instantaneously converted into frictional heat at the blockage point. According to the energy balance principle in Equation (4), this creates localized "hot spots" that can approach the minimum ignition temperature of dry biomass dust. This finding underscores a severe safety hazard, as highlighted by Amyotte & Eckhoff [7] in the *Dust Explosion Pentagon* framework, thereby necessitating a geometric redesign to mitigate thermal risks.

3.2 Analysis of Momentum Transport and Volumetric Efficiency

This section evaluates the critical factors influencing the vertical transport of cassava chips within the lift system. The analysis integrates the geometric design of the screw flights with kinematic operational parameters to determine their collective impact on momentum transfer and the resulting flow regimes.

3.2.1 Geometric Boundary Conditions

To interpret the transport mechanisms governing system performance, the geometric boundary conditions of the two screw configurations were evaluated, as illustrated in Figure 7. The analysis reveals a distinct hydrodynamic divergence between the two profiles. Type B, characterized by an extended pitch-to-diameter ratio ($P = 2D/3$), creates a larger control volume between flights. This geometry theoretically minimizes the granular packing fraction (ϕ), allowing the fibrous cassava chips to align naturally with the helical flight angle. Consequently, this configuration promotes a "plug flow regime," where the material is transported as a cohesive block with minimal internal shear, thereby maximizing the efficiency of momentum transfer.

In sharp contrast, the compressed profile of Type C ($P = D/2$) significantly restricts the available volumetric capacity per revolution. From

a granular rheology perspective, this geometric constraint increases the "arching effect" probability, forcing the biomass bed into a "compacted/shear regime." In this state, the dominant mechanical force shifts from vertical lift to lateral wall friction, explaining the theoretical tendency for energy dissipation and flow instability observed in restricted-pitch designs.

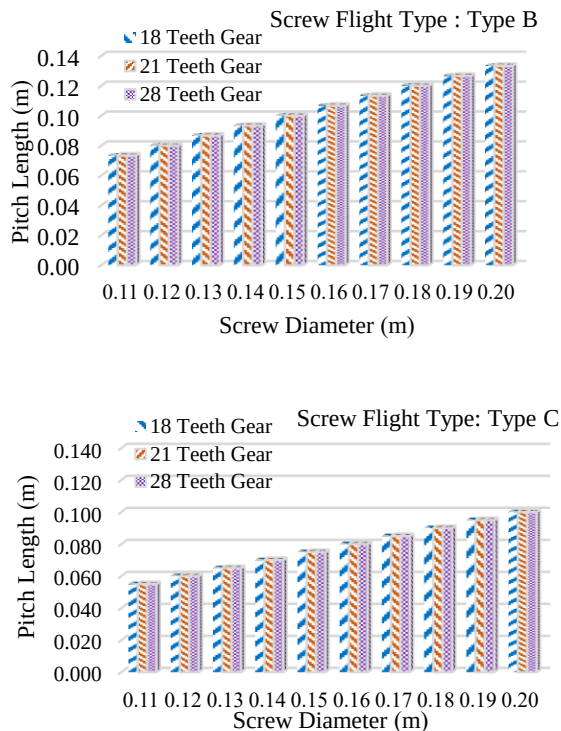


Figure 7 Comparison of screw flight diameter (D) and pitch length for Type B and Type C.

3.2.2 Kinematic Stability Validation

The stability of the drive system was verified to ensure that the screw rotational speed (N) remained independent of the geometric variables. Figure 8 delineates the operational parameters governed by the drive system setup. The rotational speed (N) was determined solely by the selected gear ratio and remained independent of the screw diameter (D). As illustrated, the 18-tooth gear set provided the highest rotational speed (~57 rpm), exceeding the 50 rpm reference line, thereby generating the highest shear rate conditions for the study. Conversely, the 28-tooth gear set yielded the lowest speed (~36 rpm). This confirmation of constant speed across varying diameters ensures that any observed differences in mass flow rate

(discussed in the next section) are attributable to screw geometry and diameter effects, rather than kinematic fluctuations.

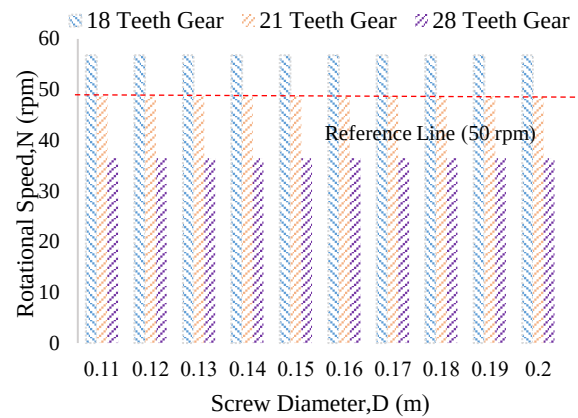


Figure 8 Relationship between screw flight diameter (D) and rotational speed for Type B and Type C configurations.

In Equation (1) (Section 2.2), the back-calculated chain-interface speed ($N_{\text{motor}} \times n_1 = 73 \times 14 = 1,022 \text{ rpm}$, $CV < 0.004\%$) confirms stable hydraulic drive output across all gear settings, validating that observed performance differences between Type B and Type C are attributable solely to P/D geometry.

3.2.3 Mass Flux Characteristics and Regime Transition

With the kinematic stability confirmed, the mass transport performance of the two screw profiles was evaluated against the pilot-scale requirement of 11.36 kg/cycle. The comparison in Figure 9 is conducted at the maximum rotational speed (18-tooth gear) to clearly demonstrate the divergence in transport efficiency between the two geometric profiles under high-load conditions.

As illustrated in Figure 9, the data demonstrates the superior capability of the Type B configuration. The system consistently achieved or exceeded the target capacity threshold (indicated by the red dashed line) at screw diameters of $D \geq 0.14 \text{ m}$. This high performance validates the theoretical assumption that the extended pitch geometry ($P = 2D/3$) reduces internal friction and promotes a "Plug Flow Regime," which maximizes the efficiency of momentum transfer from the screw to the cassava chips.

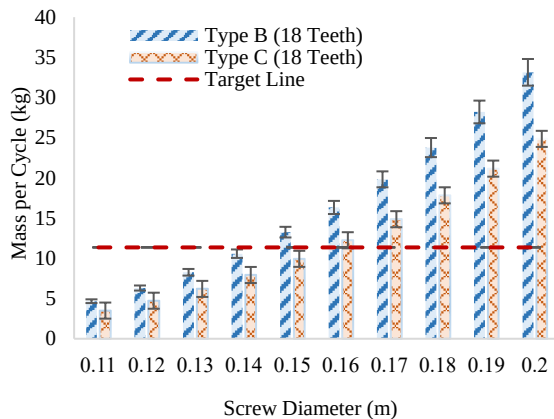


Figure 9 Comparison of conveying capacity per cycle between Type B and Type C screw flights at maximum rotational speed (18-tooth gear).

In contrast, the limitations of the restricted geometry are evident in the performance of Type C. To meet the same 11.36 kg throughput, this configuration required significantly larger diameters ($D \geq 0.16$ m) even at the maximum rotational speed. This performance lag indicates a transition into a "high-slip regime," where the restricted pitch ($P = D/2$) causes the material to rotate with the screw rather than advancing vertically. Although the narrow error bars for Type C suggest high operational stability, this is achieved at the cost of momentum decoupling, necessitating higher kinetic energy to overcome the increased frictional resistance within the confined pitch space.

The experimental analysis illustrated in Figures 10 and 11 reveals that the volumetric efficiency (η_v) of the system consistently remains below 40%. In the context of bulk solids handling engineering, this performance is theoretically consistent with the principles established by Roberts [2], which state that agricultural materials with irregular geometries and high internal friction, such as cassava chips, exhibit a low filling degree within the screw flights. This phenomenon is primarily attributed to material interlocking, where the non-spherical nature of the chips creates substantial internal voids during transport, preventing the material from fully occupying the screw's theoretical geometric volume.

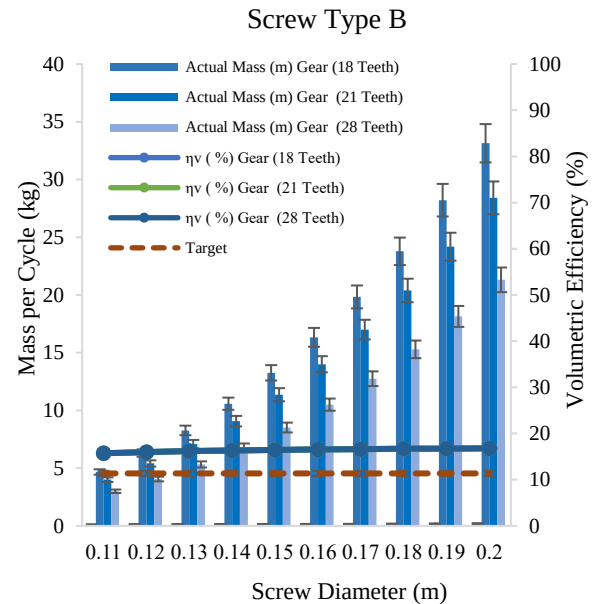


Figure 10 Comparative analysis of mass flow rates and volumetric efficiencies for the Type B screw ($P/D = 0.67$) across various screw diameters and gear configurations.

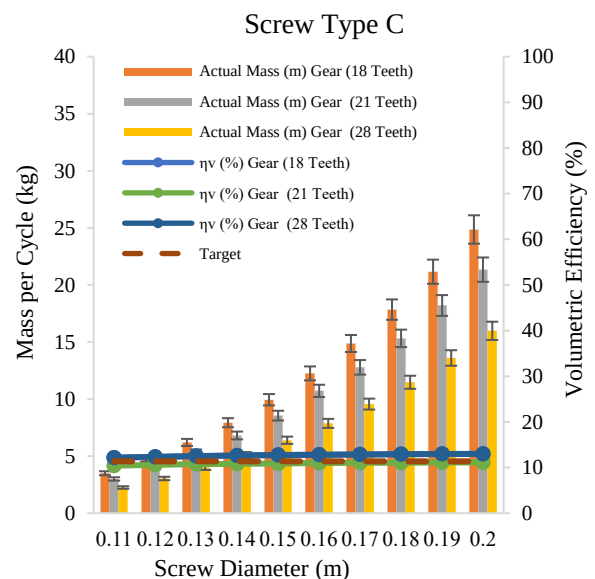


Figure 11 Comparative analysis of mass flow rates and volumetric efficiencies for the Type C screw ($P/D = 0.5$) across various screw diameters and gear configurations.

Furthermore, the observed decline in efficiency within the Type C screw ($P/D = 0.5$) compared to the Type B screw ($P/D = 0.67$) can be elucidated through the theory of vortex flow and internal shear resistance as proposed by Woodcock and Mason [16]. The restricted pitch of Type C



induces higher internal shear and circumferential slippage (momentum decoupling), further intensified at elevated rotational speeds [16].

Despite the relatively low absolute efficiency values, the comparative data underscores the superior performance of the Type B design in maintaining a stable volumetric efficiency across all tested diameters. This validates the geometric optimization hypothesis, asserting that an optimized pitch-to-diameter ratio promotes a more effective plug flow regime and mitigates material compaction. Consequently, the Type B configuration demonstrates the capacity to achieve the design target of 11.36 kg per cycle even under challenging rheological conditions, aligning with agricultural machinery design standards that prioritize operational reliability over theoretical maximum capacity [17].

3.2.4 Speed-Dependent Mass Transport Response and Pitch Geometry Influence

The experimental results illustrated in Figure 12 demonstrate a strong linear correlation between rotational speed and mass flow rate per cycle across all tested configurations ($R^2 > 0.98$). At a constant screw diameter, increasing the rotational speed from 36.50 to 56.78 rpm leads to a proportional rise in mass transport capacity. However, the rate of this increase—represented by the slope of the regression lines—is significantly governed by the pitch-to-diameter (P/D) ratio. For instance, at $D = 0.16$ m (Figure 12b), the Type B configuration ($P/D = 0.67$) exhibits a steeper gradient ($m = 0.144$) compared to the Type C configuration ($P/D = 0.50$, $m = 0.113$), indicating that a larger pitch enhances the system's sensitivity to rotational input.

From a fluid-solid dynamics perspective, the divergence between Type B and Type C geometries suggests a transition in flow efficiency. The Type B configuration facilitates a more effective axial displacement per revolution, maximizing the axial velocity of the cassava chips. In contrast, the restricted geometry of Type C ($P/D = 0.50$) appears to induce a "high-slip" regime, particularly at elevated speeds. In this state, a significant portion of the kinetic energy is dissipated through material rotation (tumbling)

within the screw flights rather than productive forward advancement. This observation aligns with the findings of Owen and Cleary [9], which suggest that optimal pitch lengths are crucial to reducing internal granular friction and maintaining flow stability.

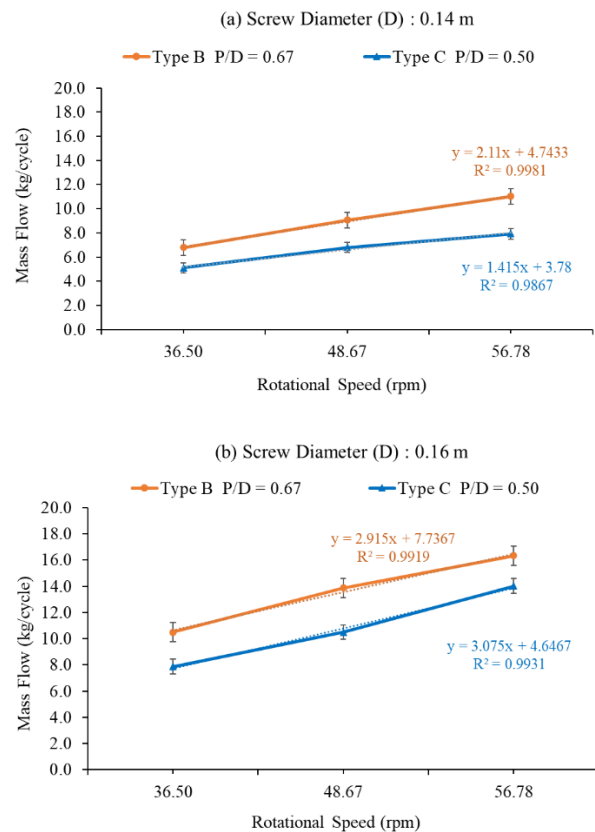


Figure 12 Effect of rotational speed on mass flow rate per cycle for Type B ($P/D = 0.67$) and Type C ($P/D = 0.50$) configurations at: (a) $D = 0.14$ m and (b) $D = 0.16$ m.

The correlation analysis further identifies the critical role of screw diameter in achieving performance targets. As shown in Figure 12a ($D = 0.14$ m), neither configuration consistently achieves the pilot-scale target of 11.36 kg/cycle, with Type B reaching a plateau near 11.0 kg/cycle. However, by increasing the diameter to 0.16 m (Figure 12b), the Type B configuration successfully surpasses the 11.36 kg/cycle threshold once the rotational speed exceeds approximately 49 rpm. Conversely, Type C fails to reach this target even at the maximum diameter and speed, confirming that momentum decoupling



occurs when the P/D ratio is too low to overcome the internal shear of fibrous granular materials.

Ultimately, these results validate the "plug flow" characteristics of the Type B design, where the material moves as a coherent mass with minimal internal velocity gradients. The high R^2 values (0.9867-0.9981) confirm that the mass transport remains highly predictable within the tested range, providing reliable empirical coefficients for engineering specifications. These findings support the principles established by Roberts [2] regarding the critical helix angle required to optimize volumetric efficiency. The study concludes that for cassava chip transport, a P/D ratio of 0.67 combined with a 0.16 m diameter is essential to ensure consistent throughput that meets industrial requirements.

3.3 Energy Dissipation characteristics and their Impact on Sampling Integrity

The analysis of energy partitioning was conducted under constant operating conditions ($p = 152$ bar, $Q_{oil} = 4.875 \times 10^{-4} \text{ m}^3/\text{s}$, $t = 104$ s, $h = 4.5$ m). The distribution of total input power (P_{in}) into effective mechanical work (P_{out}) and heat dissipation (Q_{gen}) is shown in Figure 13.

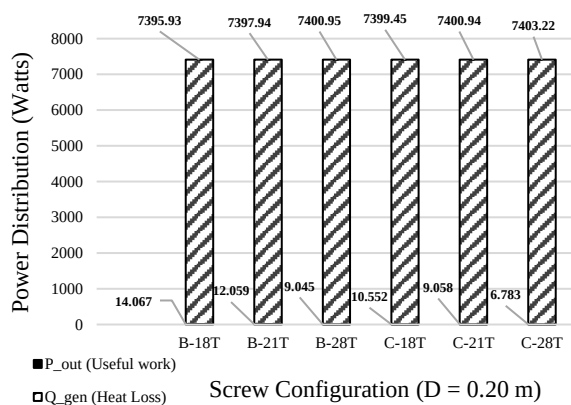


Figure 13 Distribution of total input power (P_{in}) into effective mechanical work (P_{out}) and heat dissipation (Q_{gen}) for the hydraulic vertical screw conveyor system.

Over 99% of hydraulic input power is theoretically dissipated as heat (Q_{gen}) - a theoretical upper-bound estimate from the first-law energy balance (Equation 4), as no direct

calorimetric measurement was performed. This is consistent with vertical screw conveying theory [16], which holds that most input energy overcomes internal shear resistance, wall friction, and vortex motion rather than elevating the bulk load.

Although mechanical efficiency is low across all configurations, significant differences exist between geometries. Type C ($P = 0.5D$) consistently exhibited higher SEC and greater Q_{gen} than Type B, attributable to its restricted pitch inducing higher internal compaction and frictional drag between chips and casing. The frictional energy (Q_{gen}) is transferred to the material as mechanical stress and thermal energy, increasing cumulative stress on individual chips during transport. Such elevated stress raises the risk of morphological change and may alter chip bulk density, introducing sampling bias where sample characteristics no longer accurately represent the bulk load.

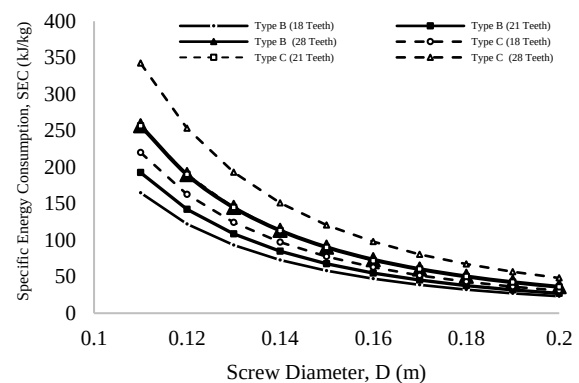


Figure 14 Effect of screw diameter on Specific Energy Consumption (SEC) for screw configurations Type B and Type C at various rotational speeds.

In contrast, Type B ($P = 0.67D$) demonstrated superior performance. As shown in Figure 14, Type B achieved the lowest SEC of 23.25 kJ/kg at $D = 0.20$ m and maximum rotational speed (18-tooth gear). Its wider pitch reduces internal compaction and frictional losses, lowering cumulative mechanical stress per unit mass conveyed and better preserving chip morphology and sampling representativeness.



According to the quantitative research in Table 2, the Type B arrangement reduces specific energy consumption (SEC) by 25.0% while increasing usable mechanical work (P_{out}) by 33.4% compared to Type C. The significant improvements confirm that the modified pitch-to-diameter ratio ($P/D = 0.67$) efficiently reduces material jamming and decreases internal friction. Despite the minimal percentage change in heat loss (Q_{gen}) of 0.05% attributed to the predominance of input power, the significant increase in mechanical output (P_{out}) demonstrates that Type B transfers available energy into material movement with greater efficiency. This efficiency lowers energy expenditures per unit mass and reduces mechanical stress on cassava roots, preserving the samples' physical integrity and allowing for reliable quality assessment.

Type B reduces SEC by 25.0% and increases useful mechanical work output (P_{out}) by 33.4% relative to Type C (Table 2). The near-identical Q_{gen} values (7,395.93 vs. 7,399.45 W; $\Delta = 3.52$ W, 0.05%) confirm that both configurations dissipated equivalent frictional heat and neither imposed thermally damaging conditions on the chips. The 25.0% reduction in SEC indicates lower cumulative mechanical stress per unit mass conveyed, directly supporting better preservation of chip morphology and sampling representativeness. This study involves conveying only - no grinding or size-reduction was performed; Q_{gen} reflects chip-to-flight wall friction

and inter-chip friction during vertical transport, not particle size reduction.

Table 2 Comparison of optimal performance parameters between Type B and Type C configurations at maximum rotational speed (18-tooth gear) and 0.20 m diameter.

Parameter	Type B ($P/D = 0.67$)	Type C ($P/D = 0.50$)	% Improvement
Heat Loss (Q_{gen})	7,395.93 W	7,399.45 W	0.05%
Specific Energy (SEC)	23.25 kJ/kg	31.00 kJ/kg	25.0%
Useful Work (P_{out})	14.07 W	10.55 W	33.4%

As shown in Table 3, the SEC of 23.25 kJ/kg achieved by Type B exceeds the 4.14–10.6 kJ/kg reported by Rackl and Günthner [10] for horizontal wood chip feeding, consistent with the higher energy demand of vertical transport against gravity and vortex motion [16]. Yuan et al. [11] demonstrated via DEM simulation that pitch geometry governs vertical conveying capacity, and Hamed et al. [13] established material-geometry interactions as principal determinants of SEC (0.5–2.0 kJ/kg for horizontal Douglas fir at 48 rpm). Collectively, these benchmarks confirm that P/D optimization alone yields statistically significant performance gains ($P \leq 0.008$) for fibrous biomass in vertical conveying applications.

Table 3 Comparison of key performance indicators with published literature on screw conveying of agricultural biomass.

Parameter	This study Type B ($P/D=0.67$)	This study Type C ($P/D=0.50$)	Rackl & Günthner [11]	Yuan et al. [15]	Hamed et al. [17]
SEC (kJ/kg)	23.25	31.00	4.14 – 10.6 ^a	-	0.5–2.0 ^b
η_v (%)	16.34	12.02	-	-	-
Mass flow	8.82 kg/cycle	6.61 kg/cycle	quasi-static	~250 t/h	60–75 kg/h
Material	Cassava chips	Cassava chips	Wood chips (spruce)	Soybean	Douglas fir
P/D ratio	0.67	0.50	1.17–1.33	N/A (variable)	1.0
Conveyor type	Vertical hydraulic	Vertical hydraulic	Horizontal	Vertical	Horizontal

^a Based on effective power consumption (E_{eff}) reported by Rackl & Günthner [10], Fig. 14

^b Specific energy at 48 rpm, from Hamed et al. [13], Fig. 6c



Table 4 One-way ANOVA and Tukey's HSD post-hoc results (Type B vs. Type C; $n = 9$ per group; $\alpha = 0.05$). ** $P < 0.01$.

Variable	D(m)	Type B (P/D=0.67) Mean $\pm$ SD	Type C (P/D=0.50) Mean $\pm$ SD	$F_{(1,16)}$	P-value	Sig.	Tukey HSD
Mass flow rate (kg/cycle)	0.14	8.817 $\pm$ 1.647	6.609 $\pm$ 1.232	10.369	0.005	**	A vs B
η_v (%)	0.14	16.340 $\pm$ 0.009	12.023 $\pm$ 0.903	205.852	< 0.001	**	A vs B
SEC (kJ/kg)	0.20	28.846 $\pm$ 5.738	38.447 $\pm$ 7.665	9.049	0.008	**	A vs B

3.4 Statistical Analysis of Performance Differences Between Screw Configurations

One-way analysis of variance (ANOVA) was performed using Minitab 19 (Minitab LLC, State College, PA, USA) to determine whether statistically significant differences existed between Type B (P/D = 0.67) and Type C (P/D = 0.50) for three primary response variables: mass flow rate, volumetric efficiency (η_v), and specific energy consumption (SEC). Each group comprised $n = 9$ observations (three gear speeds $\times$ three replicates). Levene's test confirmed equal variances for all variables (all $P > 0.05$; $\alpha = 0.05$). Complete results are presented in Table 4.

ANOVA results are summarized in Table 4. Mass flow rate ($D = 0.14$ m) differed significantly between configurations [$F(1,16) = 10.369$, $P = 0.005$], with Type B: 8.817 $\pm$ 1.647 kg/cycle vs. Type C: 6.609 $\pm$ 1.232 kg/cycle (Tukey HSD 95% CI [0.754, 3.661]). Volumetric efficiency showed the largest effect [$F(1,16) = 205.852$, $P < 0.001$]: Type B 16.340 $\pm$ 0.009% vs. Type C 12.023 $\pm$ 0.903% (95% CI [3.679, 4.954]). SEC ($D = 0.20$ m) also differed significantly [$F(1,16) = 9.049$, $P = 0.008$]: Type B 28.846 $\pm$ 5.738 vs. Type C 38.447 $\pm$ 7.665 kJ/kg (95% CI [-16.367, -2.835]). All three variables showed statistically significant differences ($P \leq 0.008$), confirming that the performance advantages of Type B are not attributable to random variation.

4. Conclusions

This study successfully identifies the optimal vertical screw conveyor design for enhancing the efficiency of automated cassava sampling systems. Through a rigorous comparative analysis between Type B (P/D = 0.67) and Type C (P/D = 0.50) configurations, the investigation reveals that increasing the screw pitch ratio significantly improves energy performance. Specifically, the

Type B configuration operating with a 0.20 m diameter and at maximum rotational speed achieved the lowest Specific Energy Consumption (SEC) of 23.25 kJ/kg. This corresponds to a 25.0% improvement in energy efficiency compared to the Type C configuration under identical conditions, confirming that the optimized pitch geometry effectively minimizes the power required per unit mass of transport.

A critical examination of energy partitioning further elucidates the mechanism behind this performance enhancement. While the analysis confirms that over 99% of the hydraulic input power is theoretically dissipated as heat - a theoretical upper-bound estimate from the first-law energy balance - due to the internal shear and frictional resistance inherent in vertical conveying, the screw geometry plays a decisive role in energy conversion. The Type B screw demonstrated a superior capability to utilize the available power, achieving a 33.4% increase in useful mechanical work (P_{out}) relative to Type C. These findings indicate that the wider pitch ratio of 0.67D effectively mitigates material compaction and reduces static friction within the screw flight, thereby allowing a greater proportion of energy to be directed towards material elevation rather than heat generation.

Ultimately, the reduction in SEC and heat dissipation observed in the Type B configuration has profound implications for sampling integrity. By minimizing cumulative frictional stress during transport, the optimized design significantly reduces the physical degradation of cassava roots. This preservation of material consistency ensures that the collected samples accurately represent the bulk load, thereby minimizing sampling bias and satisfying quality assurance requirements. Consequently, this study recommends the implementation of the Type B screw with a 0.20 m diameter and high-speed operation (18-tooth gear) as the standard for industrial applications, offering the best balance between energy economy, flow stability, and sample quality preservation.



5. Acknowledgment

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Optimization of Swine Farm Wastewater Treatment Using Mixed Microalgae: Statistical Modeling and Performance Evaluation via Response Surface Methodology

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Abstract

Swine farm wastewater contains high concentrations of organic matter and nutrients, requiring treatment approaches that are both effective and economically feasible. This study evaluated the performance of mixed indigenous microalgae for the removal of chemical oxygen demand (COD) and total phosphorus (TP) from swine farm wastewater and optimized the effects of initial pH and algal concentration using Response Surface Methodology (RSM) with a Central Composite Design (CCD). Thirteen experimental runs were conducted under outdoor conditions to reflect field applicability. COD and TP removal efficiencies ranged from 74.30–83.85% and 75.17–83.58%, respectively. Statistical analysis showed that pH significantly influenced both COD and TP removal, whereas algal concentration exerted a stronger effect on COD removal but a comparatively weak influence on TP, in agreement with ANOVA results. The quadratic model demonstrated strong predictive performance for COD ($R^2 = 0.9879$; predicted $R^2 = 0.9245$), while the TP model displayed limited predictive capability, suggesting that additional unmeasured factors may govern phosphorus reduction. Numerical optimization identified pH 7.69 and algal concentration (A600) 2.072 as the optimal conditions, yielding predicted removals of 78.21% COD and 82.00% TP. Although TP levels approached regulatory thresholds, COD remained above discharge limits, highlighting the need for a polishing step prior to release. Overall, the results demonstrate that mixed indigenous microalgae offer a robust, low-cost treatment strategy for swine wastewater and provide optimized operational conditions to support practical implementation.

Keywords: Mixed microalgae, Swine farm wastewater, COD removal, Phosphorus removal, Response Surface Methodology (RSM)

1. Introduction

Swine farming is a vital agricultural sector but generates substantial volumes of wastewater laden with high concentrations of organic matter, nitrogen, and phosphorus. While anaerobic digestion is commonly employed for primary treatment, the discharge of nutrient-rich effluents remains a critical environmental challenge, driving eutrophication and ecological imbalance in receiving water bodies [1,2]. Consequently, developing cost-effective and sustainable post-treatment technologies to mitigate these pollutant loads is an urgent priority.

Microalgae-based phycoremediation has emerged as a promising approach due to its ability

to assimilate nitrogen and phosphorus while supporting aerobic degradation through oxygen release during photosynthesis [3–5]. In addition to nutrient removal, microalgal biomass produced during treatment offers opportunities for resource recovery, contributing to circular bioeconomy strategies [6,7]. Mixed indigenous microalgal consortia, in particular, have gained attention for their higher robustness in real wastewater, stemming from functional diversity and synergistic interactions with bacteria [8–10]. These consortia also exhibit greater tolerance to fluctuating wastewater characteristics compared with monocultures, making them attractive for low-cost outdoor systems.



Despite these advantages, studies focusing on optimization of mixed microalgal consortia, especially under high-strength swine wastewater, remain limited. Most previous investigations have emphasized monoculture systems or examined single operational variables in isolation, which restricts understanding of how key factors interact to influence treatment outcomes. Environmental and operational factors such as pH, light intensity, temperature and initial inoculum concentration strongly affect microalgal activity but few studies have systematically evaluated the combined effects of pH and initial biomass density, two parameters that directly govern nutrient speciation, carbon availability, photosynthetic efficiency and algal–bacterial interactions [11]. Furthermore, most Response Surface Methodology (RSM) studies predominantly focus on monocultures, leaving mixed indigenous consortia underexplored in terms of predictive modeling and optimization [12]. This gap limits the ability to design field-deployable systems that rely on naturally occurring microalgal communities.

To address this gap, this study investigates the interactive effects of initial pH and mixed-microalgae concentration on the treatment performance of swine farm wastewater using a Central Composite Design (CCD) under RSM. The objectives were to (i) quantify how these two key operational parameters influence COD and total phosphorus (TP) removal, and (ii) determine the optimal conditions for maximizing removal efficiencies. By explicitly examining mixed indigenous consortia rather than laboratory monocultures, this study provides new insight into the operational tuning of robust, low-cost and field-relevant phycoremediation systems.

2. Materials and Methods

2.1 Sampling of Swine Farm Wastewater

Swine farm wastewater was collected from a small-scale pig farm (80–100 pigs) located in Ubon Ratchathani Province, Thailand. The raw wastewater was screened through nylon mesh to remove large solids and diluted tenfold (1:10) with natural pond water to reduce its organic load before use. This dilution ratio was selected based on preliminary observations and previous studies showing that undiluted swine wastewater may

exert strong ammonia toxicity and light attenuation which inhibit microalgal growth; thus, the 1:10 dilution reflects a practical condition commonly used in low-cost open-pond systems. Initial physicochemical characteristics of the wastewater were determined following the Standard Methods for the Examination of Water and Wastewater [13].

2.2. Preparation of Mixed Microalgae Inoculum

A consortium of indigenous mixed microalgae was isolated from a natural pond within the Ubon Ratchathani University campus. The culture was acclimated and pre-cultivated in diluted swine wastewater (1:10) under natural sunlight and ambient temperature (28–32°C). This study employed a naturally occurring consortium without targeted species selection, consistent with field-oriented phycoremediation approaches where functional performance is prioritized.

Continuous aeration was supplied at 2 L/min to maintain homogeneous mixing and prevent sedimentation while optical density at 600 nm (A_{600}) was used to estimate algal concentration. Prior to experimentation, inoculum suspensions were adjusted to the designated A_{600} levels corresponding to the experimental CCD design.

Light intensity was measured using a digital lux meter, yielding daytime values of approximately 8,000–10,000 lux under natural 12 h light: 12 h dark conditions. Measurements were conducted at the reactor surface to reflect the actual irradiance received by the culture.

2.3 Experimental Design using Response Surface Methodology

A Central Composite Design (CCD) under Response Surface Methodology (RSM) was applied to evaluate the effects of two independent variables: initial pH of the wastewater (6, 7 and 8) and mixed microalgae concentration (A_{600} = 1.000, 2.000 and 3.000). A total of 13 experimental runs, including five center points, were performed to estimate experimental variability.

Reactors (10.5 L, diameter 30.5 cm, height 28 cm) were operated under natural sunlight and room temperature. The experiments were run for a fixed retention time of 10 days which corresponded to the period where stable nutrient removal was observed under preliminary trials. Reactors were loosely covered to minimize contamination while



allowing gas exchange. Daily evaporation loss (typically <3%) was corrected using distilled water to maintain constant working volume. Continuous aeration ensured mixing and adequate oxygen transfer.

COD and TP were selected as the main response variables for assessing treatment efficiency. Removal efficiency (%R.E.) for each parameter was calculated using Eq. (1):

$$\%R.E. = \frac{(C_0 - C)}{C_0} \times 100 \quad (1)$$

where C_0 and C represent the initial and final concentrations (mg/L) of the parameter after 10 days of treatment, respectively.

2.4 Analytical Methods

Samples collected on Day 0 and Day 10 were analyzed for COD and TP following Standard Methods [13]. COD was measured using the closed reflux titrimetric method and TP was analyzed using the ascorbic acid method after persulfate digestion. Algal growth (A_{600}) and pH were monitored using a spectrophotometer (Shimadzu Corporation, Japan) and calibrated pH meter. All analytical measurements were performed in triplicate to ensure reproducibility.

2.5 Statistical Analysis

Experimental data were analyzed using Design-Expert software (Version 13, Stat-Ease Inc., USA) to fit a quadratic model. Model adequacy was assessed using R^2 , adjusted R^2 , predicted R^2 , lack-of-fit and ANOVA ($p < 0.05$). Residual plots (normal probability and residuals vs. predicted) were examined to verify regression assumptions.

The experimental data were fitted to a quadratic equation (Eqs. (2)) of the form:

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_{12} AB + \beta_{11} A^2 + \beta_{22} B^2 \quad (2)$$

where Y represents removal efficiency (%), A is the actual initial pH and B is the actual initial algal concentration. β_0 is the intercept coefficient, β_1 and β_2 are the linear coefficients, β_{12} is the interaction coefficient, and β_{11} and β_{22} are the quadratic coefficients. All regression coefficients therefore correspond to actual experimental values rather than coded factors. Model performance was

further evaluated using adequate precision and the coefficient of variation (CV%).

Three-dimensional response surface plots were prepared to visualize interaction effects and numerical optimization was performed using the desirability function.

3. Results and Discussion

3.1 Characteristics of swine farm wastewater

The raw swine farm wastewater exhibited an average pH of 7.79 ± 0.00 , COD of 6600 ± 35.5 mg/L, total suspended solids (TSS) of 226.67 ± 16.49 mg/L and total phosphorus (TP) of 78.83 ± 0.09 mg/L. These values exceeded the discharge limits stipulated by Thailand's effluent standards for livestock farms, indicating the high organic and nutrient strength typical of swine wastewater. The high COD and nutrient content make this wastewater suitable for algal cultivation, as it provides sufficient carbon, nitrogen and phosphorus for photosynthetic growth and nutrient assimilation [14].

During the treatment period, the mixed microalgae developed into a visibly dense green suspension. Within ten days, the algal population increased approximately 6.7–8.6 times compared to the initial concentration. This rapid proliferation coincided with a marked decline in both COD and TP, suggesting that the microalgae played an active role in nutrient uptake and organic matter removal. The observed reductions reflect complementary activities between microalgae and native bacteria, in which photosynthetically supplied oxygen enhances aerobic oxidation while bacterial CO_2 supports algal carbon fixation [10]. This balanced exchange promoted stable and effective pollutant removal.

3.2 COD and TP Removal by Mixed Microalgae

Across all 13 CCD experimental runs, both COD and TP removal efficiencies exhibited consistent trends with increasing treatment time and were significantly influenced by initial pH, while algal concentration exerted a strong effect on COD but a weaker influence on TP, in accordance with the ANOVA results. COD removal ranged from $74.30 \pm 0.13\%$ to $83.85 \pm 0.08\%$, while TP removal ranged from $75.17 \pm 0.10\%$ to $83.58 \pm 1.18\%$. Standard errors were used to express



variability, reflecting analytical replicates within each biological run. The increase in TSS observed was attributed to algal proliferation rather than incomplete sedimentation.

The removal patterns indicated that a moderately alkaline pH and sufficient algal concentration enhanced nutrient assimilation and organic matter degradation. pH 7-8 provided favorable nutrient speciation and enzymatic activity while lower pH suppressed microalgal metabolism, reducing overall removal efficiency. [15,16] These findings align with earlier reports showing improved nutrient removal at slightly alkaline pH in livestock wastewater [17,18].

TP removal was governed primarily by biological uptake, consistent with the growth trends observed. Under moderately alkaline conditions, pH-induced phosphate precipitation may also occur, although this mechanism could not be confirmed without direct measurement of precipitated species. Similar coupled assimilation-precipitation behavior has been reported in nutrient-rich wastewater systems [19-21].

3.3 Statistical Model Fitting and Validation

The experimental data obtained from the 13 CCD runs were analyzed using Design-Expert to evaluate the effects of initial pH (factor A) and mixed microalgae concentration (factor B) on COD and TP removal. Four model types (linear, two-factor interaction (2FI), quadratic and cubic) were compared. The cubic model produced the highest R^2 value but showed an “Aliased” message, indicating insufficient experimental runs. Accordingly, the quadratic model was selected as the most appropriate compromise between accuracy and complexity.

For COD removal (Table 1), the quadratic model was highly significant ($p < 0.0114$) with $R^2 = 0.9879$, adjusted $R^2 = 0.9506$ and predicted $R^2 = 0.9245$, indicating an excellent agreement between predicted and experimental data. For TP removal (Table 2), the same model provided a reasonable fit ($R^2 = 0.7722$) with a non-significant lack-of-fit ($p = 0.1085$). However, the predicted R^2 for TP (0.0380) was markedly lower than the adjusted R^2 , demonstrating limited predictive capacity and suggesting that TP removal was affected by unmeasured factors such as cation composition or pH drift during cultivation.

Table 1 Summary of statistical parameters for model fitting of COD removal efficiency under different model types.

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	< 0.0001	0.1201	0.8203	0.6958	
2FI	0.0761	0.1785	0.8619	0.7167	
Quadratic	0.0114	0.8310	0.9506	0.9245	Suggested
Cubic	0.8584	0.4876	0.9349	0.5645	Aliased

Table 2 Summary of statistical parameters for model fitting of TP removal efficiency under different model types.

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	0.0361	0.0435	0.3825	0.0961	Suggested
2FI	0.3139	0.0410	0.3909	-0.2405	
Quadratic	0.0257	0.1419	0.7249	0.0380	Suggested
Cubic	0.5408	0.0599	0.6988	-8.2356	Aliased



Analysis of variance (ANOVA), as shown in Tables 3 and 4, indicated that both initial pH and algal concentration significantly influenced COD removal ($p < 0.05$). The interaction term (AB) and quadratic effects (A^2 , B^2) were also statistically significant. In contrast, TP removal was driven primarily by pH and its quadratic term, while algal concentration and the AB interaction were not significant, confirming weaker or negligible effects of biomass density on phosphorus reduction. The regression models derived from the RSM analysis are presented as Eqs. (3) and (4).

$$\begin{aligned} \%R.E. \text{ COD} = & 158.156 - 21.395A + 3.615B \\ & - 1.03AB + 1.574A^2 + 0.069B^2 \end{aligned} \quad (3)$$

$$\begin{aligned} \%R.E. \text{ TP} = & -47.605 + 32.548A + 7.363B \\ & - 0.925AB - 2.05A^2 \end{aligned} \quad (4)$$

Model diagnostics (results not shown here) confirmed that the residuals followed a normal distribution and exhibited no systematic trends, supporting model adequacy. Residual versus predicted plots showed homogenous variance, supporting the validity of the quadratic model for both pollutants despite the lower predictive performance of the TP model.

Despite the acceptable performance of the TP model in terms of adjusted R^2 and lack-of-fit, its markedly low predicted R^2 indicates that phosphorus removal was influenced by additional mechanisms not fully captured by the two-factor CCD design. TP dynamics in wastewater-microalgae systems are strongly affected by physicochemical conditions, especially the availability of multivalent cations such as Ca^{2+} , Mg^{2+} and Fe^{3+} , which promote the formation of metal-phosphate precipitates and reduce soluble TP independently of algal uptake [21,22]. Moreover, pH drift during outdoor cultivation alters phosphate speciation and shifts equilibrium toward less soluble forms under alkaline conditions, thereby introducing variability across runs [21]. Microbial interactions may also contribute, as polyphosphate-accumulating bacteria can intermittently store or release phosphorus depending on redox status and carbon availability [22,23]. These unmeasured and dynamic processes likely produced heterogeneity in TP removal that reduced the predictive capability of the quadratic model, suggesting that future optimization studies should incorporate chemical speciation, cation concentrations and pH profiles to improve the accuracy of TP modeling.

Table 3 Analysis of variance (ANOVA) results for the quadratic model of COD removal

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	89.22	5	17.84	47.18	< 0.0001	significant
A-pH	12.04	1	12.04	31.83	0.0008	
B-Algae conc.	66.07	1	66.07	174.67	< 0.0001	
AB	4.24	1	4.24	11.22	0.0123	
A^2	5.97	1	5.97	15.79	0.0054	
B^2	0.0033	1	0.0033	0.0086	0.9287	
Residual	2.65	7	0.3783			
Lack of Fit	0.4739	3	0.1580	0.2907	0.8310	not significant
Pure Error	2.17	4	0.5435			
Cor Total	91.87	12				



Table 4 Analysis of variance (ANOVA) results for the quadratic model of TP removal

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	45.77	4	11.44	6.78	0.0110	significant
A-pH	24.04	1	24.04	14.24	0.0054	
B-Algae conc.	4.73	1	4.73	2.81	0.1325	
AB	3.42	1	3.42	2.03	0.1923	
A ²	13.57	1	13.57	8.04	0.0220	
Residual	13.50	8	1.69			
Lack of Fit	10.74	4	2.68	3.89	0.1085	not significant
Pure Error	2.76	4	0.6909			
Cor Total	59.27	12				

3.4 Response Surface Analysis and Optimization

Three-dimensional response surface plots illustrated the interactive effects of pH and algal concentration on pollutant removal (Figure 1 for COD and Figure 2 for TP). For COD, removal efficiency increased toward slightly alkaline conditions (pH 7.5-8.0) and peaked at moderate algal densities. Beyond this level, efficiency slightly decreased, likely due to self-shading and reduced light penetration, which limit photosynthetic oxygen production. In contrast, TP removal peaked at mid-range pH (7.0-7.5) and moderate algal concentrations ($A_{600} = 2.000$), where nutrient availability and algal uptake were well balanced.

Numerical optimization using the desirability function identified the optimal operating conditions at pH 7.69 and algal concentration (A_{600}) 2.072, giving predicted removal efficiencies of 78.21 % for COD and 82.00 % for TP. These

predictions fall within the observed experimental ranges but do not represent the maximum achieved values. This discrepancy occurs because desirability-based optimization identifies a balanced multi-response solution rather than maximizing a single pollutant removal.

Although no experimental run was conducted exactly at the optimized point, the close agreement between predicted values and nearby experimental data supports the reliability of the model for practical guidance.

To assess practical relevance, final effluent concentrations under optimal conditions were compared with Thai livestock effluent standards. While TP approached permissible limits, COD remained above national discharge thresholds, indicating that microalgal treatment alone is insufficient for full compliance and requires a secondary polishing step.

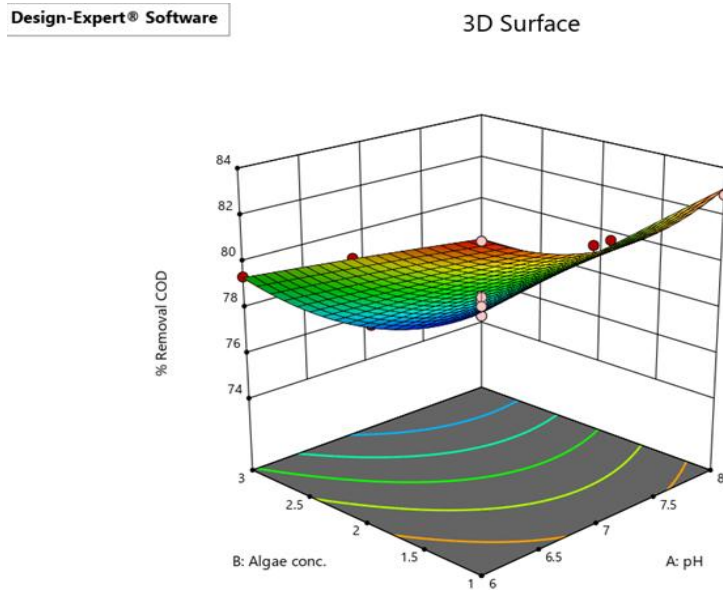


Figure 1 Response surface plots illustrating the interaction effects of initial pH and mixed-microalgae concentration on COD removal efficiency

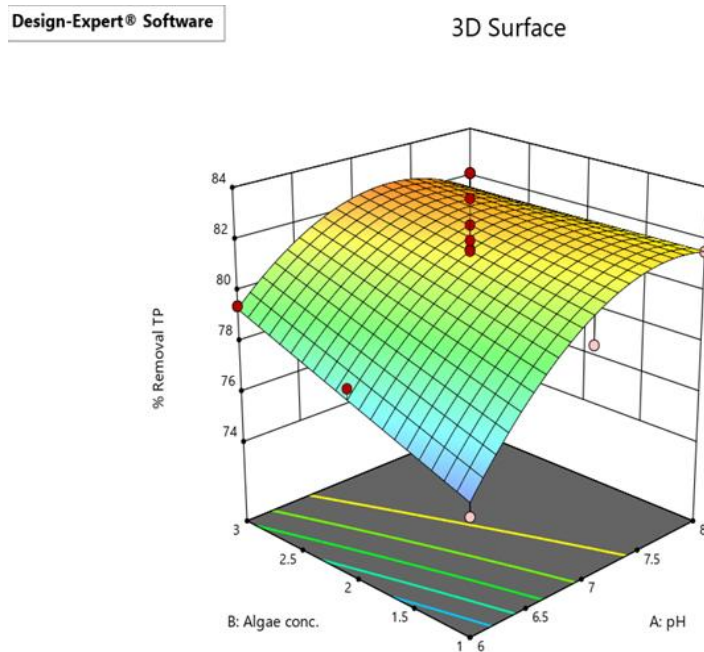


Figure 2 Response surface plots illustrating the interaction effects of initial pH and mixed-microalgae concentration on TP removal efficiency

4. Conclusions

This study demonstrated that mixed indigenous microalgae can effectively reduce COD and TP in swine farm wastewater under outdoor conditions. Initial pH and algal concentration were identified as key variables influencing removal performance

and the RSM-CCD model provided reliable predictions, particularly for COD. Optimal conditions (pH 7.69; $A_{600} = 2.072$) yielded predicted removal efficiencies of 78.21% COD and 82.00% TP.

While the optimized TP removal approached national effluent thresholds, COD remained above



regulatory limits, indicating that microalgal treatment alone is insufficient for complete compliance and will require a secondary polishing step.

The findings highlight the practical advantages of using mixed indigenous microalgae, including resilience, adaptability to outdoor conditions and low operational cost. In addition, this work contributes new insight by optimizing a naturally occurring microalgal consortium under outdoor, field-relevant conditions using actual-variable RSM rather than controlled laboratory monocultures. This approach provides an operational window that is directly applicable to decentralized livestock wastewater treatment systems and supports future scale-up.

The limited predictive performance of the TP model indicates the influence of additional chemical and microbial factors that were not included in the current design. Future work should incorporate these factors and evaluate time-resolved nutrient removal behavior and continuous metabolic indicators (e.g., dissolved oxygen profiles, pH drift) to strengthen model robustness and deepen mechanistic understanding.

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Enhancing Gypsum Ceiling Sheets with Malt Waste: Optimal Composition for Strength and Insulation

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Abstract

This study investigates the use of malt waste, a byproduct of the beer production process, as a bio-based additive in gypsum ceiling sheets to enhance mechanical performance while improving thermal insulation properties. Gypsum composite specimens were prepared by incorporating malt waste at weight ratios of 100:0, 90:10, 85:15, 80:20, 75:25, and 70:30, and the effects on density, thermal conductivity, and bending strength were systematically evaluated and compared with those of conventional gypsum boards complying with TIS 219-2009. The results show that increasing malt waste content led to a reduction in density from 1.16 g/cm³ for pure gypsum to 0.76 g/cm³ at a 70:30 ratio, representing a decrease of approximately 34.5%. Similarly, thermal conductivity decreased to a minimum value of 0.094 W/m·K, indicating improved insulation performance compared with conventional gypsum boards. However, the 85:15 gypsum-to-malt waste ratio demonstrated the optimum balance between thermal insulation and mechanical performance, achieving the highest longitudinal flexural force of 297.57 N and a thermal conductivity of 0.097 W/m·K. These findings highlight the potential of malt waste as a sustainable reinforcement material for the development of eco-friendly gypsum ceiling applications.

Keywords: Malt Waste, Gypsum, Ceiling Board, Composite Materials, Sustainable Materials

1. Introduction

Composite materials are widely used in modern construction due to their improved strength, durability, and performance achieved by combining different materials. They are commonly applied in ceiling and wall panels, where lightweight materials with good thermal insulation and structural integrity are required.

Natural fibers have increasingly been utilized in composite materials due to their availability, cost-effectiveness, and environmental benefits. Various studies have investigated the use of plant-based fibers such as coconut coir, bagasse, and water hyacinth in gypsum board production, aiming to enhance mechanical and thermal properties while addressing waste management issues. These natural fibers contribute to improved bonding strength and lower thermal conductivity, making them ideal for sustainable building materials.

Despite extensive research on natural fiber composites, the use of malt waste as an additive in gypsum boards remains largely unexplored. Malt waste, a byproduct of the beer brewing industry, is rich in cellulose fibers that can enhance the structural performance of gypsum-based materials. The rapid growth of the beer industry generates significant quantities of malt waste, raising environmental concerns related to disposal and pollution. Compared with many conventional natural fibers that often require additional processing before use, malt waste is readily available as an industrial byproduct, making it a promising and sustainable alternative for gypsum-based composite materials [1-4].

Previous research on fiber-reinforced gypsum boards has primarily focused on commonly used agricultural residues such as bagasse, coconut coir, and corn husks. These studies have demonstrated the benefits of adding natural fibers to gypsum in



terms of reducing density, enhancing thermal insulation, and increasing flexural strength. For instance, studies on bagasse-reinforced panels have shown promising results in achieving lower thermal conductivity values and improved mechanical performance, making them suitable for architectural applications [2]. Similarly, research on coconut coir-based composites has indicated improvements in water resistance and strength [1].

However, despite these advancements, the potential of malt waste as a reinforcing fiber in gypsum composites has not been fully explored. Unlike other natural fibers, malt waste has a unique fiber structure and chemical composition that could offer distinct advantages in composite applications. Additionally, the environmental impact of malt waste disposal remains a challenge for the brewing industry, highlighting the need for innovative recycling and upcycling strategies.

Furthermore, while previous studies have demonstrated the benefits of natural fiber incorporation, there is limited research on optimizing fiber content to achieve the best balance between mechanical strength and thermal insulation. Excessive fiber content can lead to reduced structural integrity due to increased porosity, which weakens interparticle bonding in the composite material [5, 6]. Therefore, it is essential to determine the optimal gypsum-to-malt waste ratio that ensures enhanced performance without compromising material durability.

This study aims to investigate whether the incorporation of malt waste into gypsum boards can enhance thermal insulation performance without significantly compromising the mechanical strength of the material. To address this objective, the effects of malt waste incorporation on gypsum board properties were systematically evaluated, focusing on density, thermal conductivity, and bending strength. The findings of this research provide valuable insights into the feasibility of using malt waste as a sustainable additive in gypsum composites, thereby contributing to environmental sustainability and the development of eco-friendly construction materials.

2. Materials and Methods

2.1 Sample Preparation

2.1.1 Malt Waste Preparation

To develop gypsum composite boards reinforced with malt waste, high-quality gypsum powder and malt waste obtained from the beer production process were used. The gypsum powder, sourced from commercial suppliers, was selected for its fine particle size and high purity to ensure optimal bonding with malt waste fibers. Malt waste, a byproduct rich in cellulose, was collected from local breweries and subjected to a drying process to remove excess moisture. The initial moisture content of malt waste was approximately 65-69%, which was reduced to a final humidity of 4-7% through controlled drying in an oven at 200-250°C for 45-60 minutes.

Figure 1 illustrates the process of extracting water from malt waste and passing it through an oven, where steam is used to dry the waste. Inside the machine, a mechanism continuously turns the malt waste from bottom to top, ensuring even drying. The initial humidity of the malt waste ranges between 65% and 69%. As it exits the oven, its moisture content is significantly reduced. Before use, the waste must undergo a further drying process to achieve a final humidity of 4% to 7%, as shown in Figure 2(a). This drying step ensures that the malt waste is adequately prepared for mixing with gypsum in the next stage of processing.

2.1.2 Gypsum Preparation

Figure 2(b) shows Siam gypsum easy plaster 120, a 25 kg cement powder designed for joining gypsum boards. It has a smooth, uniform surface, is lightweight, and is easily mixable with water. The slow-drying formula allows for a 90-minute working time and 120-minute drying time, for flexibility during application. Once dried, it offers high adhesion, a fine, crack-free finish, and is easy to sand and decorate. The recommended mixing ratio is 2:1 (cement to water by weight), with a coverage of 50-60 square meters per package and a storage period of six months.

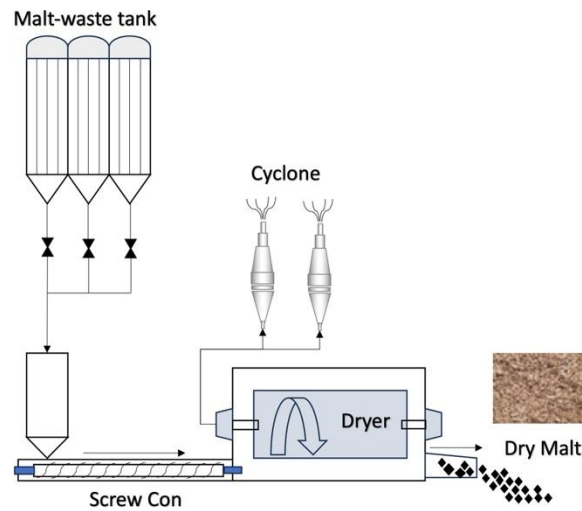


Figure 1 Malt drying process

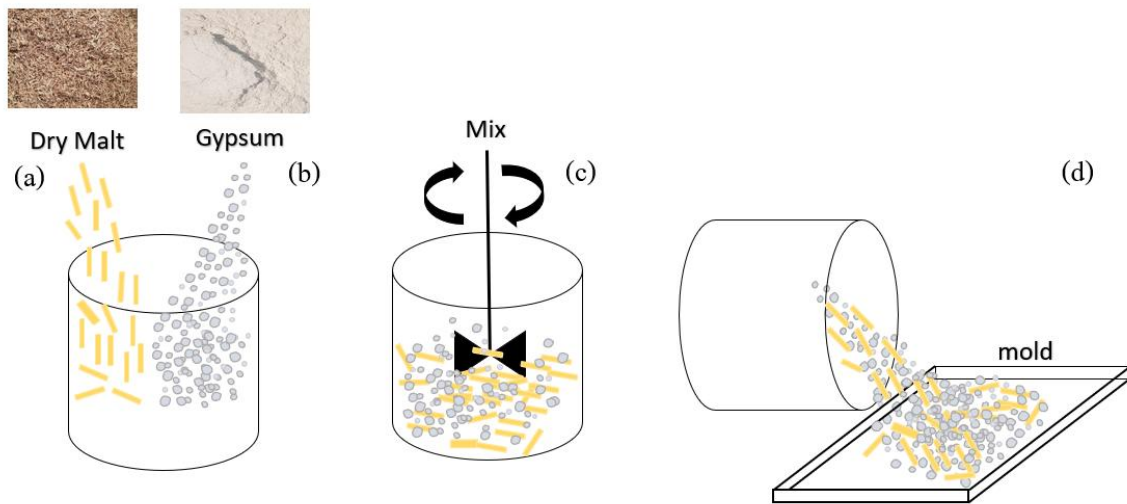


Figure 2 Forming schematic: (a) Dry malt, (b) Gypsum, (c) Mixing, and (d) Casting

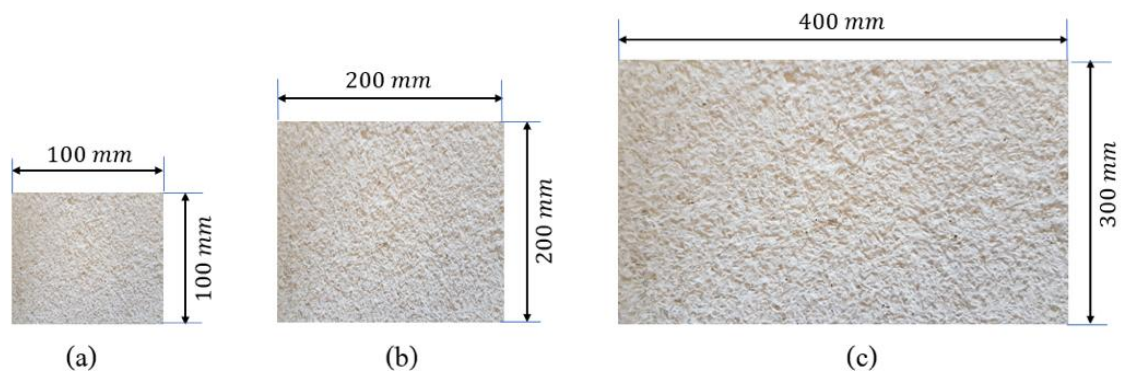


Figure 3 Specimen sizes: (a) Density, (b) Thermal conductivity, and (c) Bending testing

Table 1 Standard specimen size.

No.	Measurement and testing	Size (mm x mm)	Reference
(a)	Density	100 x 100	[1]
(b)	Thermal conductivity	200 x 200	[5]
(c)	Bending testing	300 x 400	[5]



2.1.3 Sample Preparation and Drying Process

Figure 2(c) illustrates the mixing process, in which an electric drill equipped with a mechanical stirrer was used to blend dry gypsum powder with malt waste in batch quantities. The mixing was conducted in an 18-liter polypropylene (PP) cylindrical container (milk-colored) with dimensions of 31.5 × 35.2 cm. (diameter x height). As shown in Figure 2(d), the mixer was operated until a homogeneous mixture was obtained, ensuring a uniform distribution of malt waste within the gypsum matrix. After mixing, the composite slurry was poured into molds according to the specified proportions and allowed to dry prior to mechanical and thermal testing. The hardened boards were then cut into test specimens with dimensions specified in Table 1 for subsequent property evaluation.

2.2 Experimental Study

2.2.1 Specimen Size

The dimensions of the test specimens are summarized in Table 1, while the corresponding specimen configurations are illustrated in Figure 3. The specimen sizes were determined according to the requirements of the Thai Industrial Standard for gypsum boards (TIS 219-2009) [7] for physical and mechanical property testing. To ensure accuracy and reliability, three specimens were prepared and tested for each mixing ratio.

2.2.2 Specimen Forming Process

As illustrated in Figure 2(d), test specimens were prepared by mixing gypsum cement with malt waste at ratios of 100:0, 90:10, 85:15, 80:20, 75:25, and 70:30 by weight. These ratios were selected to systematically evaluate the influence of increasing malt waste content on the physical and mechanical properties of gypsum boards and were determined based on preliminary trials and previous studies on natural fiber-reinforced gypsum composites. The mixture was poured into molds to produce boards with dimensions of 300 × 400 × 9 mm, allowed to harden at room temperature, and then oven-dried at 200-250 °C for 45-60 minutes to remove residual moisture and ensure suitability for subsequent testing.

2.2.3 Bending Testing

As depicted in Figure 3(c), the bending test is conducted in accordance with the Thai Industrial Standard 219-2009 of Gypsum Boards (TIS 219-2009) [7]. A 300 mm × 400 mm specimen is positioned longitudinally, and a load is applied at the center of the plate over a 350 mm span. A pressing head exerts force at a constant rate of 250 Newtons per minute until the specimen fractures, following the standard testing criteria.

2.2.4 Theoretical Basis of Measurement and Testing

The density of the fabricated workpiece is determined using Equation (1), which requires information on both the specimen dimensions and volume, as illustrated in Figure 3(a), together with its actual weight measured using a digital scale. The equation used to calculate the density is presented as follows:

$$\rho = \frac{m}{v} \quad (1)$$

Where: ρ = Density (kg/m³); m = Weight (kg); v = Volume (m³)

The thermal insulation performance of the material is evaluated using Equation (2). This equation is used to determine the optimal material ratio by ensuring that the sheet has the lowest possible thermal resistance. The specimen dimensions used for the thermal insulation test are illustrated in Figure 3(b). The heat transfer through the material is calculated as [6]:

$$Q = \frac{kA(T_1 - T_2)}{\Delta x} \quad (2)$$

Where: Q = Heat transfer rate (W); k = Thermal conductivity (W/m·K); A = Heat flows (m²); $T_1 - T_2$ = Difference temperature (°C); Δx = Thickness

For bending moment and mechanical strength analysis, to evaluate the bending moment capacity, Equations (3) and (4) are used. These equations help determine the flexural behavior of the material when subjected to a bending load [8]. The modulus of elasticity (E) is determined using Equation (3) [9]:

$$E = \frac{Fl^3}{48\delta I} \quad (3)$$

$$\sigma = \frac{Mc}{I} \quad (4)$$



Where: E = Modulus (N/mm^2); δ = Deflection distance (m); l = Original length of sheet (m); F = Reaction force (N); I = Moment of inertia (m^4); σ = Bending stress (N/m^2); M = Bending moment ($\text{N}\cdot\text{m}$); c = Distance from the axis of the sling (m)

The modulus of rupture (MOR), which indicates the maximum compressive strength the sheet can withstand, is determined using Equation (5) [10]:

$$\text{MOR} = \frac{3PL}{2bt^2} \quad (5)$$

Where: MOR = Modulus of rupture (kg/cm^2);

P = Maximum load received (kg);

L = Distance between supports (cm);

b = Width of workpiece sheet (cm);

t = Thickness of workpiece plate (cm)

3. Results and Discussion

3.1 Effect of Malt Waste Content on Density

Figures 4(a) and 4(b) illustrate the variation in density of gypsum boards incorporating different proportions of malt waste. The specimen containing 90% gypsum and 10% malt waste exhibited a density of 0.91 g/cm^3 . As the malt waste content increased to 15% (85:15), the density slightly decreased to 0.89 g/cm^3 and further declined to 0.88 g/cm^3 at a 20% malt waste ratio (80:20). With higher malt waste contents of 25% (75:25) and 30% (70:30), the density continued to decrease, reaching 0.86 g/cm^3 and 0.76 g/cm^3 , respectively.

The reduction in density with an increasing malt waste ratio is attributed to the replacement of gypsum powder by malt waste particles. This substitution introduces voids and air pockets, leading to a lower overall density. The presence of these voids can be linked to the fibrous and porous nature of malt waste, which reduces the compactness of the gypsum matrix.

3.2 Effect of Malt Waste on Thermal Conductivity

Figures 4(c) and 4(d) present the thermal conductivity results of gypsum boards with varying malt waste content. The gypsum board without any malt waste exhibited a thermal conductivity of $0.133 \text{ W/m}\cdot\text{K}$. When 10% malt

waste was added, the thermal conductivity dropped to $0.105 \text{ W/m}\cdot\text{K}$. As the malt waste content increased to 15% and 20%, the thermal conductivity further decreased to $0.097 \text{ W/m}\cdot\text{K}$ and $0.096 \text{ W/m}\cdot\text{K}$, respectively. At higher malt waste ratios of 25% and 30%, the thermal conductivity stabilized at $0.094 \text{ W/m}\cdot\text{K}$.

This trend indicates that the addition of malt waste improves the insulation properties of gypsum boards. The fibrous and porous structure of malt waste creates air pockets within the gypsum matrix, which act as thermal barriers and reduce heat transfer, resulting in lower thermal conductivity. These results highlight the potential of malt waste as an insulating material for energy-efficient construction applications.

3.3 Effect of Malt Waste on Flexural Strength

Figures 4(e) and 4(f) illustrate the longitudinal flexural force of gypsum boards with different malt waste ratios. The gypsum board without malt waste exhibited a longitudinal flexural force of 98.10 N. When 10% and 15% malt waste were incorporated, the longitudinal flexural force significantly increased to 196.2 N and 297.57 N, respectively. However, as the malt waste content increased beyond 15%, the bending strength began to decline. At 20%, 25%, and 30% malt waste content, the longitudinal flexural force dropped to 166.77 N, 156.96 N, and 107.91 N, respectively.

The increase in flexural force at 10-15% malt waste content indicates enhanced load-bearing capacity, which is associated with higher modulus of rupture (MOR) and improved stress distribution within the composite. This behavior is further supported by improved stiffness and reduced deflection, reflecting stronger fiber-matrix interaction and greater resistance to deformation at the optimal composition. However, at higher malt waste ratios (>15%), the decline in flexural performance can be attributed to reduced effective stiffness and weakened structural integrity due to increased porosity and poorer interfacial bonding.

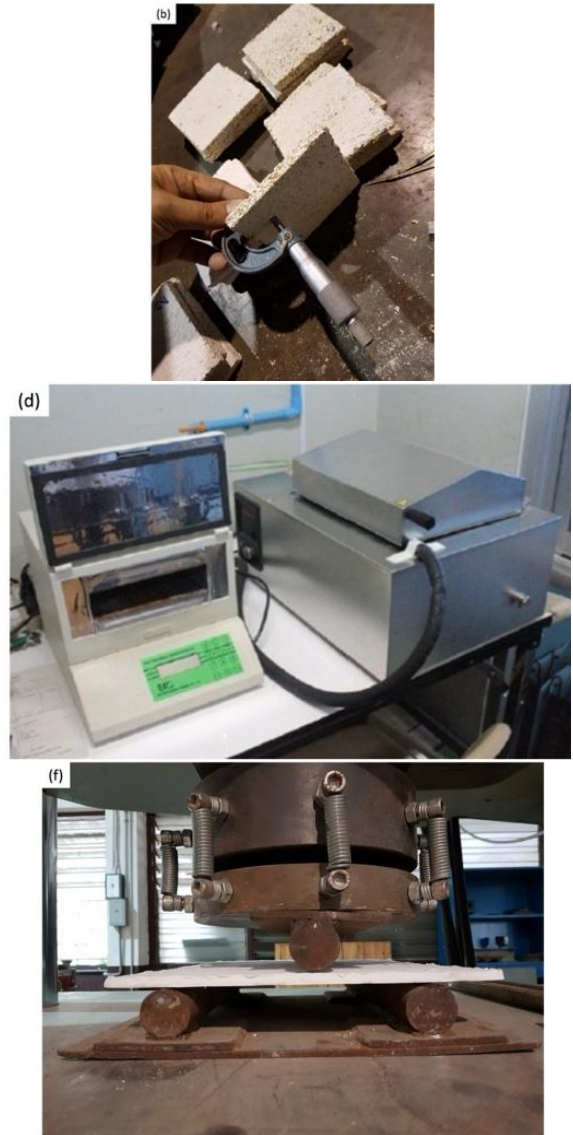
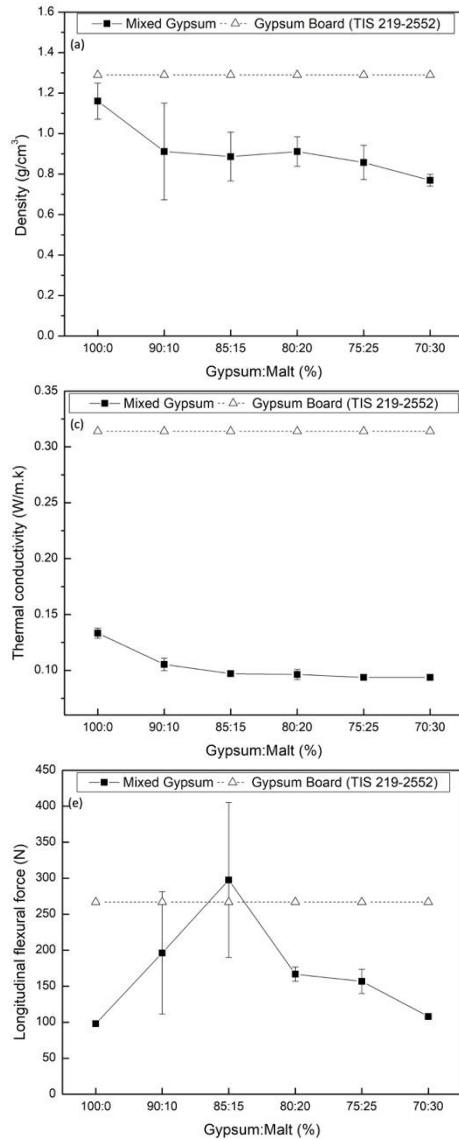


Figure 4 Measurement and testing results: (a) Density graph, (b) Density measurement, (c) Thermal conductivity graph, (d) Thermal conductivity testing, (e) Longitudinal flexural force graph, and (f) Longitudinal flexural force testing

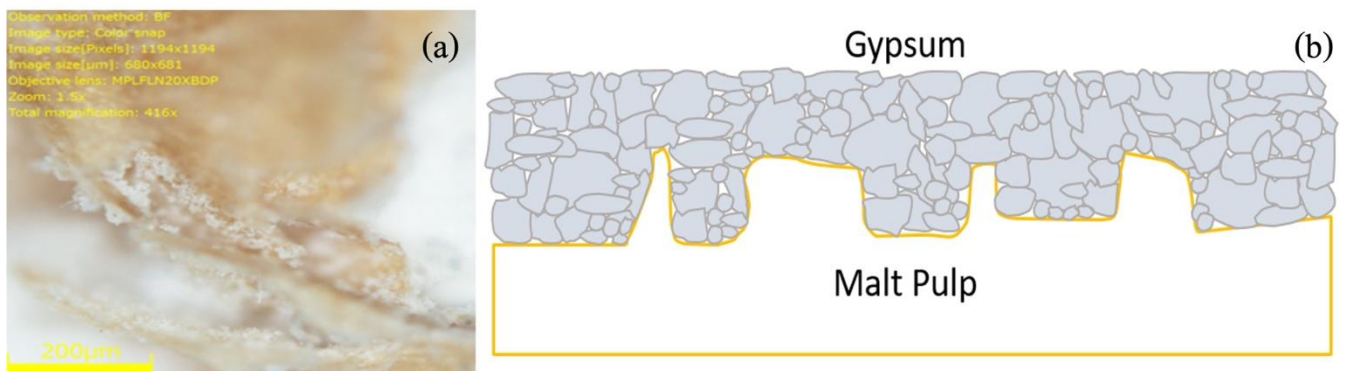


Figure 5 Mechanical adhesion: (a) Microscopic photo (1.5x) and (b) Adhesion distribution mechanism



3.4 Adhesion Characteristics of Gypsum and Malt Waste

Figure 5(a) presents an image captured using an industrial digital microscope (DSX510 series), which reveals surface adhesion characteristics that are not visible to the naked eye. The bonding mechanism between gypsum and malt waste primarily involves mechanical adhesion.

As illustrated in Figure 5(b), mechanical adhesion occurs when gypsum particles penetrate the pores on the surface of the malt waste. This process enhances physical interlocking by increasing the contact surface area between the gypsum and the malt waste, thereby improving hardness and overall strength. Initially, the liquid gypsum spreads across the surface of the material, filling the micropores before gradually hardening. During the drying process, the gypsum particles continue to infiltrate and anchor within the malt waste's structure, further reinforcing the adhesion [11, 12].

Additionally, chemical adhesion takes place when gypsum molecules interact with the surface of the malt waste. This adhesion mechanism is particularly strong due to molecular interactions at the interface. Since the malt waste surface is naturally rough and porous, these interactions further contribute to the overall bonding strength, enhancing the integrity of the composite material.

4. Conclusion

This study demonstrated that incorporating malt waste into gypsum ceiling sheets significantly enhances their thermal insulation and mechanical properties while contributing to sustainability. The experimental findings revealed that increasing malt waste content generally reduced the density and thermal conductivity of gypsum boards, making them more suitable for energy-efficient building applications. Among the tested ratios, the 85:15 gypsum-to-malt waste composition was identified as the optimal balance, providing the highest longitudinal flexural force (297.57 N) and an improved thermal conductivity of 0.097 W/m·K.

The observed improvements in mechanical properties at moderate malt waste levels can be

attributed to enhanced fiber-matrix interactions. However, as the malt waste content exceeded 15%, the structural integrity of the boards declined due to increased porosity and weaker bonding between particles. This highlights the importance of optimizing material ratios to ensure durability while maintaining desired insulation properties.

An economic analysis indicated that gypsum boards incorporating malt waste could be produced at an estimated cost of approximately 135 baht per 3,240 cm³. For comparison, commercially available gypsum boards of similar dimensions (60 × 60 × 0.9 cm) in the Thai market are priced at approximately 415 baht for an equivalent volume. This represents a potential cost reduction of about 280 baht, or approximately 67%. These results suggest that gypsum boards containing malt waste may offer a cost-effective alternative to conventional gypsum products for construction applications.

Beyond performance enhancements, this study underscores the environmental benefits of using malt waste in construction materials. By repurposing a byproduct of the beer industry, this approach contributes to waste reduction, mitigates air pollution from malt waste disposal, and promotes the development of eco-friendly building materials. The integration of malt waste into gypsum boards offers a practical and scalable solution to both construction and environmental challenges.

Future research should further investigate the long-term performance of gypsum boards incorporating malt waste, including factors such as aging behavior, moisture resistance, and fire resistance, which are critical for practical construction applications. Evaluating these properties would provide a more comprehensive understanding of the durability and safety of the developed composite material under real service conditions. In particular, future studies may focus on enhancing fire resistance by incorporating flame-retardant agents, such as borax, or by adding sodium hydroxide (NaOH) solution [13]. These additives have the potential to improve the flame-retardant performance of the material and should



be further explored to optimize the overall properties of gypsum-malt waste composites.

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Rail Freight Container Management System Utilizing Radio Frequency Identification and Cargo Tracking Technology

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Abstract

Real-time monitoring of cargo in transit is essential for improving safety and operational efficiency in public railway transportation systems. Although technologies such as Radio Frequency Identification (RFID) and Global Positioning System (GPS) have been widely applied in logistics, their systematic implementation within the Railway of Thailand remains limited. This paper proposes a real-time railway freight container management system designed to reduce operational errors and prevent cargo loss. The proposed system integrates UHF RFID technology with GPS-based tracking, enabling continuous identification and localization of cargo containers. Tracking data is transmitted to a centralized web-based platform via wireless communication networks for real-time monitoring and management. Experimental evaluation conducted under real operational conditions demonstrates that the system achieves an average end-to-end latency of 185 ms, with a maximum observed delay of approximately 310 ms, confirming its suitability for real-time railway logistics operations. GPS-based container localization yields a mean absolute positioning error of 4.8 meters, with a 95% confidence interval of 4.2–5.4 meters, based on 200 ground-truth samples. Comparative analysis shows that the parcel misplacement rate is reduced from 2.3% under manual handling procedures to 0.4% after system deployment, representing an 82.6% reduction in operational errors. The software platform adopts standard design patterns to enhance reliability and maintainability, while secure authentication is ensured using a bcrypt-based hashing mechanism. The results confirm the practicality and effectiveness of the proposed system for large-scale railway freight logistics.

Keywords: Logistic, Radio Frequency Identification, Global Positioning System, Web Browser, and Railway



1. Introduction

In recent years, Thailand has made continuous efforts to develop national rail system standards, with a focus on advancing both technological innovations and regulatory frameworks. Among these efforts, the development of freight rail transport technology presents a significant challenge that requires further attention. This challenge arises primarily from the diverse nature of the country's freight transport system, which integrates maritime, air, and land transport, each characterized by distinct operational processes and resource demands. Currently, both public and private sectors are actively involved in the logistics industry, leading to intense competition in critical areas such as delivery times, cost efficiency, and customer service [1]. In response to these pressures, many logistics providers have undertaken substantial initiatives to enhance their operations. Rail-based freight transport continues to be a widely utilized mode of transportation in Thailand, and due to the increasing market competition, rail freight operators are now under pressure to expedite the development of infrastructure and logistics management systems in order to improve operational efficiency and secure a competitive edge.

The logistics system has been defined in [2] as the management of product flow from the point of origin to the point of consumption in order to meet customer requirements. In [3], logistics is further characterized as a component of the supply chain responsible for managing transportation, warehousing, and the efficient flow of products. These definitions underscore the importance of aligning logistics development efforts with established theoretical frameworks. Consequently, many organizations have enhanced their freight logistics operations through the adoption of technologies such as web applications and Radio Frequency Identification (RFID). A web application is a software system that allows users to send and retrieve data from a database via an internet-connected web browser [4]. RFID, by contrast, is a contactless automatic identification technology that utilizes radio waves to identify and

track objects, thereby enabling faster data exchange [5].

Numerous systems can be integrated into freight management [6], which typically includes four main components: (1) order fulfillment and data management, (2) planning and control systems with functional capabilities, (3) accurate and timely response systems, and (4) statistical analysis and decision-making functionalities [7]. Previous research has demonstrated the integration of web services and web application technologies into logistics systems [8]. However, web applications alone may not fully address the complex operational needs of real-world logistics. Therefore, it is crucial to incorporate Radio Frequency Identification (RFID) technology to enhance logistics management effectiveness. For example, S. J. Barro-Torres *et al.* developed a maritime freight container management system using RFID, which facilitated traceability, efficient container reservations, and accurate vehicle dispatching to final destinations [9]-[10]. In 2012, RFID technology was further applied to communication between autonomous vehicles and cargo, enabling automation in transportation and handling systems, thereby improving precision and reducing processing times [11].

While web and RFID technologies have significantly advanced logistics systems, they have yet to be specifically designed or validated for rail-based freight logistics in Thailand. Therefore, this study proposes the design of a rail freight container management system that integrates RFID and cargo tracking technologies. The structure of this paper is as follows: Section 2 provides theoretical background, Section 3 outlines the system design, Section 4 discusses the implementation and evaluation, and Section 5 draws the conclusion.

2. Materials, Equipment, and Research Methodology

2.1 Radio Frequency Identification System

RFID technology shares architectural similarities with smart card systems, as it stores data within a memory unit embedded in an RFID tag or transponder. These tags may vary in form and are not limited to plastic cards. Communication between the RFID reader and the



tag occurs through the transmission of radio frequency (RF) signals, with air serving as the transmission medium. Consequently, technical standards are necessary to regulate data transmission and power exchange between the reader and the tag [12-13].

A critical factor in selecting RFID equipment is the operating frequency, which refers to the frequency at which the reader transmits signals. The tag may respond using the same or a different frequency band, typically distinguished by load modulation techniques. RFID systems are generally classified into four frequency bands, as outlined in Table 1.

Table 1 Frequency bands used in RFID Systems.

Frequency Band	Range	Wavelength	Operating Distance
Low Frequency (LF)	30 kHz - 300 kHz	10 km - 1 km	<50 cm
High Frequency (HF)	3 MHz - 30 MHz	100 m - 10 m	<3 cm
Ultra High Frequency (UHF)	300 MHz - 3 GHz	1 m - 10 cm	<9 m
Microwave	3 GHz - 300 GHz	30 cm - 1 mm	>10 m

As shown in the table, the effective operating distance increases with frequency. However, practical deployment is influenced by several factors, including reader power output, antenna gain, positioning of the reader and tag, data transmission techniques, and the type of tag. In practice, Low Frequency (LF) and High Frequency (HF) systems generally use standardized frequencies across countries (e.g., 135 kHz for LF and 13.56 MHz for HF), whereas Ultra High Frequency (UHF) and Microwave frequencies vary by region. This research focuses on the UHF band between 920-925 MHz, in accordance with Thailand's national telecommunications equipment standard for RFID systems [14].

2.1.1 Safety Regulations

When the human body is exposed to radio frequency (RF) environments, it may absorb RF energy, which can be harmful if it exceeds

specified limits. Potential effects of excessive RF energy exposure include cell expansion, disruption of the blood-brain barrier, and alterations in brainwave activity. The absorption of RF energy by the body is quantified by the Specific Absorption Rate (SAR), which is calculated using the following formula:

$$SAR = \frac{CE^2}{d} \quad (1)$$

where C represents tissue conductivity (S/m), E is the electric field strength (V/m), and d is the mass density of the tissue (kg/m³). Safety limits for RF exposure vary by region, as detailed in Table 2.

Table 2 SAR limits for RFID equipment.

Standard	SAR Limit
IEEE (Institute of Electrical and Electronics Engineers)	0.2 W/kg (whole-body exposure)
FCC (Federal Communications Commission)	1.6 W/kg (measured over 1 gram of tissue)
Europe (European Committee for Electrotechnical Standardization)	2.0 W/kg (measured over 10 grams of tissue)

2.1.2 Electromagnetic Wave Reflection

When a transmitting antenna emits electromagnetic waves toward a target, the waves propagating through the air may encounter obstacles or various objects. This interaction can cause part of the wave energy to be absorbed by these objects, converting it into heat. The remaining energy may scatter in multiple directions with varying intensities depending on the angle of incidence. Some of this scattered energy may also be reflected back toward the transmitting antenna. Radar technology leverages this principle of wave reflection to measure the distance and position of target objects. Similarly, RFID systems using backscatter techniques rely on the reflection of electromagnetic waves to transmit data from RFID tags to readers.

The reflective properties of objects generally improve with higher operating frequencies. As a result, RFID systems often operate in high-frequency bands, such as 900 MHz, 2.45 GHz, or

even higher. In RFID systems, the reader antenna emits electromagnetic waves omnidirectionally with an effective isotropic radiated power (P_{EIRP}). The power flux density W that reaches the RFID tag can be calculated using Equation (2). The tag antenna then reflects a portion of the received power, denoted as P_S , back to the reader.

$$P_S = \sigma W \quad (2)$$

where σ denotes the Radar Cross Section (RCS) [15–16]. Generally, the electromagnetic wave reflected from the RFID tag radiates omnidirectionally into free space, forming a spherical pattern originating from the point of reflection, as illustrated in Figure 4. The power of the reflected wave decreases proportionally to the square of the distance (r_2^2) from the reflection point. Therefore, the power density incident on the reader antenna can be determined using Equation (3).

$$\begin{aligned} W_B &= \frac{P_S}{4\pi r_2^2} = W \left(\frac{\sigma}{4\pi r_1^2} \right) = \frac{P_{EIRP}}{4\pi r_1^2} \left(\frac{\sigma}{4\pi r_2^2} \right) \\ &= \frac{P_{EIRP}\sigma}{(4\pi r_1 r_2)^2} = \frac{P_{EIRP}\sigma}{(4\pi)^2 r^4} \end{aligned} \quad (3)$$

As illustrated in Figure 1, within the RFID system

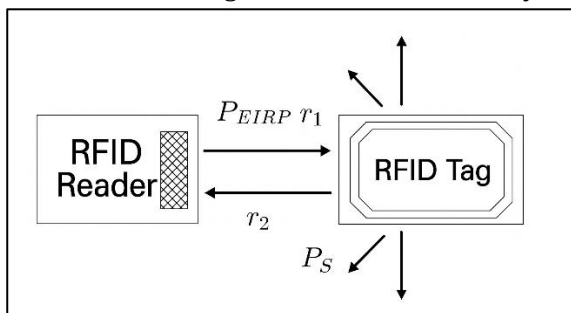


Figure 1 Signal reflection from a RFID Tag.

As shown in Figure 1, within the RFID system, the radar cross-section (RCS) is a key parameter used to quantify an object's ability to reflect electromagnetic waves. The RCS value depends on several factors, including the object's size, material composition (e.g., metal reflects signals more effectively than plastic), surface texture characteristics that influence signal reflection, the wavelength of the operating frequency, and the polarization of the incident waves.

2.2 Global Positioning System

The Global Positioning System (GPS) is a satellite-based navigation system that has been operational since the mid-1990s. It consists of 24 satellites orbiting the Earth twice daily, ensuring that at least four satellites are visible from any location on Earth at any given time. This system enables continuous, all-weather global position and altitude determination with accuracies ranging from centimeters to 20 meters, depending on the quality of the receiver and the measurement method used. Positioning is achieved by calculating the distance between satellites and receivers using the formula: Distance = Speed × Time. A minimum of three satellite signals is required for accurate location determination. GPS comprises three main segments [17]:

1. Space Segment: Managed by the U.S. Department of Defense, the NAVSTAR GPS constellation includes 24 satellites (21 active and 3 backups) that orbit at approximately 20,162.81 km above the Earth's surface. These satellites are arranged in six orbital planes inclined at 55 degrees relative to the equator. Although initially developed for military purposes, civilian access is now allowed, albeit with reduced precision (approximately 5–15 meters). Each satellite is equipped with atomic clocks, which maintain an accuracy of 3 nanoseconds.

2. Control Segment: Ground stations communicate with the satellites via radar to monitor and ensure accurate satellite orbits, altitude, and speed, transmitting corrections as necessary. This segment includes five monitoring stations, such as those located in Diego Garcia and Hawaii, along with a master control station in Colorado Springs, USA.

3. User Segment: The user segment includes both civilian and military entities. Civilian users have developed modern GPS receivers capable of providing high-precision positioning on a global scale.

GPS has achieved widespread adoption globally, with significant public familiarity facilitated by the integration of digital traffic systems and organized urban planning. GPS devices are commonly used in taxis, and travelers often replace paper maps with PDAs or



smartphones equipped with GPS. Current GPS systems can provide navigation down to street-level addresses or telephone numbers. In this study, GPS technology is applied to track railway freight containers.

2.3 Hardware

The RFID system operates within the Ultra High Frequency (UHF) range (920-925 MHz), which is commonly utilized in warehouse applications. The hardware components include computers, both desktop and handheld RFID readers, and RFID tags. The software includes a web application and an Android-based mobile application designed for data management and visualization.

When a customer initiates a shipment, a service counter staff member records the shipment details (sender, receiver, destination station, phone number) and attaches an RFID tag to the cargo. This tag enables the RFID reader to capture shipment data, which is then transmitted through a web application and API to a centralized database. The item is subsequently loaded into a freight container and shipped. The final stage involves the receipt of the item at its destination.

Cargo and container tracking is facilitated through the use of an NB-IoT Shield, an Arduino Uno board, and a GPS module. These components are assembled and programmed to transmit the latitude and longitude of the cargo to a server database. Users can access tracking information via a mobile application by entering a tracking key issued on the shipping receipt. The application displays shipment details, including the sender and receiver names, origin and destination stations, and the delivery status.

3. Design and Implementation

3.1 System Architecture

This research proposes a railway freight container management system that integrates Radio Frequency Identification (RFID) technology with cargo tracking through a mobile application utilizing global positioning data. The system aims to automate key operations within the railway logistics network of the State Railway of Thailand.

To implement this system, RFID readers are deployed with network connectivity and adapted to interface seamlessly with existing rail transport workflows. These workflows include parcel intake and dispatch, item verification before container loading, in-transit tracking, and final destination confirmation. The destination of each parcel is incorporated into a process designed to be fully compatible with the operational framework of the State Railway of Thailand. By adopting this method, the system enables the tracking of cargo within freight containers, whether it is loaded, unloaded, or mistakenly left behind in a specific container. Data collection is conducted via a wireless Local Area Network (LAN), as most RFID readers are installed at operational points to support real-time inspection and future scalability.

Each container is equipped with a dedicated RFID tag, and each train is fitted with a GPS module for precise location tracking. The system supports real-time monitoring of train locations. For instance, when a train is at Hua Lamphong Station, the system reflects the status of parcel intake, loading operations, and tracks the goods in transit between stations. As shown in Figure 2, the system overview diagram illustrates the interconnected functions, including container management, train localization, cargo transportation, parcel status verification, and shipment operations. Shipping workflows follow the regulations of the State Railway of Thailand, with each container identified by its origin and destination data.

The system receives input from both users and devices, which is then processed by specialized software. This software communicates with APIs to transmit and receive data. Upon data transmission, access authorization is verified through a security framework before the data is stored in the database. Communication occurs over a UDP/IP network, enabling long-distance interaction between various system states and clients.

The software platform features a graphical user interface (GUI) developed using .NET technology, which interacts with the database and RFID readers. The software architecture

incorporates multiple design patterns, including Façade, Abstract Factory, Data Access Object (DAO), and Value Object (VO) [18], optimizing

system modularity and maintainability, as shown in Figure 3.

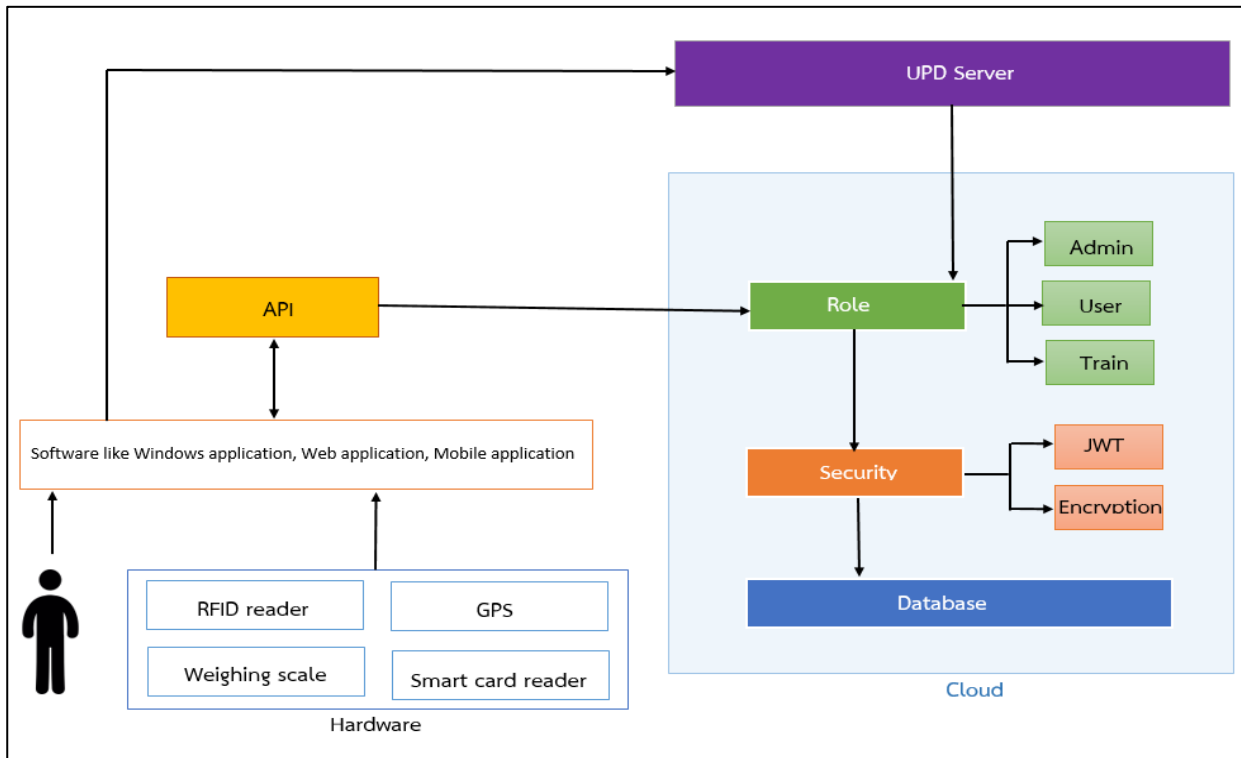


Figure 2 System architecture diagram.

The RFID-based railway freight container management system supports three levels of user access permissions: 1. User – General station staff with limited access to specific features via the web application, such as parcel intake and dispatch, cargo tracking, and individual reporting. 2. Train – Onboard personnel with access to portable RFID reader functions, enabling them to add, remove, modify, and verify cargo using RFID tags assigned to containers and trains. 3. Super Admin – High-level users, such as station masters and managers, with full access to all web application features, including shipment auditing, tracking oversight, station-wide reporting, and user activity monitoring.

3.2 System Operation

During system operation, when data is received from devices such as weighing scales, national identification card readers, or RFID tags, the collected information is forwarded to

the software platform. This data is transmitted via an API for processing and is then returned to the software for display and user interaction.

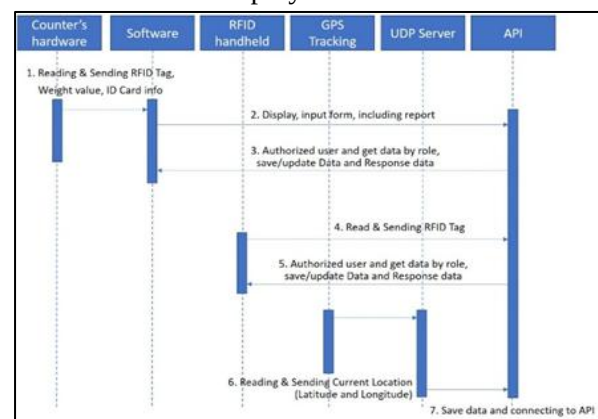


Figure 3 System operation workflow.

Similarly, for handheld RFID readers, once the data is captured, it is transmitted to the API for processing and subsequently returned to the device for display. In the case of GPS data, once the

location information is obtained, it is first sent to a UDP server, which then forwards the data to the API for further processing.

The system was deployed under real operational conditions and evaluated across multiple freight-handling processes. Performance data were collected during 200 live operational events, covering parcel intake, container loading, in-transit tracking, and delivery confirmation.

3.3 Data Security

To ensure data security during user registration and system login, users are required to authenticate using a username and password. Passwords are encrypted according to the bcrypt standard, which provides high security and is non-reversible. Bcrypt utilizes the Eksblowfish algorithm, a one-way hashing method that makes decryption infeasible. Each encryption result is unique, as the algorithm employs multiple rounds of processing.

All user login sessions are secured using a token-based authentication mechanism implemented through the JSON Web Token (JWT) standard, with authentication tokens generated from JSON-formatted data and encoded using Base64Url encoding for secure session management. RFID communication follows the EPC Gen2 protocol operating in the 920–925 MHz frequency band, while GPS tracking data are transmitted to the central system using UDP/IP to support low-latency data delivery. Together, these communication and security protocols ensure secure authentication, controlled access, and reliable data exchange across the proposed system.

Furthermore, external access to the database is strictly restricted. It is not accessible via public IP addresses and can only be accessed through a Secure Shell (SSH) connection, providing an additional layer of system-level security.

4. Experimental Results

4.1 Demonstration and Operational Workflow

The operational workflow of the railway freight container management system, which utilizes RFID technology, is designed to

optimize processes by integrating both hardware and software components. In this system, hardware is employed to capture data, which is then transmitted to the software for storage in a database, where it can be managed and processed subsequently.

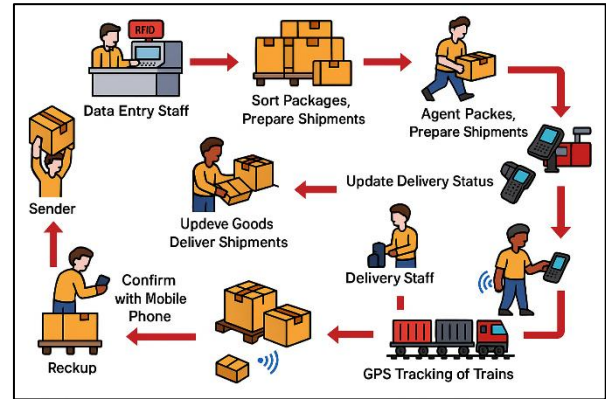


Figure 4 Railway freight container management system using RFID.

As illustrated in Figure 4, when a sender arrives at the station to ship a parcel, the station staff registers the shipment into the system and attaches an RFID tag to the item. Upon the train's arrival, the staff loads the tagged parcel onto the designated freight container. The RFID system then scans the train, container, and parcel to capture all relevant data. Throughout the journey, as the train passes through various stations, both the sender and recipient can track the parcel in real-time via a mobile application. Upon arrival at the destination station, the onboard freight staff scans the parcel again and hands it over to the station officer for collection by the recipient.

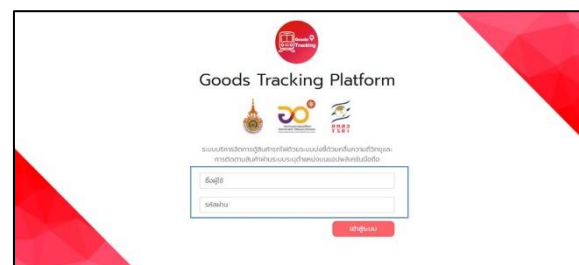


Figure 5 Web application interface for staff operations.

Shipment data, including sender and receiver names, as well as the destination station, is managed through a web application interface at the sending station, as shown in Figure 5. The system

allows staff to input shipment details, generate and print the RFID tag, and scan it using a desktop RFID reader. After validating all data, the staff confirms the entry to store the information in the database, as illustrated in Figure 6. A printed receipt is then issued to the sender, as shown in Figure 7.

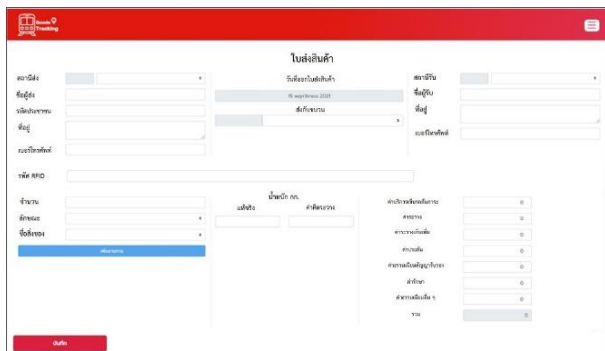


Figure 6 Web application interface for generating shipping orders.

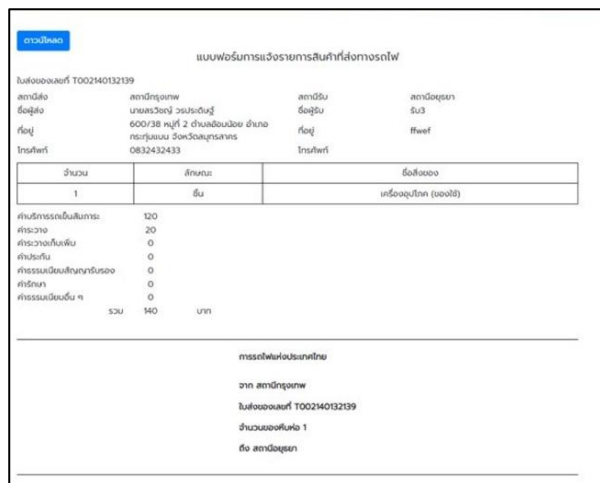


Figure 7 Receipt detailing shipment information.

When it is time to load the parcel into the freight container, the staff opens the RFID handheld reader application, as shown in Figure 8, and scans the RFID tags on the parcel, the container, and the train. Alternatively, the relevant data can be selected from a menu within the application for ease of use. Once the train departs, staff can verify the items that need to be unloaded at each station and summarize the delivery information through the web application. Upon reaching the final destination, the staff uses the RFID handheld reader to scan the

parcel tag and update its delivery status to "Delivered at Destination Station."

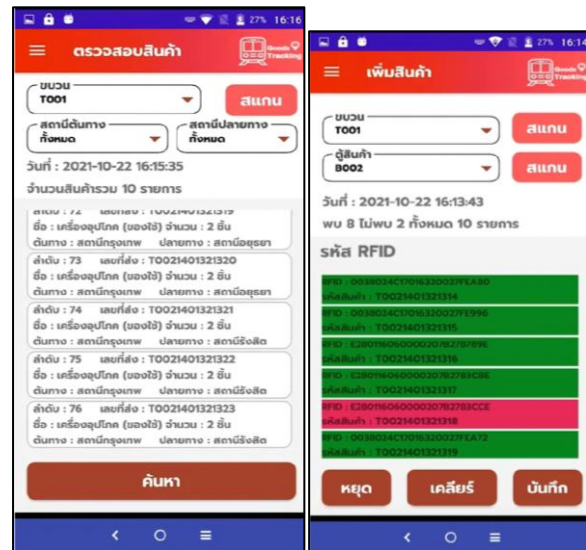


Figure 8 RFID-Based parcel verification application for staff.

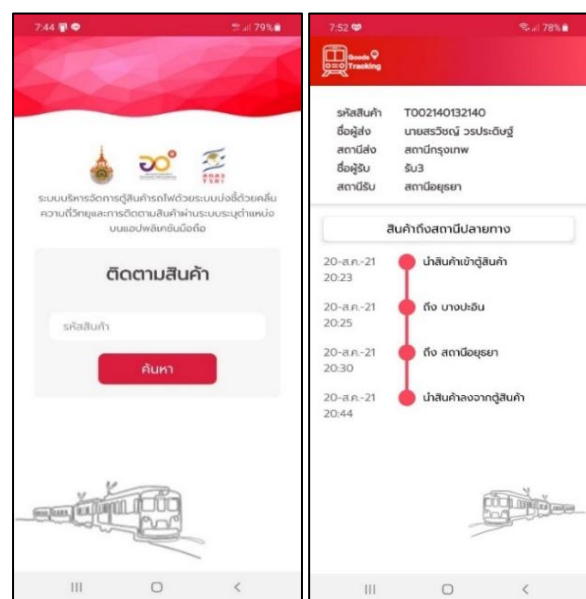


Figure 9 Application for parcel tracking.

Finally, when the customer arrives to collect the parcel, the service counter staff scans the RFID label on the item using a desktop RFID reader. This action updates the parcel status to "Delivered." Both the sender and recipient can verify the parcel's location through the mobile application's GPS-based tracking system, as shown in Figure 9, by entering the tracking number provided on the receipt.



4.2 Performance Evaluation and Operational Impact Analysis

RFID readers were installed at parcel intake and loading points within railway stations, while handheld RFID readers were used by onboard staff during loading and unloading operations. Each freight container was equipped with a UHF RFID tag, and GPS tracking modules were installed on trains to enable continuous location monitoring during transit. The installation setup and device interactions are illustrated in the accompanying diagrams, reflecting real operational conditions as presented in figure 10.

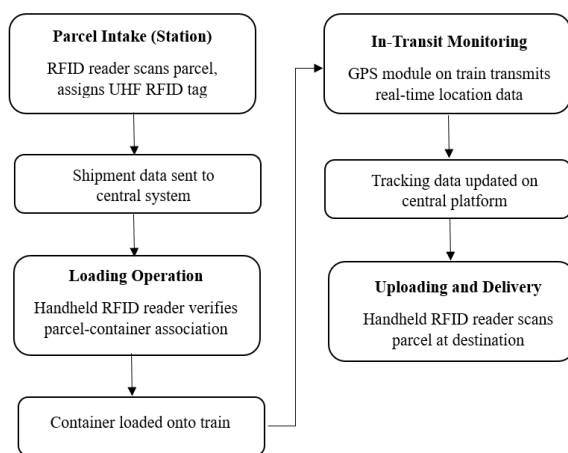


Figure 10 Installation setup and operational workflow of the RFID–GPS-based railway freight container management system.

The proposed system architecture integrates UHF RFID readers, GPS tracking modules, and a centralized web-based platform to support real-time railway freight monitoring. System performance was evaluated under real operational conditions by measuring the end-to-end processing time from RFID tag detection to database update. The results indicate an average latency of 185 ms, with a standard deviation of 42 ms, based on 200 recorded transactions, while the maximum observed latency was approximately 310 ms. These results confirm that the system satisfies real-time operational requirements for railway logistics. In addition to latency performance, the accuracy of GPS-based container localization was assessed using ground-truth reference data. The system achieved a mean absolute positioning error of 4.8 meters, with a 95% confidence interval of 4.2–5.4

meters, calculated from 200 reference measurements, which is adequate for container-level tracking in railway environments.

To evaluate the operational impact of the proposed system, a comparative analysis was conducted between conventional manual handling procedures and the RFID–GPS-based workflow. The results demonstrate a substantial improvement in handling accuracy after system deployment. Specifically, the parcel misplacement rate was reduced from 2.3% under manual operations to 0.4% after implementation, corresponding to an 82.6% reduction in operational errors. This reduction highlights the system’s effectiveness in minimizing human error and improving the reliability of railway freight operations. Overall, the findings indicate that the proposed system not only meets technical performance requirements but also delivers measurable operational benefits in real-world railway logistics environments.

The total system implementation cost was 420,000 THB. Annual operational savings, primarily due to reduced labor requirements and improved loss prevention, were estimated at approximately 310,000 THB per year, resulting in a return-on-investment period of 16.3 months.

4.3 Contextual and Organizational Implications

As depicted in Figures 11 and 12 [19–20], the findings align with the State Railway of Thailand’s Enterprise Development Plan (2015–2024), specifically under Strategic Goal 2: Increasing Revenue and Reducing Costs, and Strategy 2.1: Enhancing Efficiency in Core Business Operations. Within this framework, Program 2.1.2: Increasing Revenue from Passenger and Parcel Transport outlines two key initiatives: 1. The Parcel Delivery Service Enhancement Project in collaboration with Thailand Post, and 2. The “SRT EXPRESS” Fast Cargo Delivery Project — both of which closely correspond to the objectives of this research. As shown in Figure 10, the personnel structure within the Passenger Service Division is categorized into two groups: an approved workforce of 1,330 positions and the actual workforce numbers of 676, 684, 715, 739, and 723 personnel in 2020, 2021, 2022, 2023, and 2024, respectively. This results in an average staffing level of approximately 50% of the approved capacity. Consequently, the scope of



service delivery remains constrained due to limitations in workforce availability.

Staffing Levels of the Passenger Service Division

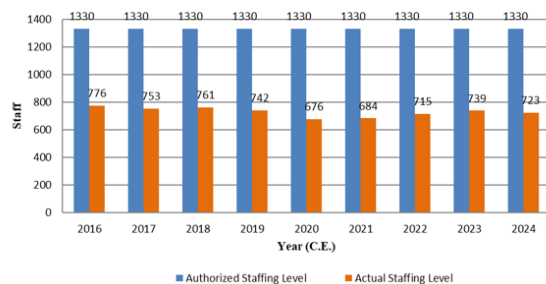


Figure 11 Graph showing personnel allocation in the passenger service division responsible for parcel handling.

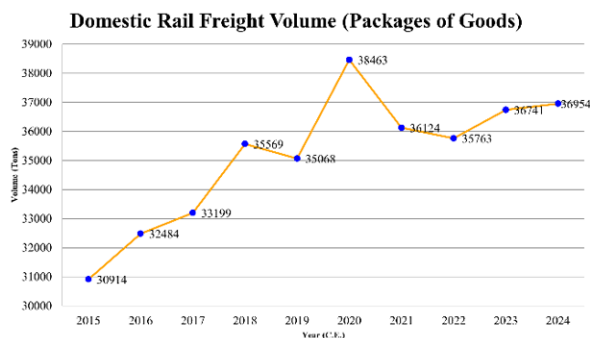


Figure 12 Graph showing domestic rail freight volume.

In contrast, Figure 12 illustrates the domestic rail freight volume (parcel shipments), showing an upward trend. In 2019, the total volume was 35,068 tons, which increased to 38,463 tons in 2020. Although there was a slight decline to 36,124 tons in 2021, the volume still exceeded the 2019 levels. This comparison highlights a significant discrepancy: while freight volume has consistently grown year-over-year, actual staffing levels have steadily decreased. This disparity underscores a critical capacity gap and reinforces the necessity for the proposed management system, which has been designed to support the anticipated growth in the railway parcel logistics sector in the coming years.

5. Conclusion

This research presents a railway freight container management system that integrates UHF RFID technology with GPS-based real-time cargo tracking to improve operational efficiency and

reliability in railway logistics. The proposed system combines RFID hardware, GPS modules, and a web-based software platform supported by a centralized database and API-based communication framework, with secure user authentication implemented using a bcrypt-based hashing mechanism.

Experimental evaluation under real operational conditions demonstrates that the system achieves an average end-to-end latency of 185 ms, with a maximum observed delay of approximately 310 ms, confirming its suitability for real-time railway freight monitoring. GPS-based container localization attains a mean absolute positioning error of 4.8 meters, with a 95% confidence interval of 4.2–5.4 meters, while operational errors are significantly reduced, as evidenced by a decrease in parcel misplacement rate from 2.3% under manual handling procedures to 0.4% after system deployment, representing an 82.6% reduction in errors. In addition, the system demonstrates economic feasibility, with a total implementation cost of 420,000 THB and an estimated payback period of 16.3 months. Future work will focus on extending the system to support larger-scale deployment across additional railway lines and integrating advanced data analytics techniques to further enhance predictive monitoring and operational decision-making.

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Sustainable Acoustic Absorbers: Fabrication and Sound Absorption Performance of Compression-Molded Composites Derived from Bamboo Leaf Waste

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Abstract

This research addresses the issue by developing a novel, eco-friendly acoustic absorbing material that aligns with the principles of the Bio-Circular-Green (BCG) Economy. The study utilizes dry bamboo leaf powder as the primary natural fiber and *Persea kurzii* powder, a natural resin/binder, as the binding agent. Standard circular specimens were fabricated using a compression molding technique. Three different ratios of fiber-to-binder were investigated: Sample A (90:10), Sample B (80:20), and Sample C (70:30). The sound absorption properties were strictly tested using the Transfer-function method (ISO 10534-2). The results demonstrated that the specimen with highest fiber loading, Sample A (90:10), exhibited the most effective acoustic performance. This optimal sample achieved a high Noise Reduction Coefficient (NRC) of 0.44 and showed maximum absorption with a Sound Absorption Coefficient (SAC) of 61.96% at a key mid-frequency of 500 Hz. The results strongly suggest that a higher proportion of bamboo leaf fiber is crucial for developing and maintaining the necessary porous structure within the composite, which facilitates effective sound dissipation. These findings demonstrate the potential of bamboo leaf composites as sustainable, cost-effective alternatives to synthetic sound-absorbing panels, successfully valorizing agricultural waste into high-value products.

Keywords: Bamboo leaves, Nature binder, Acoustic absorbers, Compression molding

1. Introduction

An extensive challenge of sustainable waste management and resource utilization is a critical issue globally, particularly concerning the vast quantities of agricultural residues generated in developing economies. In Thailand, this problem is severe within the agricultural sector, particularly in highland monoculture areas. The prevailing and often simplest disposal method—open burning—is a primary contributor to severe air pollution (PM_{2.5}), smog, and widespread degradation of the ecosystem, including soil, water, and forest resources. To moderate this environmental crisis, the Mae Chaem model plus project was initiated to reduce single-crop cultivation areas, curb burning practices, and promote the substitution of maize with bamboo as an economic crop. Bamboo is a fast-growing plant that requires minimal fertilizer or pesticides, offers diverse benefits across its structure, effectively sequesters carbon dioxide, and improves soil quality. The abundant seasonal

leaf shedding situation underscores the urgent need for developing creative management strategies for agricultural waste. Utilizing bamboo leaves as a local resource not only helps relieve environmental problems but also generates economic value for the community. Furthermore, the development of environmentally friendly materials aligns with the Bio-Circular-Green (BCG) economy model [1] for transformative change, income generation, and sustainability, directly contributing to the Sustainable Development Goals (SDGs) [2] offering a pathway to mitigate environmental crises while generating local income. Accordingly, this research focuses on the valorization of natural waste material, specifically bamboo leaves, for the development of an acoustic absorption product for building interiors, utilizing the compression molding technology [3]. Compression molding process approach inherently aligns with the principles of eco-design [4], which mandates the

use of environmentally conscious materials and production processes, and the circular economy [5], which emphasizes waste minimization and resource reuse. Economically, the potential cost reduction is substantial: the bamboo leaf acoustic material has the potential to significantly undercut the cost of synthetic fiber acoustic panels currently on the market, with an estimated production cost averaging 200 THB/m² compared to market prices often reaching 3,000 THB/m². Global research is increasingly focused on developing acoustic absorption materials from agricultural by-products such as coconut coir, kenaf fiber, rice husk, and orange peel, aiming to replace environmentally impactful synthetic fibers. The sound absorption efficacy of these porous materials is not solely determined by the material type but is primarily governed by key physical parameters: Increased thickness enhances absorption in the low-to-mid frequency ranges; higher density generally correlates with improved sound absorption; and the porous structure and air voids are crucial for improving low-frequency absorption and optimizing material usage [6]. Existing studies demonstrate a wide range of Noise Reduction Coefficient (NRC) values for natural materials, such as coconut coir (0.20-0.43) and peanut shell (0.23-0.54). The influence of internal structure is paramount, as demonstrated by studies on wood. [7] summarized acoustic performance is directly controlled by the material's anatomical features and porosity. The creation of a back air cavity can significantly increase the Sound Absorption Coefficient (SAC) in the low-frequency range, with woods like hackberry and oak achieving high NRC values (0.55 and 0.53) at a 4 cm cavity depth. This highlights that high porosity and large pore sizes enhance low-frequency sound absorption. A key challenge for natural waste materials includes inherent limitations in low-frequency absorption and concerns regarding environmental durability (moisture, decay) and fire safety. Recent innovations aim to overcome the low-frequency limitation by integrating structures like Micro-Perforated Plates (MPP) [8] into the composite structure. Despite these advancements, a significant research gap remains regarding the use of bamboo leaf waste as a primary fiber in compression-molded composites. Furthermore, while innovations like Micro-Perforated Plates (MPP) have been used to enhance low-frequency absorption, there is limited research on 100% bio-based composites that utilize natural binders.

This study addresses these limitations by developing a novel, eco-friendly acoustic panel derived from bamboo leaf powder and Persea

kurzii (a natural resin). The objectives are to: 1) design and develop a sound-absorbing product from bamboo leaf composites, and 2) fabricate a specific compression molding die for its production. This research validates a method for transforming agricultural waste into a high-value green alternative for the construction industry.

2. Materials

2.1. Dried Bamboo Leaves

The dried bamboo leaves utilized in this research are agricultural residues sourced from the natural shedding of the native 'Fah Mon' bamboo species (a local variety of *Dendrocalamus asper* or similar giant timber bamboo). These bamboo groves are cultivated by the Pai Ngoen Lan Community Enterprise in Tha Pha subdistrict, Mae Chaem district, Chiang Mai province. This specific source is highly significant as 'Fah Mon' bamboo produces a substantial volume of waste, averaging 1,000 kg of leaves per shedding cycle annually, which is predominantly disposed of via open burning, composting, or landfilling. Figure 1(a) and (b) illustrated bamboo forest and dried bamboo leaves, respectively.

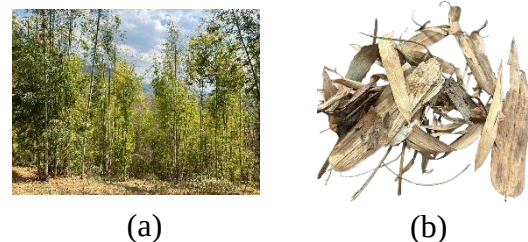


Figure 1 Natural material (a) bamboo forest (b) dried bamboo leaves

The preparation process for the bamboo leaves began with collection from the research area. The collected leaves were then cleaned thoroughly to remove surface contaminants and dust. Following cleaning, the leaves were sun-dried or oven-dried at 60°C for 8 hours until 10% residual moisture to reduce the moisture content to a level appropriate for subsequent molding and processing. The dried leaves were then subjected to size reduction processes, such as shredding, milling, and grinding, to ensure a uniform particle size distribution. This consistency in particle size is crucial for achieving optimal dispersion within the binding matrix, which directly influences the final structural and acoustic properties of the product. Quality control from collection through preparation is essential to ensure consistent properties in the resulting sound-absorbing product.

2.2. Natural Binder (Bong Resin)

This research utilizes *Persea kurzii* powder, locally known as "Bong resin" as the natural binding agent, consistent with the objective of developing an eco-friendly product and promoting the utilization of local resources. Beyond its sustainability and bio-based origin [9], the selection of Bong resin is justified by its specific engineering properties. It contains high polysaccharide content (mucilage), which acts as a natural adhesive when activated under the heat and pressure of compression molding. This mucilage facilitates strong interfacial bonding between the bamboo leaf fibers, ensuring the structural integrity of the composite. Additionally, its inherent chemical composition provides natural resistance to termites, weevils, and ants, making it a desirable bio-based additive. Furthermore, it is compatible for blending with various natural fibers. The selection of Bong resin directly aligns with the project's goal of utilizing natural resources to create value and economic opportunities for the local community. It also supports the Bio-Circular-Green (BCG) economy concept by emphasizing the recirculation of bio-based materials. The Bong resin will be prepared and mixed with the dried bamboo leaf powder at optimized ratios. This process is crucial to ensure that the binder is uniformly distributed and provides the necessary adhesion properties for the final product's structural integrity. The optimized mixing ratio will be determined experimentally. Figure 2 (a) and (b) shows the Bong tree bark and the Bong resin powder, respectively.



Figure 2 Natural binder (a) Bong tree bark (b) Bong resin powder [10]

2.3. Compression Molding

The acoustic absorbing product from the bamboo leaf fiber and natural binder will be fabricated using compression molding technique. This is a process where a material charge is subjected to a compressive force to shape it according to the geometry of the mold cavity. This method is highly suitable for natural fiber

composites due to its effectiveness and, critically, the lower cost of mold creation compared to other molding techniques. The fundamental components of the mold assembly consist of an upper movable mold part (core) and a lower fixed mold part (cavity). The compressive force (F) exerted by the upper mold half squeezes the material charge, placed between the two halves, to conform to the shape defined by the mold cavity, as schematically shown in Figure 3. The compressive force required for forming the composite is calculated based on the necessary molding stress (σ). The relationship between the force, stress, and the surface area of compression is defined by Equation (1):

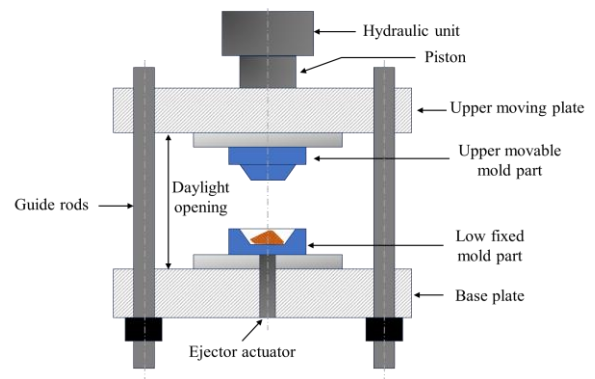


Figure 3 Schematic setup of compression molding process [11]

$$\sigma = F/A \quad (1)$$

where: σ is the stress applied to the material (N/mm^2), F is the applied force (N). A is the cross-sectional area where the force is applied (mm^2) [12].

2.4 Sound Absorption

Sound absorption is the fundamental mechanism crucial for sound energy dissipation. When sound waves strike a material, a portion of the incident energy is converted into thermal energy through various processes. The core mechanism for sound absorption in porous materials (such as natural fibers or foam) is viscous friction (or Visco-thermal damping). This occurs as air molecules oscillate and encounter resistance within the tortuous, open-pore structure of the material. This restricted movement of air within small cavities results in the transfer of the sound wave's kinetic energy into heat, thereby attenuating the acoustic energy. The sound absorption performance of a material is quantified by the sound absorption coefficient (α) at specific frequencies. An important average measure is the Noise Reduction Coefficient (NRC), which is the

arithmetic average of (α) at the principal speech frequencies (250, 500, 1000, and 2000 Hz). The essential physical parameters influencing the material's absorption efficiency include: optimal thickness, density, and open porosity structure (This is arguably the most critical factor, as it dictates the airflow resistivity and the internal surface area available for viscous friction.) [13]. The sound absorption properties in this research were measured according to ISO 10534-2: Acoustics - Determination of sound absorption coefficient and impedance in impedance tubes - Part 2: Transfer-function method [14]. This standard provides a method for determining the normal incidence sound absorption coefficient (α_n) and the surface acoustic impedance using an impedance tube (or Kundt's tube) [15-16]. The sound absorption coefficient (α) is calculated using Equation 2 [17].

$$\alpha = 1 - |R|^2 \quad (2)$$

where: (α) is the sound absorption coefficient ($0 \leq \alpha \leq 1$). $|R|^2$ is the magnitude squared of the reflection coefficient, which signifies the proportion of acoustic energy reflected back. The complex acoustic transfer function (H_{12}) between microphone 1 and microphone 2 is defined in Equation 3 [2.5.1-2]:

$$H_{12} = \frac{P_2}{P_1} = \frac{e^{-jkx_1} + R_p e^{jkx_2}}{e^{-jkx_2} + R_p e^{jkx_1}} \quad (3)$$

where: H_{12} is the complex acoustic transfer function between microphones 1 and 2. P_1 and P_2 are the complex sound pressures measured at the positions of microphone 1 and 2, respectively. k represents wavenumber (m^{-1}), when; $k = \frac{\omega}{c_0} = \frac{2\pi f}{c_0}$, which ω is the angular frequency (rad/s), c_0 is the speed of sound in air inside the room (m/s), f is the frequency (Hz), x_1, x_2 ; the distance from the test surface to microphone 1 and microphone 2, respectively (m), R_p is the normal-incidence pressure reflection factor (also known as the reflection coefficient). The scheme of two-microphone transfer function method can be shown in Figure 4.

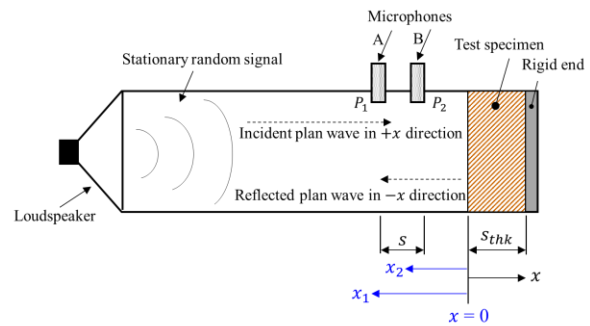


Figure 4 Scheme of two-microphone transfer function method [14]

2.5 Specimen Preparation for Sound Absorption Testing

Specimens for determining the Noise Reduction Coefficient (NRC) were prepared according to the ISO 10534-2 standard (Transfer-function method). The specimens were molded into a cylindrical shape with a uniform thickness of 2.5 cm. To cover the required range of sound frequencies for testing, two different specimen diameters were prepared for use with the appropriate impedance tube sizes. Large diameter specimen 9.8 cm used for the low-frequency zone (up to 1,600 Hz), covering the primary speech frequencies. Small diameter specimen 2.8 cm used for the high-frequency zone (1,600-4,000 Hz). The final composite panels, created using the compression molding method, were cut into these precise cylindrical dimensions to ensure an accurate fit within the impedance tube fixtures, as shown in Figure 5 (a) and (b).

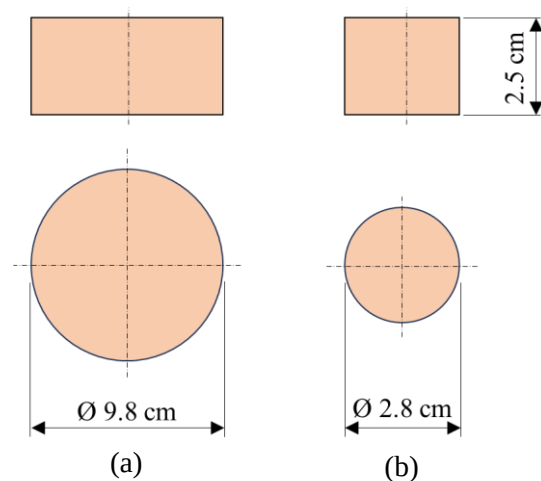


Figure 5 Specimen dimension [18] (a) low-sensitivity zone testing (b) high-sensitivity zone testing



3. Methods and Experimental Procedure

The experimental investigation followed the systematic procedure outlined in the flowchart shown in Figure 6. The methodology can be categorized into three main stages: (1) material preparation for both bamboo fiber and binder, (2) mixing ratio, and (3) compression of materials.

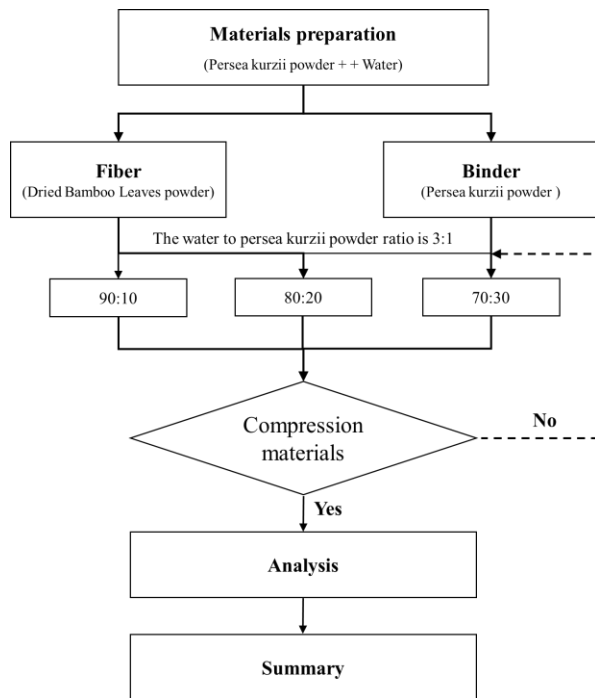


Figure 6 Methodology schematic

3.1 Material Preparation

The material preparation process was conducted to transform raw bamboo residues into a consistent natural fiber powder. The procedure consisted of the following stages: (1) Drying and Grinding: Collected dry bamboo leaves were oven-dried at 60°C for 8 hours to eliminate residual moisture until a stable moisture content of 10% and prevent biological degradation. The dried leaves were then mechanically ground using a high-speed grinder to reduce the fiber size. (2) Sieving and Particle Size Selection: To ensure a uniform internal structure within the composite, the resulting powder was sieved using a U.S. Standard Sieve No. 4, which corresponds to a mesh opening of 4.75 mm. This sieving process is critical for controlling the aspect ratio of the fibers and ensuring consistent void distribution within the final acoustic panel. (3) Final Material Formulation: The fraction passing through the sieve was collected as the primary bamboo leaf powder. This specific particle size (≤ 4.75 mm) was selected to provide an optimal balance between fiber surface area for binder adhesion and

the formation of interconnected pores necessary for sound wave dissipation. The prepared bamboo leaf powder, as shown in Figure 7, was subsequently blended with the natural binder at the specified experimental ratios.

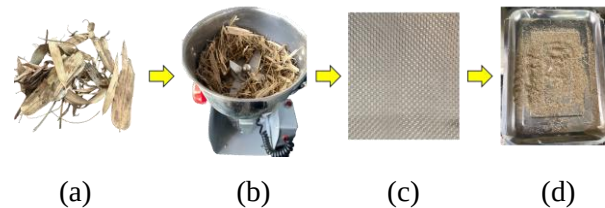


Figure 7 Material Preparation (a) Dried bamboo leaves (b) Bamboo leaves grinding (c) Sieve no.4 (d) Bamboo leaves powder

Prepared bamboo leaf powder was subsequently mixed with Persea kurzii powder (natural binder) and water. The components were thoroughly mixed to achieve a homogeneous mixture. The main mixing ratios established between the dry bamboo leaf powder and the Persea kurzii powder were investigated at three levels (fiber: binder), ensuring a total of 100 parts; 90:10, 80:20, and 70:30. Furthermore, the amount of water added during the mixing process was determined based on the quantity of the Persea kurzii powder (binder) at a ratio of 3:1 (water: natural binder). The resulting mixture is demonstrated in Figure 8.

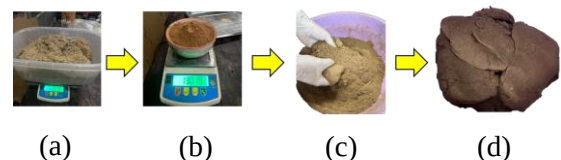


Figure 8 Mixing Process (a) Bamboo powder weighing (b) Persea kurzii powder weighing (c) Mixing (d) Moldable Material

3.2 Compression Molding Process

Acoustic absorbing panels were fabricated using a controlled compression molding process. The following equipment and specifications were utilized; Ward-Forsyth VO30E/10 hydraulic press machine with Maximum Opening Distance 400 mm. Working table dimensions 460 mm x 500 mm. Maximum compressive force is 60 Ton. The hydraulic press, as shown in Figure 9, was used to apply a predefined pressure to the mixed bamboo leaf and binder compound inside the molds, enabling the consolidation of the composite specimens.

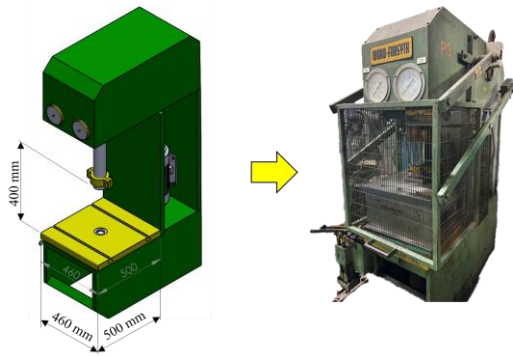


Figure 9 Ward-Forsyth VO30E/10 hydraulic press machine

The acoustic panel was fabricated using a specially designed compression mold with dimensions of 450 x 500 x 300 mm. The mold operates based on uniaxial compression principle, where the pressing force is applied in a vertical, top-to-bottom direction to densify the composite mixture into the final product shape, as shown in Figure 10.

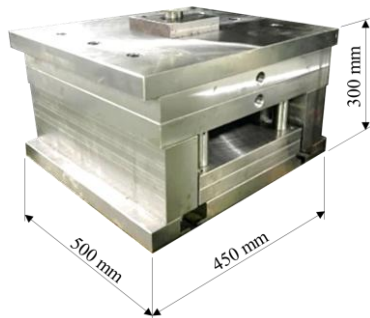


Figure 10 Compression molding

3.3 Experimental Testing

The experimental testing of the fabricated acoustic panels was divided into two main parts. To ensure methodological robustness and data reliability, all tests were performed in triplicate ($n=3$ per fiber-to-binder ratios per size), and the mean values were reported.

3.3.1 Specimens for Sound Absorption Testing and Noise Reduction Coefficient (NRC) Determination

Specimens for sound absorption testing were designed in accordance with the ISO 10534-2 standard (Transfer-function method). Specimen Configuration: Cylindrical specimens were fabricated in two different diameters: 9.8 cm (for low-to-mid frequency range) and 2.8 cm (for high frequency range), each having a uniform thickness of 2.5 cm. These specimens were specifically sized to fit the impedance tube apparatus. The dimensions and setup are illustrated in Figure 11.



Figure 11 Acoustic absorption test specimens (ISO 10534-2) (a) Specimen with a diameter of 9.8 cm (b) Specimen with a diameter of 2.8 cm

Experimental Control: The specimens were precisely machined to ensure a tight fit within the impedance tube, minimizing acoustic leakage. Ambient temperature and humidity were monitored and kept constant during the measurements to eliminate environmental interference with the sound speed. **Data Reliability:** For each material composition, three independent specimens were tested. The results were averaged to determine the Sound Absorption Coefficient and the Noise Reduction Coefficient (NRC), ensuring that the data were representative and reproducible.

3.3.2 Final Acoustic Panel Fabrication

The final acoustic panel was designed with nominal dimensions of 300 mm x 300 mm x 25 mm (WxLxH). The required compression force (F) for panel molding was calculated based on the following relationship: $F = \sigma \times A$ where; F is the Compression Force required for forming the specimen (N). σ is the Material Stress (or required molding pressure) applied to the material. A is the Cross-sectional Area of the material (m^2). **Process Control and Consistency:** To strengthen the methodological robustness, the calculated compression force was maintained at 21,567 N (approximately 21.6 kgf.). Other critical process variables, including the molding temperature and the holding time (dwell time), were strictly controlled and kept uniform for every panel produced. This consistency ensures that the physical properties of the panels are directly comparable across different material ratios. The complete molding setup is illustrated in Figure 12.

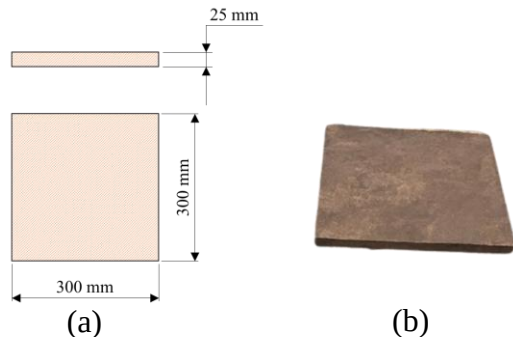


Figure 12 Final design and fabricated prototype
(a) Schematic of the acoustic panel design (b) Final compression-molded acoustic panel

4. Results

4.1 Sound Absorption Coefficient (SAC) and Noise Reduction Coefficient (NRC)

The acoustic absorption properties of the developed sound-absorbing panels-fabricated from dry bamboo leaf powder and Bong Resin (*Persea kurzii* powder) via the Compression Molding technique-were evaluated in accordance with the ISO 10534-2: Transfer-Function Method standard. All tests were conducted at the Center for Building Innovation and Technology (CBIT). To ensure the statistical reliability of the data, each sample was tested in triplicate, and the mean values are presented in Table 1 and Figure 4.1. The specimens were categorized into three groups based on the ratio of dry bamboo leaf powder to Bong Resin (Fiber: Binder): Sample A (90:10), Sample B (80:20), and Sample C (70:30).

Table 1 SAC and NRC values for the developed acoustic panels at varying fiber-to-binder ratios.

Samples	A	B	C
Type	(90:10)	(80:20)	(70:30)
250 Hz. (SAC)	30.44 %	31.78 %	18.34 %
500 Hz. (SAC)	61.96 %	41.51 %	39.50 %
1000 Hz. (SAC)	46.93 %	35.99 %	48.60 %
2000 Hz. (SAC)	37.79 %	38.37 %	35.98 %
Average (SAC)	44.28 %	36.91 %	35.60 %
NRC*	0.4428	0.3691	0.3560

Remark: The Noise Reduction Coefficient (NRC) is defined as the arithmetic average of the sound absorption coefficients (α) measured at the four standard one-third octave band center frequencies: 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz.

4.2 Analysis of Sound Absorption Performance

4.2.1 Porosity and Structural Influence on SAC

Sample A (90:10) exhibited the highest NRC of 0.44, with a peak SAC of 61.96% at 500 Hz. From a structural perspective, the high fiber-to-binder ratio in Sample A maintains a high volume of interconnected open pores. When sound waves enter this porous matrix, acoustic energy is dissipated through two primary mechanisms:

(1) Viscous Losses: The friction between the oscillating air molecules and the complex cell wall structures of the bamboo leaf powder.

(2) Thermal Dissipation: The conversion of sound energy into heat as the pressure fluctuations interact with the large internal surface area of the fiber network. The peak at 500 Hz suggests that the pore size distribution and the thickness of the panel (25 mm) are optimally tuned to the wavelength of mid-frequency sound, providing maximum flow resistance in this range.

4.2.2 Impact of Binder Concentration on Tortuosity and Flow Resistance

As the proportion of the *Persea kurzii* powder (Bong Resin) binder was increased-from 10% in Sample A, 20% in Sample B, to 30% in Sample C-the corresponding Noise Reduction Coefficient (NRC) showed a consistent decline in NRC (0.443, 0.369, and 0.356, respectively). This trend can be explained by the mechanical filling effect of the binder:

(1) Pore Blockage: The increased binder volume fills the interstitial spaces between bamboo fibers, reducing the effective porosity of the material.

(2) Increased Tortuosity: As pores become clogged, the paths for sound wave penetration become more restricted or closed. While a certain level of tortuosity is beneficial, an excess of binder (as seen in Sample C) leads to a "closed-pore" structure, reflecting sound waves rather than absorbing them.

(3) Mechanical Rigidity: Higher binder content increases the structural stiffness of the panel. From a mechanical evaluation standpoint, a more rigid and less permeable matrix reduces the membrane-like vibration of the fibers, which otherwise contributes to low-to-mid frequency absorption.

4.2.3 Statistical Significance and Trend Analysis

The downward trend in NRC relative to binder concentration ($A > B > C$) indicates a strong correlation between binder ratio and acoustic impedance. Statistical evaluation suggests that the



10% binder threshold is critical; exceeding this limit results in a significant loss of mid-frequency absorption (a 33% drop at 500 Hz from Sample A to B). This confirms that Sample A (90:10) achieves the optimal balance between structural integrity (mechanical bonding) and acoustic permeability.

5. Conclusion

This research successfully designed and developed a bio-based sound-absorbing product utilizing agricultural waste. The material was fabricated using dry bamboo leaves sourced from the local "Fah Mon" bamboo species in Mae Chaem District, Chiang Mai, combined with Bong Resin (a natural binder), through a compression molding process. The developed acoustic panel demonstrated the highest sound absorption efficiency at the 90:10 ratio of dry bamboo leaf powder to Bong Resin (Sample A). This optimal formulation yielded a high Noise Reduction Coefficient (NRC) of 0.44, which is suitable for use as non-structural acoustic material in building applications, with its peak performance reaching 61.96% Sound Absorption Coefficient at 500 Hz. Experimental results clearly indicate that the proportion of dry bamboo fiber is the primary factor influencing sound absorption performance. The high fiber content effectively preserves the porous structure necessary for sound energy dissipation by maximizing the frictional resistance of air molecules. Conversely, increasing the quantity of Bong Resin binder led to a reduction in the measured NRC values. Ultimately, this work successfully applies manufacturing technology to valorize agricultural residues (specifically, up to 1,000 kg of bamboo leaves per cycle per year) into a high-value product. This initiative strongly aligns with the Bio-Circular-Green (BCG) Economy model and the Sustainable Development Goals (SDGs), particularly by mitigating the severe environmental issue of open burning and creating economic value for local communities. While this study provides a successful proof-of-concept for bamboo-leaf-based acoustic panels, certain limitations remain to be addressed in future work: Mechanical and Durability Testing: This study focused primarily on acoustic performance. Future research should evaluate the mechanical properties, flammability and biological resistance, as well as scale-up and transmission loss.

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RFID-Driven Smart Border Passing Architecture for Cloud-Integrated Vehicle Authentication

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Abstract

As global trade and tourism continue to expand, cross-border vehicle traffic has significantly increased, demanding more efficient and secure inspection systems. Conventional border checkpoint operations in Thailand rely on manual document verification, which is time-consuming and error-prone. This study proposes the design and implementation of a smart border passing system using Radio Frequency Identification (RFID) to enhance the identification and monitoring of vehicles at border checkpoints. The proposed system integrates three main components: a portable RFID reader, a flexible RFID tag sticker, and a cloud-based database dashboard for data synchronization and tracking. The RFID reader was developed as a compact, battery-powered device capable of reading UHF tags and transmitting data via Wi-Fi in real time. Experimental results demonstrate that the reader achieved 100% detection accuracy within 1.8 meters, with reliable tag readability for 30 days under real outdoor conditions. The web-based dashboard successfully displayed ENTRY, EXIT, and TIMEOUT events, enabling efficient vehicle tracking and administrative reporting. The system offers a practical and cost-effective solution for smart border management, reducing manual workload and supporting proactive detection of unauthorized crossings or vehicle theft. Future enhancements will focus on improving adhesive durability, expanding wireless communication, and integrating predictive analytics for real-time anomaly detection.

Keywords: smart border passing, radio frequency identification: RFID, vehicle identification, cloud database, UHF tag, IoT-based monitoring, real-time authentication

1. Introduction

Globalization has led countries worldwide to expand trade and tourism, resulting in a dramatic increase in cross-border traffic. Vehicle crossings between countries such as the United States and Mexico or among European Union nations continue to rise. In Asia, China's One Belt, One Road initiative has accelerated logistics and tourism routes. Within Southeast Asia, the ASEAN Economic Community (AEC) has

encouraged open-border policies among member nations. According to Thailand's Office of Transport and Traffic Policy and Planning (OTP), annual vehicular border crossings have reached over 14 million, underscoring the need for efficient inspection and monitoring systems [1].

Traditionally, border inspection procedures rely heavily on manual document verification, where immigration officers check passports, driving licenses, and vehicle permits before

granting passage. This manual approach is time-consuming, prone to human error, and inadequate for handling large traffic volumes. To improve operational efficiency, smartcard and Radio Frequency Identification (RFID) technologies have been proposed for automated identity verification at border checkpoints [1].

A smart border passing system using RFID consists of three main components: 1) an RFID reader for scanning tags via radio frequency waves, 2) an RFID tag containing encrypted identification data linked to the vehicle and owner, and 3) a cloud-based database for storing and verifying user information. Numerous studies have demonstrated RFID's usefulness in applications such as access control, electronic toll collection (ETC), public transport fare payment, and logistics management [2-4]. However, most implementations focus primarily on improving traffic flow rather than ensuring secure and traceable vehicle identity verification. To address security concerns, researchers have introduced lightweight authentication protocols and encryption schemes to mitigate cloning and traceability issues [4-11]. These studies have built trust in RFID applications, paving the way for their adoption in security-critical systems.

In addition, recent work has explored the development of RFID tag antennas optimized for UHF operation and sensing applications [12-17]. Yet, most of these antennas are fabricated on rigid FR4 substrates, suitable for card-based systems but

unsuitable for flexible, adhesive-type tags used on vehicles.

Unlike conventional RFID applications, a vehicular border pass system imposes unique mechanical and environmental constraints. The RFID tag must adhere firmly to curved or uneven vehicle surfaces-such as windshields, doors, or hoods-while remaining resistant to heat, moisture, and vibration. Any damage or removal attempt should render the tag unusable, ensuring tamper evidence. Furthermore, the tag must be flexible, low-cost, and easily replaceable [18-20].

While prior studies have demonstrated RFID applications in tolling systems, access control, and livestock monitoring, these works primarily focused on fixed-reading infrastructure and rigid card-based identification. None of them addressed the unique requirements of vehicular border authentication, where temporary permission, return-tracking, and easily removable tags are essential. This research therefore extends those previous concepts by incorporating a handheld reader, a flexible RFID sticker tag, and real-time cloud-based checkpoint validation.

Therefore, this research aims to design and implement a smart border passing system using RFID technology that integrates a compact handheld reader, a flexible RFID sticker tag, and a cloud-based database dashboard. The proposed system targets real-time identification, data synchronization, and operational durability under practical border checkpoint conditions.



Figure 1. System architecture of the proposed RFID-driven smart border passing system.



2. System Architecture

RFID technology was selected over alternatives such as QR codes and automatic license–plate recognition (ALPR) due to its mid-range passive reading capability, low operational cost, and reliability in outdoor environments. QR-based identification requires close proximity and is sensitive to moisture and glare, while ALPR systems involve significantly higher infrastructure costs and are prone to misread plates when vehicles are dusty or obstructed. RFID provides a balanced option suitable for handheld inspection and scalable deployment.

The proposed smart border passing system using RFID, as shown in Fig. 1 is designed to enhance the vehicle verification process at border checkpoints through wireless identification and real-time data management. The overall system integrates RFID-based vehicle tagging, portable reader devices, and a centralized cloud database, enabling automated registration, authentication, and tracking of vehicles crossing the border.

2.1 System Overview

As illustrated in Figure 1, the system comprises three main components:

1. RFID Reader - a handheld reader equipped with an embedded Wi-Fi microcontroller and LCD display. Officers use this device to scan vehicle tags during border entry and exit operations.

2. RFID Tag Sticker - a passive UHF RFID tag attached to the vehicle's surface (e.g., windshield, hood, or door). Each tag contains a unique identification code (UID) linked to the registered vehicle and owner data stored in the cloud database.

3. Cloud Database System - a centralized database that stores, verifies, and updates vehicle records. It communicates with the reader via Wi-Fi, allowing seamless synchronization of data across all checkpoints.

When a vehicle owner applies for a border pass, an officer registers the vehicle and owner information into the database. The RFID tag is issued and attached to the vehicle. During border crossing, the officer uses the reader to authenticate the tag against the stored records. The result is displayed instantly on both the reader's LCD screen and the officer's web-based interface.

If a registered vehicle fails to return within a specified duration (such as 30 days), the system automatically triggers a timeout notification and exports a report in Excel format to alert responsible officials. This feature improves administrative efficiency and ensures reliable monitoring of temporary cross-border traffic. In addition, the timeout function provides an early indication for tracking irregular vehicle movements and supports data traceability for administrative follow-up.

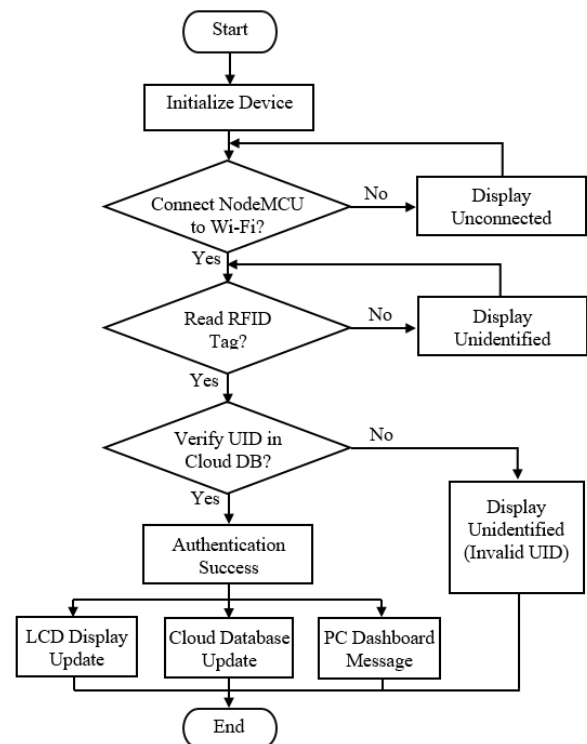


Figure 2 Operational workflow for the proposed RFID-driven smart border passing system.

RFID systems may be susceptible to cloning attacks and unauthorized tag reading in open environments. To mitigate these risks, the proposed system performs cloud-based identity matching and expiration–time validation at the server side, ensuring that duplicated or replayed identifiers cannot gain access. In addition, the security–code mechanism described in our prior work [5] is applicable for advanced protection when deployed at scale.

2.2 System Operational Workflow

The operational workflow of the system is depicted in Figure 2. The process begins when the

RFID reader initializes its components and attempts to connect to the cloud database via Wi-Fi. Once the connection is established, the reader scans for RFID tag signals:

1. If no tag is detected, an “Unidentified” message is displayed.
2. When a valid tag is detected, the reader retrieves the tag’s UID and sends it to the database for verification.
3. If the UID matches a registered record, the database authenticates the vehicle, updates the status log, and displays confirmation messages on both the LCD screen and the officer’s monitoring interface.
4. The updated status is stored in the cloud database, ensuring real-time tracking of vehicle entries and exits.

This workflow supports real-time bidirectional communication between the handheld reader and the cloud database, enabling fast verification even under high traffic conditions at border checkpoints. In cases where a tag cannot be read or the UID does not match an active entry record, the system automatically flags the case on the dashboard and requires manual document-based inspection. Unregistered vehicles are temporarily directed to a secondary inspection lane where identity and permit validation are performed. Once returning vehicles are authenticated, officers may reset their status through the dashboard, after which the tag may be removed by the driver. The process is designed such that a single officer can adequately manage one lane using the handheld device and web-based dashboard.

3. Hardware Reader Development

The hardware reader was developed as a portable RFID-based identification unit for field officers at vehicle border checkpoints. The hardware design emphasizes compactness, low power consumption, and reliable wireless data transmission, suitable for on-site inspection and registration tasks.

The fundamental antenna resonance frequency f_r for a half-wave dipole structure used in the UHF RFID module can be approximated for Equation (1) below

$$f_r = \frac{c}{2L\sqrt{\epsilon_{eff}}} \quad (1)$$

where c the speed of light (3×10^8 m/s), L is the effective length of the antenna, and ϵ_{eff} is the effective dielectric constant of the substrate.

The impedance of the dipole element can be estimated as shown in Equation (2).

$$Z_A = R_A + jX_A \quad (2)$$

where R_A and X_A represent the real and imaginary parts of the input impedance. The impedance matching between the antenna and RFID IC ensures maximum power transfer and reading efficiency within the UHF band (860-960 MHz).

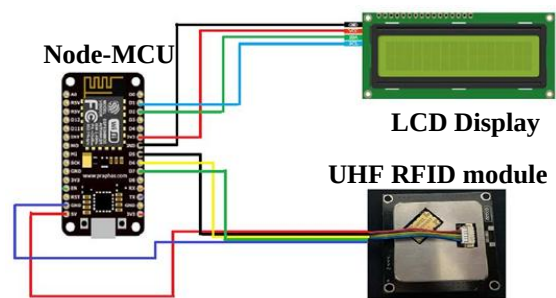


Figure 3 RFID reader diagram showing UHF module, Wi-Fi microcontroller, and LCD display.



Figure 4 Prototype of compact handheld RFID reader for border checkpoint operations.

3.1 Hardware Design

The system circuit, shown in Figure 3, consists of three main components:

1. UHF RFID Reader Module - responsible for generating the interrogation signal and reading the RFID tag’s unique identification code (UID) through electromagnetic coupling.
2. Wi-Fi Microcontroller Unit - serves as the main control processor, handling data communication between the RFID reader, LCD display, and cloud database via wireless protocol.
3. LCD Display Module - displays the system’s operational status and tag identification messages, such as “MODE: REGISTER - Present TAG...” during registration and scanning.



The prototype operates using a rechargeable 6,800 mAh lithium-ion battery pack, which provides sufficient power for continuous field operation throughout a typical working day. The device is designed in a handheld form factor suitable for single-hand use, as illustrated in Section 6, and can be further miniaturized in future development when transitioning to a commercial product. The material cost of the assembled prototype is approximately 4,000 THB, which is significantly lower than that of commercial UHF handheld readers (typically 20,000-50,000 THB), supporting cost-effective deployment.

3.2 Prototype Implementation

The assembled prototype is shown in Figure 4. The unit is enclosed in a durable, lightweight casing designed for handheld use by officers. The internal layout integrates the RFID module, Wi-Fi controller, and power unit efficiently within the limited enclosure space. The LCD interface allows real-time display of operational states, simplifying the verification process.

When the reader detects an RFID tag, it retrieves the UID, verifies it with the cloud database, and updates the authentication result immediately. The combination of hardware and software integration ensures real-time synchronization, reducing manual workload and improving operational speed.

Field evaluation confirmed that the prototype operated reliably under typical field conditions, demonstrating stable wireless connectivity, consistent tag detection, and efficient power management.

4. RFID Tag Sticker

The RFID tag sticker serves as the primary identification element in the proposed smart border passing system. It is designed for attachment to vehicles crossing border checkpoints and provides a unique, tamper-resistant, and weatherproof identifier linked to the owner's registration record in the database.

4.1 Tag Design and Material

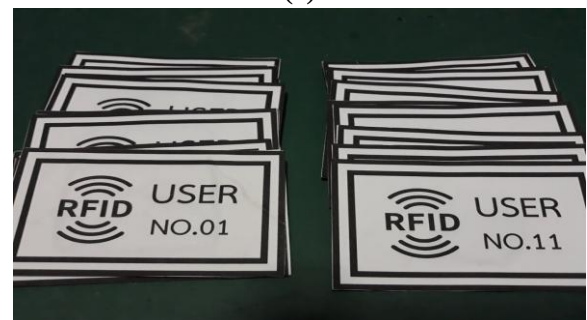
The RFID sticker tag used in this study is a passive UHF EPC-Gen2 (ISO-18000-6C) sticker incorporating a meandered aluminum dipole

antenna ($\approx 70 \times 15$ mm) printed on a PET roll-laminated substrate. The prototype utilized a commercially available tag due to cost and compatibility with the ESP32-UHF reader; however, a custom-designed antenna may be developed in future iterations to improve mounting performance on curved windshields. For large-scale deployment, roll-to-roll PET etching enables cost reduction from approximately 4 THB/unit in prototype quantities to 1.2-1.5 THB/unit when manufactured at $>100,000$ units. Tags may be adhered externally using automotive-grade adhesive or positioned at the inside corner of a windshield using removable low-tack adhesive, supporting quick disposal after vehicle return.

The tag's physical flexibility and small form factor enable installation on various locations such as windshields, doors, or rear panels. Once applied, any attempt to peel or remove the sticker will irreversibly damage its conductive layer, preventing reuse and thus ensuring anti-tampering integrity.



(a)



(b)

Figure 5 RFID tag sticker. (a) Internal structure (IC+antenna). (b) External view with adhesive backing.

4.2 Functional Characteristics

The RFID tag communicates passively with the handheld reader, meaning it does not require an internal power source. Instead, it is energized by

the electromagnetic field emitted from the reader's antenna. The tag's unique identifier (UID) is transmitted wirelessly to the reader, which verifies its authenticity through the cloud database.

The tag exhibits several advantageous characteristics for border checkpoint operations:

1. High durability: resistant to sunlight, dust, and moisture, ensuring long-term performance in outdoor environments.
2. Low cost: suitable for large-scale deployment across border checkpoints.
3. Reliable detection range: optimized for UHF operation, allowing consistent recognition within a few meters.
4. Reusability control: adhesive strength is calibrated to balance secure attachment and ease of replacement during re-registration.

The selection of UHF passive RFID technology provides an ideal balance between cost-effectiveness, reading distance, and operational stability, making it highly suitable for vehicular identification applications in smart border control environments.

5. Database Development

The database subsystem was developed to manage vehicle registration, verification, and return records associated with the RFID-based border passing process. The system employs MySQL as the primary database engine and phpMyAdmin as the web-based management interface. This configuration enables efficient creation, modification, and retrieval of records while supporting real-time communication with the handheld RFID reader through the cloud.

			id	uid	plate	owner	updated_at
☐				3	E1120209600015525670		2025-10-13 02:14:40
☐				4	E1120206510017355333		2025-10-13 02:14:40
☐				5	E1120206460018422086		2025-10-13 02:14:40
☐				6	E200A1B2C3D4E5F611223344		2025-10-13 02:14:40
☐				7	E2009F8E7D6C5B4A33CCBBAA		2025-10-13 02:14:40
☐				8	E20011223344AABCCDDDEE00		2025-10-13 02:14:40
☐				9	E200DEADBEEF001122334455		2025-10-13 02:14:40
☐				10	E200CAFEBABE010203040506		2025-10-13 02:14:40
☐				11	E2000A1B2C3D4E5F60718293		2025-10-13 02:14:40
☐				12	E20055AA55AA55AA55AA55AA		2025-10-13 02:14:40
☐				13	E200ABCDEF1234567890ABCD		2025-10-13 02:14:40
☐				14	E20013579BDF02468ACE1357		2025-10-13 02:14:40
☐				15	E200F0E1D2C3B4A596877869		2025-10-13 02:14:40
☐				16	E2000F1E2D3C4B5A69788776		2025-10-13 02:14:40
☐				17	E200AAAA5555FFFF00001111		2025-10-13 02:14:40
☐				18	E2001234ABCD5678EF901234		2025-10-13 02:14:40
☐				19	E200FACEFEEDC001D00D1234		2025-10-13 02:14:40
☐				20	E20076AB34CD12EF98BA5432		2025-10-13 02:14:40
☐				21	E20089ABCDEF0123456789AB		2025-10-13 02:14:40

Figure 6. Simulated vehicle user database implemented in MySQL (phpMyAdmin view).



5.1 Database Structure

The database was designed to store and manage essential vehicle and user information for identification and monitoring purposes. As illustrated in Figure 6, each record contains the following key fields:

- *id* - the sequential identifier of each record entry.
- *uid* - the unique RFID code read from the tag attached to a vehicle.
- *plate* - the vehicle's license plate number registered in the system.
- *owner* - the name of the vehicle's owner or driver.
- *updated_at* - the timestamp of the latest system update, automatically refreshed during authentication events.

All records are stored and synchronized in real time to the cloud database, allowing officers to perform registration and verification directly from the handheld RFID reader. The web-based dashboard additionally supports editing, deletion, and CSV/Excel export for administrative reporting. To support multi-location deployment, the database follows a centralized schema that enables simultaneous access from multiple border checkpoints, ensuring consistent information across the monitoring network.

The overall data handling workflow is summarized as follows: the reader transmits a detected *uid* to the server → the database queries the associated record → updates the status and timestamps → and synchronizes the result back to the dashboard. Example screenshots in this paper have been anonymized to prevent exposure of sensitive personal information such as license plates or driver names.

5.2 Operational Features

The system supports three operational functions, consist of registration, verification, and monitoring.

- During registration, officers input vehicle and owner details into the database while associating each record with a unique RFID tag.
- During verification, the reader scans the tag and queries the cloud database. If the UID matches an existing record, the system updates the

updated_at field and confirms successful authentication.

- For monitoring, the system automatically checks the duration of each vehicle's border pass. If the permitted period (e.g., 30 days) expires without a recorded return, the database generates an alert and exports a summary report in Excel format for administrative review.

This database design ensures data integrity, traceability, and easy scalability. It effectively supports the operation of the smart border passing system by providing real-time monitoring, automated record management, and reporting capability for cross-border vehicle control.

6. Experiment and Results

6.1 RFID Reading Accuracy

To evaluate the performance of the developed RFID reader, experiments were conducted to measure the tag detection accuracy at varying distances between the handheld reader and the RFID sticker tag. The purpose of this test was to determine the effective operational range of the device for real-world border checkpoint applications. The evaluation also aimed to verify the stability of wireless communication and the consistency of tag response under controlled environmental conditions.

The detection accuracy *A* of the RFID reader was evaluated using Equation (1) below

$$A = \frac{N_{\text{success}}}{N_{\text{total}}} \times 100\% \quad (3)$$

where N_{success} is the number of successful tag readings and N_{total} is the total number of read attempts at a given distance.

In addition, the standard deviation of the detection rate was calculated to evaluate reading stability across repeated trials, given in Equation (4)

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (4)$$

where x_i represents the accuracy at each distance and $\bar{x}$ is the mean accuracy value.

The experimental setup is illustrated in Figure 7. The RFID reader was placed on a flat surface, and a metric tape was used to precisely position the

RFID tag at different distances ranging from 0.1 m to 3.0 m, in 0.3 m increments. Each distance was tested with 100 independent reads to obtain statistically robust detection rates. The results were recorded based on successful detections (SUCCESS) and failed readings (FAIL), and the overall accuracy percentage was calculated accordingly, as reported in Table 1.

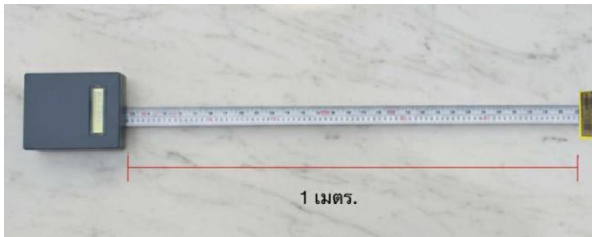


Figure 7 Distance measurement setup for RFID reading-range evaluation.

Table 1 RFID tag detection accuracy at different reading distances (100 reads per distance).

Distance (m)	Number of Tests	SUCCESS	FAIL	Accuracy (%)
0.1	100	100	0	100
0.3	100	100	0	100
0.6	100	100	0	100
0.9	100	100	0	100
1.2	100	100	0	100
1.5	100	100	0	100
1.8	100	100	0	100
2.0	100	92	8	92
2.5	100	66	34	66
3.0	100	0	100	0

The experimental results reveal that the RFID reader achieved 100% detection accuracy within the range of 0.1-1.8 meters. Beyond this distance, the detection rate gradually decreased to 92% at 2.0 meters and 66% at 2.5 meters, while no successful readings were obtained beyond 3.0 meters. The reduction in performance at longer distances is primarily attributed to signal attenuation and the limited gain of the compact antenna used in the handheld reader. Nevertheless, the observed effective range remains well-suited for field operations, ensuring reliable tag recognition without requiring close physical contact with the vehicle.

This indicates that the optimal operational range of the developed RFID reader is approximately 1.8 meters, which is adequate for field deployment at vehicle inspection checkpoints. Such a distance provides officers with sufficient working space and ensures reliable tag detection without requiring close contact with the vehicle. Furthermore, maintaining this range helps minimize signal interference between adjacent readers operating in multi-lane inspection areas. It enhances user safety and convenience by allowing smooth vehicle flow during scanning operations.

Overall, the experiment confirms that the proposed RFID reader delivers high accuracy, stable response, and suitable range for practical applications in smart border passing systems. The obtained results also validate the effectiveness of the hardware design and its readiness for real-world deployment.



Figure 8 Vehicle identification durability test - examples of tag placement on windshields.

6.2 Vehicle Identification Durability Test

A long-term field experiment was conducted to evaluate the durability and stability of RFID tag identification when installed on real vehicles. As illustrated in Figure 8, ten vehicles were equipped with RFID sticker tags, each installed at ten different points on their windshields. This experimental setup was chosen due to its practical feasibility-testing with a large number of vehicles (e.g., 100) would be logistically challenging for



both installation and continuous monitoring. The vehicles remained outdoors in standard roadside parking conditions and were naturally exposed to sunlight, heat (approximately 32-35 °C daytime

temperature), dust accumulation, and intermittent rainfall throughout the observation period. These real environmental conditions provide practical stress factors similar to those expected at border checkpoint deployments.

Table 2 Vehicle identification results per period (10 vehicles × 10 tags each).

Vehicle No.	Period (Day)								
	Day1	Day2	Day3	Day5	Day7	Day10	Day15	Day20	Day30
Vehicle No.1	10	10	10	10	10	10	10	10	10
Vehicle No.2	10	10	10	10	10	10	10	10	10
Vehicle No.3	10	10	10	10	10	10	10	9	9
Vehicle No.4	10	10	10	10	10	10	10	10	10
Vehicle No.5	10	10	10	10	10	10	10	10	10
Vehicle No.6	10	10	10	10	10	10	10	10	10
Vehicle No.7	10	10	10	10	10	9	9	9	9
Vehicle No.8	10	10	10	10	10	10	10	10	10
Vehicle No.9	10	10	10	10	10	9	9	9	9
Vehicle No.10	10	10	10	10	10	10	10	10	10
Total	100	100	100	100	100	98	98	97	97
% of success	100	100	100	100	100	98	98	97	97

The RFID reader was used to scan each vehicle's tag periodically on Day 1, 2, 3, 5, 7, 10, 15, 20, and 30 after installation to determine whether the tag could still be identified successfully. The summarized results are shown in Table 2.

6.3 Result Discussion

The experimental results show that during the first seven days, all RFID sticker tags were successfully detected with a 100% identification rate, confirming excellent initial adhesion and signal stability. After Day 10, a slight reduction in the success rate to 98-97% was observed toward the end of the 30-day test period.

Importantly, further inspection revealed that all unreadable cases were caused by sticker detachment, not by device malfunction. For the stickers that remained properly attached to the vehicle surfaces, the RFID reader maintained 100% reading accuracy throughout the entire period. This finding verifies the high reliability and consistent performance of the developed RFID reader hardware.

However, the experiment also highlights a practical consideration regarding adhesive selection for tag assembly. If the adhesive layer is too weak, the tag may detach under outdoor

conditions such as heat, rain, or car washing. Conversely, using an overly strong adhesive can make sticker removal difficult and may damage the vehicle surface when the tag is replaced or reissued. Therefore, selecting a balanced adhesive formulation-strong enough to resist environmental effects but still removable without residue-is critical for long-term deployment in smart border passing systems. As an alternative installation method, the tag may also be applied at an inside corner of the vehicle windshield, where a lighter, removable adhesive can be used without risking detachment. This allows users to peel off the sticker conveniently after authentication and database reset are completed.

Overall, these findings confirm that the proposed RFID reader and tag combination provides 100% functional reliability, while future optimization should focus on improving adhesive durability and environmental resistance for extended field use. In addition, further refinement of material composition and protective coating could enhance long-term tag performance under varying climatic and operational conditions.

6.4 Dashboard System Demonstration

A demonstration test was conducted to verify the functionality of the cloud-based dashboard used in the smart border passing system. As shown in Figure 9, the web interface displays real-time

vehicle transaction data within a 30-day observation period. Each record includes the RFID tag UID, vehicle plate number, owner name, and status log consisting of ENTRY, EXIT, and TIMEOUT events.

Home User Data Registration Read Tag ID Dashboard

Dashboard (30 วันล่าสุด)

UID: กรณ UID เพื่อกรอง		ช่วงวัน: 30	Filter					
ID	UID	ทะเบียน	เจ้าของ	Status	Entry	Due	Exit	นาที
57	E1120206510017355333			ENTRY	2025-10-29 04:52:50	2025-10-29 05:07:50		
56	TEST12345			TIMEOUT	2025-10-20 01:21:21	2025-10-20 01:24:21	2025-10-20 01:27:11	5.00
55	E1120209600015525670			EXIT	2025-10-20 00:39:03	2025-10-20 00:49:03	2025-10-20 00:39:03	0.00
54	E1120209600015525670			EXIT	2025-10-19 19:29:20	2025-10-19 19:39:20	2025-10-19 19:29:20	0.00
53	E1120209600015525670			EXIT	2025-10-19 19:20:52	2025-10-19 21:20:52	2025-10-19 19:20:52	0.00
52					2025-10-19 19:04:48	2025-10-19 21:04:48		
51	E1120206460018422086			ENTRY	2025-10-19 23:29:23			
50	E20011223344AABCCDDE00			TIMEOUT	2025-10-19 23:21:52		2025-10-19 23:24:47	120.00
49	E1120206460018422086			TIMEOUT	2025-10-13 22:25:27		2025-10-14 02:33:30	248.05
48	E1120206510017355333			TIMEOUT	2025-10-13 22:25:21		2025-10-14 02:33:41	120.00
47	E1120209600015525670			TIMEOUT	2025-10-13 22:25:16		2025-10-14 02:33:50	248.57

Figure 9. Example of system testing via the web-based dashboard showing ENTRY, EXIT, and TIMEOUT events.

When a vehicle passes through the checkpoint, the system automatically records an ENTRY event. Upon return within the authorized period, an EXIT event is logged, updating the database and resetting the record status. Conversely, if a vehicle does not return before the specified due date, the system generates a TIMEOUT alert, which is displayed in red on the dashboard and prompts administrative review.

This feature is particularly valuable for monitoring cross-border traffic behavior, such as identifying potential unauthorized crossings or preventing vehicle theft across national boundaries. Furthermore, the dashboard allows officers to filter transactions by UID or date range and export detailed reports for further analysis.

7. Conclusion and Future Work

This research presented the RFID-driven smart border passing architecture, integrating hardware, software, and cloud-based data management to enhance the efficiency and security of vehicle inspection at border checkpoints. The developed framework demonstrates how IoT-enabled identification and centralized data sharing can streamline operations and reduce verification errors.

The system architecture was composed of three main components: a portable RFID reader, a UHF RFID tag sticker, and a cloud database with a web-based dashboard. The prototype reader demonstrated 100% tag detection accuracy within an operational range of up to 1.8 meters, providing



a suitable working distance for field officers. In addition, the long-term durability test confirmed that all RFID tags that remained properly attached maintained 100% identification success throughout 30 days, with failed readings attributed solely to sticker detachment rather than hardware malfunction.

The developed dashboard interface successfully displayed real-time vehicle entry, exit, and timeout events, serving as an effective administrative tool for tracking cross-border movements. This capability supports not only faster verification at checkpoints but also enhances monitoring and enforcement against unauthorized crossings or vehicle trafficking incidents.

Furthermore, the low-cost nature of the prototype-approximately 4,000 THB for the handheld reader and around 4 THB per sticker tag-indicates strong cost-effectiveness and practical scalability for regional or nationwide deployment, especially in resource-constrained border provinces.

Future development of the system will focus on several directions:

1. Improving tag adhesion materials-optimizing adhesive formulations to balance long-term durability and ease of removal.
2. Expanding communication reliability-integrating LTE or 5G connectivity to extend coverage beyond local Wi-Fi range.
3. Enhancing data analytics - implementing anomaly detection algorithms to automatically flag suspicious traffic behavior.
4. Integrating biometric or QR-based verification for dual authentication, improving the identity assurance of both driver and vehicle.

In conclusion, the proposed smart border passing system demonstrates a practical, cost-effective, and scalable solution for modern border management. With continued refinement and field testing, it has strong potential to be deployed across regional checkpoints as part of a national intelligent transportation and security infrastructure. The outcomes of this study also provide a foundation for future integration with advanced analytics and AI-driven decision support

to enhance operational efficiency and situational awareness.

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