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Talenta pro patria et humanitate

Proceeding

ECoGREEN International Conference

Beyond Ecological Literacy:

From Knowledge to Actionable Practices for Sustainability

Semarang, 21 - 22 January 2026

Soegijapranata Catholic University

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UNIVERSITAS KATOLIK SOEGIJAPRANATA

PROCEEDING
ECOGREEN INTERNATIONAL CONFERENCE

Theme

Beyond Ecological Literacy: From Knowledge to Actionable Practices for Sustainability

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FOREWORD

ECoGREEN INTERNATIONAL CONFERENCE Committee

The International Conference on “Beyond Ecological Literacy: From Knowledge to Actionable Practices for Sustainability” was the output of ECoGREEN Consortium that brings together diverse academic traditions and regional perspectives from Parahyangan Catholic University, Soegijapranata Catholic University, Universitas Katolik Atma Jaya Indonesia, Trisakti University, University of Surabaya, Wahid Hasyim University, Wageningen University & Research, and Hasselt University.

These two-days conference were held in Soegijapranata Catholic University, attracted 75 articles to be presented either offline or online. Following the presentations, there are three options that were being offered by the committee for publication. The presented papers can be sent to our collaborative journals, after being curated by the journal’s editors, namely Journal of Natural Resources and Environmental Management (Q3), and Journal of Environmental Health (Q4). The third option is published in our conference proceeding. The rest depends on the presenter to where they would be published.

In this proceeding, there are nine articles that have been curated by the committee. The papers examine pathways for translating ecological understanding into actionable practices across education, governance, law, business, technology, and civil society.

These nine articles aim to serve scholars, practitioners, policymakers, and students as a catalyst for deeper collaboration and practical innovation. By advancing beyond awareness toward implementation, experimentation, and measurable impact, the ECoGREEN Consortium affirms the pivotal role of higher education institutions in shaping sustainable futures.

These papers showed the academic contributions and at the same time provided real field experiences that inviting the global community to reimagine sustainability not solely as knowledge to be acquired but as practice to be enacted. It is anticipated that the publication of these collected papers will reach a wide audience and inspire further engagement. Keep it simple and sustain, happy reading.

Benny D. Setianto
Chairperson of the Committee

ABOUT THE CONFERENCE

ECoGREEN INTERNATIONAL CONFERENCE
Beyond Ecological Literacy: From Knowledge to Actionable Practices for Sustainability

Background

The global sustainability movement has reached a critical juncture. While ecological literacy has become a foundational goal in education and policy, the transition from knowledge to meaningful action remains elusive. Around the world, individuals and institutions are increasingly aware of environmental challenges—yet awareness alone has not translated into the scale of change required to address climate instability, biodiversity collapse, and resource inequity.

In recent decades, the concept of *ecological literacy*—the understanding of natural systems and our role within them—has gained traction across educational institutions, policy circles, and civil society. Coined by David Orr and further developed by Fritjof Capra, ecological literacy emphasizes the need for individuals and communities to comprehend the principles of sustainability and the interconnectedness of life.

However, despite growing awareness and widespread dissemination of ecological knowledge, the global response to environmental challenges remains fragmented and insufficient. Climate change, biodiversity loss, pollution, and resource depletion continue to escalate, revealing a critical gap between knowing and doing.

This conference emerges from the urgent need to bridge that gap—to move beyond ecological literacy as a theoretical framework and toward actionable, context-sensitive practices that drive real-world sustainability. It recognizes that knowledge alone does not catalyze change; transformation requires systems thinking, cultural shifts, policy innovation, and community empowerment.

This international conference, *Beyond Ecological Literacy: From Knowledge to Actionable Practices for Sustainability*, is designed to confront this disconnect head-on. It recognizes that ecological literacy must evolve from a cognitive framework into a practical, participatory, and transformative force. The conference seeks to explore how ecological understanding can be operationalized—through curriculum design, community engagement, policy reform, and technological innovation—to foster resilient, regenerative societies.

The conference also responds to a global call for interdisciplinary collaboration. Sustainability is not the domain of environmental science alone—it intersects with economics, education, technology, indigenous knowledge, urban planning, and ethics. By convening diverse voices and perspectives, the event aims to foster a holistic approach to sustainability that is both inclusive and pragmatic.

Indonesia, as the host country, offers a compelling backdrop. With its rich biodiversity, vibrant indigenous cultures, and pressing environmental challenges, it exemplifies the tensions and opportunities of sustainability in the Global South. Hosting the conference in Java—a hub of ecological tourism and cultural heritage—underscores the importance of place-based solutions and community-led innovation.

In essence, *Beyond Ecological Literacy* is a call to action: to reimagine sustainability not as a distant ideal, but as a lived, shared responsibility. It invites participants to co-create pathways from knowledge to practice, from awareness to agency, and from ecological literacy to ecological leadership.

The rationale for this gathering is grounded in three urgent realities:

- **The limits of awareness**: While ecological education has expanded, behavioural and systemic change lag behind. We must explore why knowledge often fails to inspire action and how to overcome these barriers.
- **The need for integration**: Sustainability solutions must be interdisciplinary, combining science, ethics, economics, and culture. This conference will serve as a platform for cross-sector dialogue and collaboration.
- **The power of place-based action**: Global strategies must be adaptable to local contexts. By hosting the conference in Indonesia—a nation rich in biodiversity and cultural heritage—we highlight the importance of indigenous wisdom, community led innovation, and regional leadership.

Ultimately, this conference is not just a forum for discussion—it is a launchpad for action. It invites participants to co-create strategies, share tools, and build networks that will continue to drive sustainability long after the event concludes.

By convening thought leaders, innovators, educators, policymakers, and practitioners from diverse sectors and regions, the conference aims to:

- Bridge the gap between ecological theory and sustainable practice • Showcase innovative models for embedding sustainability in education, governance, and business
- Foster cross-sector collaboration for systemic change
- Empower communities and institutions to implement localized sustainability solutions
- Develop a global action framework for post-conference implementation

Keynote Speakers

- Dr. Rebecca Meckelburg: Murdoch University Australia
- Prof. Dr. Y. Budi Widianarko – Soegijapranata Catholic University
- Prof. Dr. Tom Kuppens: Hasselt University Belgium
- Dr. Rippin Karla: University of Westminser United Kingdom
- Prof. Jein-Wen, Chen, Ph.D.: Cheng Shiu University Taiwan

- Dr. Ansje Lohr: Open University Netherland
- Dr. Renate Wesselink: Wageningen University Netherland
- Mr. Aryono Bambang Ardhyo: Director of Friesland Campina Kievit Indonesia

Paralel Session Topics

1. Education for sustainability
2. Traditional Ecological Knowledge and Wisdom
3. Environmental Policy and Governance
4. ESG and Sustainability Reporting
5. MSMEs and Sustainability
6. Design for sustainability
7. Technology and engineering for Sustainability
8. Sustainable Energy
9. Water sustainability
10. Sustainable food system

Detailed Schedule

Wednesday, 21 January 2026

Time	Activity	Notes
08:00 - 08:30	Registration	
08:30 - 09:00	Coffee Break	
09:00 - 09:10	Opening MC	
09:10 - 09:45	Opening speeches	*SCU Rector, Ecogreen Leader, Chairperson, 10 min each*
09:45 - 09:55	Opening performance	*Kembang Taru (2 person)*
09:55- 10:00	MC Invite Moderator	
10:00 - 10:30	Plenary Session : Dr. Rebecca Meckelburg	*Topic : Sustainable Entrepeneuship Pedagogy ONLINE*
10:30 - 11:00	Plenary Session : Prof. Budi Widianarko, Souvenir presentation, MC closing	*Topic : Human-centered development for sustainability OFFLINE*
11:00 - 11:15	Movement to parallel session	
11:15 - 12:15	Parallel session (1)	
12:15 - 13:00	Lunch	
13:00 - 13:10	Movement to Plenary room	
13:10 - 13:15	Opening by MC,	
13:15 - 13:45	Plenary Session : Dr. Tom Kuppen	*Topic : SFSC & Sustainable Food System*
13:45 - 14:15	Plenary Session : Dr. Ripin Kalra	*Topic : Grey Water Management*
14:15 - 14:20	MC Closing	
14:20 - 14:30	Movement	
14:30 - 15:00	Coffee Break	
15:15 - 16:30	Parallel Session (2)	
17:00 - 20:00	Social Evening	

Thursday, 22 January 2026

Time	Activity	Notes
08:00 - 08:30	Registration	
08:30 - 09:30	Parallel Session (3)	
09:30 - 09:45	Coffee Break	
09:45 - 10:00	Movement	
10:00 - 10:15	MC opening + performance (Gratia Voice) + MC invites Moderator	
10:15 - 10:45	Plenary Session : Prof. Chen	*Topic : "Solving marine-litter and plasticpollution: A multi-faceted approach from a Global Plastics Treaty to Local Action"*
10:45 - 11:15	Plenary Session : Dr. Ansje	*Topic : "The Strategic Importance of Environmental Laboratory in Sustainable Development"*
11:15 - 11:45	Plenary Session : Pak Aryo (3)	*Topic : Industry Practices*
11:45 - 12:15	Plenary Session : Dr. Renate	
12:15 - 12:20	Souvenir Presentation	
12:20 - 12:45	Closing Ceremony + Awarding	*Awarding = Best presenter 1,2,3. Closing speech : Ketua panitia (Benny) dan Ketua Konsortium (Joanna)*
12:45 - 13:30	Lunch	
13:30 – 16.00	City Tours	

Consortium Member

1. Universitas Parahyangan
2. Universitas Katolik Soegijapranata
3. Universitas Katolik Atma Jaya Indonesia
4. Universitas Trisakti
5. Universitas Surabaya
6. Universitas Wahid Hasyim
7. The University of Hasselt – Belgium
8. Wageningen University of Research

Venue

Soegijapranata Catholic University – BSB Campus
Jalan RM. Hadisoebeno No. 1
Semarang

TABLE OF CONTENT

Air Quality Prediction Using Internet of Things Data and Machine Learning Algorithms: A Case Study in Urban Environments

Sub-Theme: *Technology and Engineering for Sustainability*

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ABSTRACT

Urban air pollution is a critical challenge in densely populated cities such as Jakarta, where timely and accurate air-quality predictions are needed to reduce health risks and support environmental planning. This study develops an IoT- and machine-learning–based system to predict PM2.5 levels in the Universitas Trisakti area, Jakarta. Historical data collected from 2021–2024 by PT Nafas Indonesia IoT sensors included PM1, PM2.5, PM10, NO_2, O_3, temperature, humidity, and air pressure. The dataset was preprocessed through missing-value interpolation, outlier removal, normalization, and labeling, then split into 80% training and 20% testing sets. Four models were evaluated: Decision Tree, Naive Bayes, Random Forest, and Long Short-Term Memory (LSTM). Results indicate that Random Forest delivered the best overall performance (RMSE 0.55 µg/m³; accuracy 94.56%), followed by LSTM (RMSE 0.72 µg/m³; accuracy 91.78%). The selected model was deployed as a backend service using Flask and hosted on the Railway platform. The proposed system provides a scalable approach for urban air-quality monitoring and can support real-time pollution alerts and smart environmental management to improve public health outcomes.

Keywords: *Air Quality, Internet of Things, Machine Learning, PM2.5, Random Forest*

INTRODUCTION

Air pollution remains a major urban environmental challenge, driven by emissions from transportation, industry, and household activities. According to the WHO Global Air Quality Guidelines, exposure to fine particulate matter (PM2.5) is associated with increased health risks, which motivates continuous monitoring and short-term forecasting in densely populated cities (World Health Organization, 2021).

Beyond direct health impacts, air pollution is increasingly discussed in the broader sustainability context, including links with urbanization patterns, energy use, and plastic-related emissions across life cycles (OECD, 2022). The World Air Quality Report also

highlights persistent PM2.5 exposure in many urban regions, motivating local monitoring and forecasting efforts to inform mitigation actions (IQAir, 2024).

In Jakarta, air quality can deteriorate during certain periods, with elevated PM2.5 levels reported by national monitoring and public information portals. To communicate air quality to the public and support mitigation actions, the Air Quality Index (AQI) is commonly used as an interpretable indicator of health-related air pollution levels (Badan Meteorologi, Klimatologi, dan Geofisika (BMKG), 2024) (U.S. Environmental Protection Agency, 2014).

Machine learning has been widely adopted for short-term air quality prediction because it can model nonlinear relationships between meteorological variables and pollutant concentrations. Common approaches include ensemble methods (e.g., Random Forests (Breiman, 2001) and Gradient Boosting (Friedman, 2001)), kernel-based methods such as Support Vector Machines (Cortes & Vapnik, 1995), and deep learning models such as Long Short-Term Memory (LSTM) networks for sequence modeling (Hochreiter & Schmidhuber, 1997).

This study aims to design an IoT-based air quality prediction system focused on estimating PM2.5 concentrations in the Universitas Trisakti area, Jakarta. Historical data collected from 2021 to 2024 are processed and analyzed using multiple machine learning algorithms to evaluate their predictive performance. The most accurate model is integrated into a backend web application, simulating a real-time prediction service. The outcomes of this research are expected to contribute to the development of intelligent environmental monitoring systems, support early warning mechanisms, and inform urban policy interventions for better air quality management.

MATERIALS AND METHODS

This study adopted a quantitative experimental methodology, integrating Internet of Things (IoT)-based air quality data with machine learning techniques to construct a predictive system for PM2.5 concentrations in urban areas. The methodology consisted of six main stages: data collection, preprocessing, model development, model evaluation, system deployment, and analysis. Each stage was systematically designed to ensure that the model produced accurate, reliable, and scalable results.

Preprocessing methods

Outlier handling and missing-value treatment were performed prior to model training to improve robustness. Feature scaling was applied (min-max or z-score normalization depending on the model requirements). Time features (hour, day-of-week, and seasonality indicators) were derived to capture temporal patterns in AQI. A rolling-window strategy was used to create supervised learning samples for short-term forecasting.

Research Design

The research utilized a supervised learning approach, where input variables (PM1, PM2.5, PM10, NO_2, O_3, temperature, humidity, pressure) were used to predict PM2.5 concentrations. The focus was on comparing the predictive performance of various algorithms using real-world

data from a localized urban sensor. The study also emphasized the integration of the best-performing model into a backend system that could potentially support a real-time web-based dashboard for urban air quality monitoring (U.S. Environmental Protection Agency, 2024).

Data Source and Collection

Air quality data were collected from IoT sensors provided by Nafas Indonesia, installed at Plaza Universitas Trisakti, West Jakarta. The sensors recorded pollutant concentrations and meteorological parameters with high temporal resolution. The dataset spans over three years, from September 2021 to October 2024, and includes daily averages of:

1. Particulate Matter: PM1, PM2.5, PM10
2. Gases: Nitrogen Dioxide (NO_2), Ozone (O_3)
3. Weather parameters: Temperature, Humidity, Atmospheric Pressure

The data were retrieved through the Nafas cloud API and then converted into CSV format for offline analysis. The comprehensive time series dataset allowed the identification of seasonal trends, diurnal variations, and pollution spikes commonly found in urban environments.

Implementation was carried out in Python using scikit-learn (Pedregosa et al., 2011) for classical machine-learning models, while deep learning experiments used TensorFlow (Abadi et al., 2016) with the Keras API (Chollet et al., 2015).

System Architecture

Figure 1 summarizes the end-to-end pipeline used in this study: (i) IoT sensors collect air quality and meteorological variables at the edge, (ii) measurements are transmitted to cloud storage and backend services for preprocessing and feature preparation, and (iii) prediction models are trained and evaluated to support analytics and visualization for decision-making and public communication. The Air Quality Index (AQI) concept is referenced for communicating health risk levels. (U.S. Environmental Protection Agency, 2014).

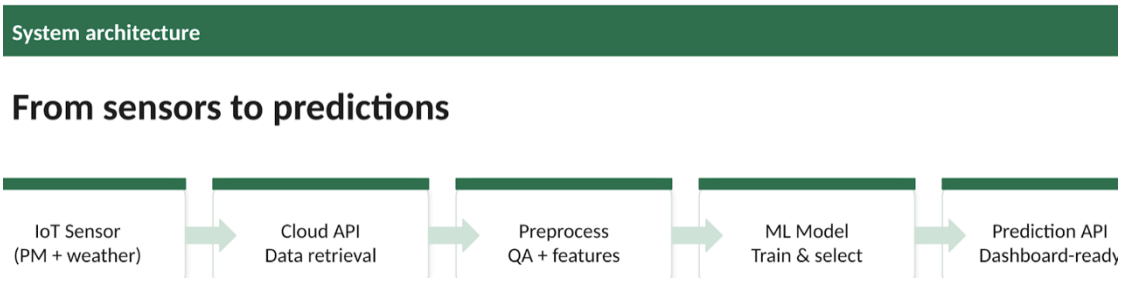

Figure 1. End-to-end IoT-to-ML pipeline for air quality prediction

Preprocessing Data

Effective preprocessing is crucial to ensure model reliability. The following steps were taken:

1. Handling Missing Values:

   Gaps in the data due to sensor downtime or communication failures were addressed using linear interpolation techniques. This approach preserves trend continuity in time-series datasets.

2. Outlier Detection and Removal

   Outliers were identified using statistical techniques such as z-score thresholding. Values beyond ±3 standard deviations were removed to prevent distortion in training.

3. Normalization

   Numerical input variables were scaled to a range of 0 to 1 using Min-Max normalization. This step ensures that features with larger numeric ranges (e.g., pressure) do not dominate model learning over smaller scale features (e.g., NO_2).

4. Labelling and Classification

   PM2.5 values were categorized into air-quality levels using widely adopted Air Quality Index (AQI) breakpoints (e.g., Good, Moderate, Unhealthy for Sensitive Groups, Unhealthy). This conversion enabled classification models (e.g., Naive Bayes and Decision Tree) to be evaluated alongside regression and time-series models (U.S. Environmental Protection Agency, 2014).

The dataset was then split into training (80%) and testing (20%) sets using stratified sampling to preserve class distribution and ensure balanced learning.

5. Model Development

Four different machine learning algorithms were implemented:

a. Decision Tree: A rule-based classifier that splits data based on feature thresholds. It is interpretable and fast but prone to overfitting.
b. Naive Bayes: A probabilistic model suitable for categorical data and efficient for small datasets. It assumes independence between features.
c. Random Forest: An ensemble method of multiple Decision Trees that reduces variance and increases robustness. Known for its accuracy and ability to handle nonlinear relationships (Breiman, 2001).
d. Long Short-Term Memory (LSTM): A type of Recurrent Neural Network (RNN) capable of learning long-term dependencies in sequential data, making it ideal for time-series prediction (Hochreiter & Schmidhuber, 1997).

The models were developed using Python 3.10 with scikit-learn (Pedregosa et al., 2011) for classical machine learning and Keras/TensorFlow (Chollet et al., 2015; Abadi et al.,

2016) for neural-network training. Hyperparameter tuning was performed using grid search and cross-validation. For LSTM, training used the Adam optimizer (Kingma & Ba, 2014).

6. Model Evaluation

Model performance was assessed using:

a. Accuracy (for classification models): Measures the percentage of correct predictions over total samples.
b. Root Mean Squared Error (RMSE) (for regression models): Captures the average magnitude of prediction error in µg/m³.
c. Confusion Matrix: Used to evaluate classification performance across predicted versus actual air quality classes.
d. R^2 Score: Applied for regression models to evaluate the proportion of variance explained by the model.

The evaluation results show that the Random Forest regressor achieved the best overall performance for PM2.5 prediction, with MAE = 0.39 µg/m³, RMSE = 0.55 µg/m³, and R^2 = 1.000. For deep learning, the LSTM model reached MAE = 0.65 µg/m³, RMSE = 0.72 µg/m³, and R^2 = 0.995. In addition, a Naive Bayes classifier achieved 93.2% classification accuracy on the label-based task (Hochreiter & Schmidhuber, 1997).

RESULTS AND DISCUSSION

This section presents the performance outcomes of the four implemented machine learning algorithms—Decision Tree, Naive Bayes, Random Forest, and Long Short-Term Memory (LSTM)—in predicting PM2.5 concentrations using IoT sensor data. The results are analyzed quantitatively based on accuracy, RMSE, and R^2 score, and qualitatively in terms of each model's suitability, generalizability, and potential for deployment in real-world environments (Hochreiter & Schmidhuber, 1997).

Model Performance Evaluation

All four models were trained on an 80% subset of the dataset and tested on the remaining 20%. The summary of performance metrics is provided in Tables 1 and 2.

Table 1. Regression model performance (MAE, RMSE, and R^2)

Model	MAE (µg/m³)	RMSE (µg/m³)	R^2 Score
Decision Tree Regressor	0.50	0.82	0.998
Random Forest	0.39	0.55	1.000
LSTM	0.65	0.72	0.995

Table 2. Classification performance (accuracy)

Model	Accuracy
Naive Bayes Classifier	93.2%
LSTM	91.78%

From the results above, the Random Forest model consistently outperformed the others across all evaluation metrics. Its ensemble structure, which aggregates multiple

decision trees and introduces randomness, helps in reducing variance and improving predictive accuracy. Moreover, the R^2 score of 1.000 indicates perfect variance of the test data, which reflects the model's robustness (Breiman, 2001).

The LSTM model also demonstrated strong performance, especially considering its ability to capture temporal trends. Although it slightly underperformed Random Forest in terms of accuracy and RMSE, it remains a viable option for time-dependent forecasts, especially for multi-step or long-horizon predictions (Hochreiter & Schmidhuber, 1997).

Meanwhile, Naive Bayes and Decision Tree produced relatively lower accuracy and higher error rates. The simplicity of these models, especially the assumption of feature independence in Naive Bayes, limited their performance in a dataset with highly correlated environmental variables.

Confusion Matrix Analysis

A confusion matrix was used to analyze the classification performance of the models, particularly in categorizing PM2.5 into "Good," "Moderate," "Unhealthy for Sensitive Groups," and "Unhealthy" classes.

The Random Forest confusion matrix demonstrated minimal misclassifications, especially between adjacent categories such as "Moderate" and "Unhealthy for Sensitive Groups." The model showed high precision and recall in all classes, indicating its capability to distinguish subtle differences in PM2.5 concentrations (Breiman, 2001).

In contrast, Naive Bayes tended to misclassify cases in the "Moderate" and "Unhealthy" range due to overlapping distributions and its probabilistic assumptions, which are less effective when feature interactions are strong.

Discussion and Interpretation

The findings confirm that Random Forest is well-suited for air quality prediction tasks using IoT-based sensor data due to its capacity to manage nonlinear relationships, noise, and feature interactions. Its strong performance without overfitting suggests the model generalizes well across unseen data points, which is critical for environmental applications where external conditions frequently vary (Breiman, 2001).

The results also validate the effectiveness of using open-source, low-cost sensors combined with machine learning to generate high-value environmental predictions. This has practical implications for smart city development, enabling early warning systems, citizen engagement through apps, and more localized pollution interventions.

The LSTM model, while slightly less accurate, remains highly relevant for future work involving sequential multi-day prediction. Its temporal memory structure allows modeling of pollution trends over time, which could be beneficial for predicting pollution build-up during long dry seasons or post-holiday traffic surges (Hochreiter & Schmidhuber, 1997).

In contrast, the performance limitations of Naive Bayes and Decision Tree highlight the need for richer model structures in environments with complex, correlated variables such as meteorological factors and pollution sources.

Limitations

Despite promising results, this study has several limitations:

1. The dataset is limited to a single sensor location in West Jakarta, which may not generalize to different urban or rural contexts.

2. The meteorological data used were limited to basic weather parameters; additional variables like wind speed, rainfall, and solar radiation could improve model robustness.

CONCLUSION

This study demonstrated that IoT sensor data combined with machine-learning models can provide accurate short-term PM2.5 prediction for an urban monitoring point in Jakarta. Among the evaluated models, Random Forest achieved the best overall regression performance and offers a practical balance between accuracy and deployment simplicity, while LSTM remains promising for future multi-step forecasting that leverages temporal dependencies. Future work should extend the dataset to multiple locations and incorporate additional meteorological features to improve generalizability.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization and methodology: R.R. and H.C.; software and experiments: R.R.; data curation: R.R. and I.K.; writing—original draft: R.R.; writing—review and editing: H.C., H.Y., E.D., Y.K.N., and I.K. All authors approved the final manuscript.

ETHICAL STATEMENT

Not applicable. This study used environmental sensor data and did not involve human or animal subjects.

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Food Ethics and Biological Alignment : Rethinking Human Health In A Contaminated World

Sub-Theme: *Education for Sustainability*

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ABSTRACT

We are living in the Anthropocene, an era in which human activity profoundly shapes food systems and environmental conditions. While advances in agriculture and food technology have improved food availability, they have also intensified chronic exposure to chemical contaminants, including heavy metals, synthetic pesticides, and food contact chemicals. Conventional toxicological risk assessment emphasizes exposure avoidance and regulatory thresholds, effectively preventing acute toxicity but offering limited insight into health outcomes associated with chronic, low-dose, and cumulative exposure. This literature review synthesizes current evidence on chronic food-related chemical exposure through the framework of biological alignment. Cadmium, glyphosate, and bisphenol A were selected as representative toxicants reflecting cumulative accumulation, regulatory-permitted exposure, and dependence on individual detoxification capacity within modern food systems. The reviewed evidence indicates that risk under chronic exposure is shaped not only by external dose but also by internal biological mediation, including detoxification efficiency, oxidative stress regulation, endocrine sensitivity, nutritional status, and metabolic health. Biomonitoring studies consistently demonstrate measurable internal exposure across populations despite compliance with regulatory thresholds, highlighting substantial interindividual variability in biological response. Integrating biological alignment with conventional exposure-based assessment may strengthen public health protection by accounting for physiological variability and adaptive capacity while remaining consistent with regulatory frameworks and food system governance.

Keywords: *Anthropocene, Biological Alignment, Food Toxicology, Chronic Exposure, Detoxification*

INTRODUCTION

Human Health in the Anthropocene Era

Human health is increasingly shaped by environmental conditions created through modern industrial and agricultural activities. Large-scale food production, intensified farming, and widespread chemical use have improved food availability, but have also introduced persistent

chemical contaminants into everyday diets. Bouida et al. (2022) reported that heavy metals and synthetic compounds, are now commonly detected across multiple food categories. This indicates dietary exposure has become continuous rather than incidental.

Unlike earlier toxicological concerns that focused mainly on acute poisoning events, current exposure patterns are predominantly chronic and low-dose. Suhani et al. (2021) highlighted that long-term dietary intake represents one of the most consistent exposure pathways for environmental toxicants. Particularly when contaminants are embedded within staple foods. As a result, food consumption has emerged as a primary route, through which chemical stressors enter the human body on a daily basis.

Cadmium provides a clear example of this shift. Genchi et al. (2020) demonstrated that although naturally occurring, cadmium becomes concentrated in food crops through fertilizer application, industrial emissions, and soil contamination. Qing et al. (2023) further showed that dietary intake alone can lead to cumulative cadmium exposure approaching regulatory limits in certain populations, even in the absence of occupational exposure. These findings suggest that chronic intake, instead of isolated exposure events, drives toxicological risk for many food-related contaminants.

Similar patterns are observed for anthropogenic compounds such as glyphosate and bisphenol A (BPA). Gillezeau et al. (2019) found that glyphosate residues are frequently detected in cereals and processed foods, resulting in repeated low-level exposure across the lifespan. EFSA (2023) also reported that food contact materials remain a significant source of exposure, particularly through canned and packaged products, despite regulatory restrictions and reformulation efforts.

This exposure landscape challenges the assumption that human health can be protected through avoidance of contaminants only. Complete avoidance seems unrealistic within modern food systems, especially for widely used agricultural chemicals and packaging materials. Instead of implying ethical acceptance of contamination, this reality underscores the need to understand how biological systems respond to unavoidable chemical exposure.

Recognizing exposure as an ongoing condition shifts the focus of toxicological interpretation. Health outcomes cannot be explained by external dose alone, but must also account for internal physiological processes that have impacts on absorption, detoxification, and tissue response. Understanding these biological factors is essential for interpreting toxicological risk under real-world dietary exposure conditions.

Current Paradigms in Toxicological Risk Management

Toxicological risk management in food safety is primarily based on exposure-centered assessment models. Regulatory agencies including EFSA (2015) establish safety thresholds such as Acceptable Daily Intake (ADI), Tolerable Weekly Intake (TWI) , and No Observed Adverse Effect Levels (NOAEL) to define limits that are considered protective for human health. These benchmarks play an essential role in guiding policy decisions, food monitoring programs, and consumer protection strategies.

This approach has been effective in reducing acute toxicity and preventing high-dose exposure events. Regulatory evaluations focus on identifying critical toxicity endpoints and estimating exposure levels across populations to ensure that intake remains below established thresholds (EPA, 2020). As a result, exposure reduction has become the dominant strategy for managing chemical risks in food systems.

Cadmium shows how this regulatory framework is applied in practice. Exposure limits for cadmium are largely derived from renal toxicity endpoints, with benchmark dose modeling used to estimate intake levels associated with kidney damage (Nogawa et al., 2021). These limits are designed to prevent clinically apparent toxicity and irreversible organ injury under typical dietary conditions.

Glyphosate has undergone a similar regulatory process. Risk assessments have focused on toxicological data from animal studies, exposure modeling, and epidemiological evidence to determine acceptable intake levels for consumers (EFSA, 2023). These evaluations emphasize population-level protection and compliance with regulatory standards instead of individual biological variability.

While exposure-based regulation remains essential, it implicitly assumes that individuals respond similarly to equivalent exposure levels. Therefore, human biology is treated primarily as a passive recipient of chemical exposure, with risk defined largely by external dose instead of internal physiological response.

Limitations of Exposure-Centered Models

Growing evidence suggests that exposure-centered models are not enough for explaining health outcomes associated with chronic, low-dose chemical exposure. Individuals with comparable dietary intake often show markedly different biological responses, indicating that internal physiological factors play a significant role in toxicological risk (Satarug et al., 2022).

Cadmium is a clear example of this limitation. Epidemiological studies show that cumulative cadmium exposure is associated with renal dysfunction and metabolic disturbances even when estimated intake remains within regulatory limits (Qing et al., 2021). These findings indicate that long-term accumulation and biological retention are critical determinants of toxicity.

Glyphosate exposure presents a similar challenge. Chronic low-dose exposure has been linked to oxidative stress and alterations in gut microbiome composition, effects that are not fully captured by traditional toxicity endpoints (Mesnage & Antoniou, 2020). These biological changes may occur without exceeding established exposure thresholds.

In the case of BPA, toxicological concern arises from continuous re-exposure rather than persistence within the body. Although BPA is metabolized very fast, repeated dietary intake results in sustained internal exposure with documented endocrine-related effects at very low doses (EFSA, 2023). This pattern challenges the assumption that such rapid clearance necessarily equates to low biological risk.

Eventually, these findings demonstrate that regulatory compliance does not always correspond to biological neutrality. Exposure thresholds are necessary for population-level protection, but they may not fully reflect individual susceptibility under real-world conditions.

Biological Alignment Framework

The limitations of exposure-based toxicology emphasize the need for an interpretive framework that incorporates biological mediation of chemical risk. Internal factors such as detoxification efficiency, nutritional status, metabolic health, oxidative balance, and endocrine sensitivity influence how chemical exposure translates into human health outcomes (Genchi et al., 2020).

Biological alignment is introduced in this review as a framework that describes the capacity of physiological systems to maintain functional stability under conditions of unavoidable chemical exposure. Instead of replacing regulatory control, this perspective complements existing risk assessment approaches by accounting for biological variability.

By integrating evidence from toxicology, nutrition science, and physiology, biological alignment reframes toxicological risk as an interaction between exposure and biological response. This approach supports a shift away from avoidance-based narratives toward a more realistic understanding of health within contemporary food systems.

Understanding biological mediation does not imply ethical acceptance of contamination. Instead, it reinforces the responsibility of governance structures to minimize preventable exposure while

acknowledging the biological realities faced by populations living within contaminated environments.

MATERIALS AND METHOD

Study Design

This study employed a **narrative literature review** design to synthesize scientific evidence on chronic food-related chemical exposure, biological mediation of toxicological risk, and ethical dimensions of food systems. A narrative approach was selected to enable integrative analysis across multiple disciplines, including environmental toxicology, nutritional biochemistry, endocrine physiology, microbiome science, and public health ethics, which are not readily addressed through quantitative meta-analysis.

Literature Identification and Selection

The literature corpus focused on three representative food-related toxicants: cadmium**,** glyphosate**,** and bisphenol A (BPA)**.** These toxicants were selected to reflect distinct exposure profiles, including cumulative bioaccumulation (cadmium), policy-mediated agricultural exposure (glyphosate), and detoxification-dependent consumer exposure (BPA).

Approximately 50 peer-reviewed publications published between 2005 and 2024 were reviewed, with emphasis on studies from the last decade. Literature sources included peer-reviewed journal articles, authoritative review papers, and regulatory assessments issued by recognized agencies. Inclusion criteria comprised studies addressing:

(1) chronic or low-dose dietary exposure,
(2) biological or physiological mechanisms of toxicity, and
(3) health outcomes relevant to renal, metabolic, endocrine, immune, or microbiome-related pathways.

Studies focused exclusively on acute poisoning, non-dietary exposure routes, or lacking biological relevance were excluded.

Analytical and Conceptual Synthesis

Rather than quantitative effect estimation, this review applied qualitative conceptual synthesis to integrate findings across toxicological mechanisms and physiological systems. Analytical dimensions included exposure characteristics, biological mediation processes, and contextual modifiers such as nutritional status, metabolic health, and regulatory environment.

From this synthesis, the framework of biological alignment was developed to describe the capacity of human physiological systems to maintain functional stability under chronic chemical exposure. Ethical considerations related to food systems, governance, and environmental responsibility were subsequently integrated to contextualize toxicological risk within broader public health and sustainability frameworks.

RESULTS AND DISCUSSION

Results

Evidence of Chronic Dietary Exposure to Food-Related Toxicants

Across the reviewed literature, consistent evidence indicates that human exposure to food-related chemical contaminants is widespread, measurable, and chronic. Biomonitoring and dietary assessment studies demonstrate detectable internal exposure to cadmium, glyphosate, and BPA across diverse populations and geographical regions.

For cadmium, dietary exposure through staple foods such as rice, cereals, and leafy vegetables frequently approaches or even exceeds established tolerable intake levels in high-consumption populations. Multiple studies report significant associations between urinary cadmium concentrations and renal biomarkers, including reduced glomerular filtration rate and evidence of tubular dysfunction, even when estimated intake remains within regulatory limits (Qing et al., 2021; Nogawa et al., 2021; Satarug et al., 2022). Food surveillance and exposure analyses further demonstrate heterogeneous cadmium burden linked to dietary patterns and agricultural context (Qing et al., 2023).

Glyphosate exposure is similarly characterized by high prevalence and repeated intake. Biomonitoring studies consistently report detectable urinary glyphosate in the majority of sampled individuals, often exceeding 70% detection frequency, indicating continuous

dietary exposure through cereals, grains, and processed foods (Gillezeau et al., 2019; Zoller et al., 2020). These findings persist across regions despite differences in regulatory thresholds and agricultural practices (EFSA, 2023).

BPA shows a different pattern. Its dietary exposure is driven primarily by food contact materials. Analytical studies document continuous low-dose exposure through canned foods and packaged products, with BPA and its analogs detected in both animal- and plant-based food matrices (Chiu et al., 2024; Geueke et al., 2025). Although BPA is rapidly metabolized, frequent dietary contact results in sustained internal exposure, as reflected in biomonitoring data and regulatory reassessments (EFSA, 2023).

Together these findings confirm that exposure to major food-related toxicants occurs as chronic, low-dose intake rather than isolated events, supporting the characterization of contemporary toxicological risk as cumulative and persistent.

Association Between Chronic Exposure and Biological Outcomes

The reviewed studies consistently report associations between chronic dietary exposure and measurable biological outcomes, particularly involving renal, metabolic, oxidative, endocrine, and microbiome-related markers.

For cadmium, epidemiological and dose–response studies demonstrate significant associations between cumulative exposure and renal outcomes. Urinary cadmium concentrations correlate with biomarkers of kidney injury and reduced renal function, with effects observed even below conventional regulatory thresholds (Qing et al., 2021; Satarug et al., 2022). These associations are further supported by benchmark dose modeling and experimental findings indicating progressive tissue accumulation over time (Nogawa et al., 2021).

Mesnage and Antoniou (2020) reported that repeated low-dose glyphosate exposure is associated with oxidative stress responses and alterations in gut microbiome composition, even when systemic toxicity thresholds are not exceeded. Similar findings were reported by Walsh et al. (2023), who observed measurable changes in redox balance and microbial diversity across both experimental and observational settings. Biomonitoring evidence further supports these observations, with Zoller et al. (2020) reporting that such biological outcomes occur within exposure ranges commonly observed in the general population.

Evidence from experimental, analytical, and regulatory research indicates that BPA can produce endocrine-related effects even at low levels of exposure. Studies by Chiu et al. (2024) and EFSA (2023) report detectable BPA concentrations in food matrices alongside evidence of endocrine sensitivity and altered hormonal signaling, particularly under conditions of continuous dietary exposure. These findings align with earlier analytical investigations by Braunrath et al. (2005), Grumetto et al. (2008), and Cao et al. (2009), which documented the presence of BPA residues in canned and packaged foods.

Impact of Physiological Factors on Toxicological Outcomes

Multiple studies indicate that toxicological outcomes are shaped not only by external exposure levels but also by internal physiological factors. Cadmium provides a clear example of this pattern. Dietary exposure through commonly consumed staple foods, such as rice, cereals, and leafy vegetables, often approaches, and in some populations exceeds, established tolerable intake levels. Studies by Qing et al. (2021), Nogawa et al. (2021), and Satarug et al. (2022) report significant associations between urinary cadmium concentrations and indicators of renal impairment, including reduced glomerular filtration rate and evidence of tubular dysfunction, even when estimated intake falls within current regulatory limits. Food surveillance and exposure assessments further indicate that cadmium burden varies markedly across populations, reflecting differences in dietary practices and agricultural conditions (Qing et al., 2023).

Oxidative stress pathways and gut microbiome integrity play an important role in shaping biological responses to chronic glyphosate exposure (Mesnage and Antoniou, 2020). Peillex and Pelletier (2020) also observed disruptions in antioxidant defense systems under prolonged low-dose exposure, suggesting impaired redox regulation. Walsh et al. (2023) further identified changes in gut microbial composition associated with repeated dietary glyphosate intake, indicating that endogenous redox capacity and microbiome resilience may influence toxicological outcomes even when exposure remains within regulatory limits.

For BPA, regulatory and experimental evidence indicates that detoxification efficiency is a key determinant of internal exposure. EFSA (2023) documented that although BPA undergoes rapid Phase II metabolism, continuous dietary intake leads to repeated internal exposure. As also reported by Chiu et al. (2024), individual metabolic capacity and endocrine sensitivity influence biological responses under conditions of ongoing low-dose exposure.

Summary of Exposure Profiles and Biological Mediation

The combined reviewed results demonstrate that cadmium, glyphosate, and BPA represent distinct but converging exposure profiles within modern food systems. Cadmium exhibits cumulative bioaccumulation with long biological persistence, glyphosate demonstrates high-frequency dietary exposure with low environmental persistence, and BPA represents a detoxification-dependent exposure characterized by continuous re-intake. The summarized exposure characteristics, regulatory reference points, and associated biological findings are presented in Table 1.

Table 1.
Representative Exposure Characteristics of Key Food-related Toxicants

Toxicant	Primary Food / Exposure Source	Reported Exposure / Biomonitoring Data	Regulatory Reference Point	Key Sources
Cadmium	Rice, cereals, leafy vegetables	Dietary exposure frequently approaches or exceeds TWI in high-consumption populations; urinary Cd significantly associated with reduced GFR and rena tubular damage even below limits	TWI 2.5 µg/kg bw/week (EFSA)	Qing et al., 2021; Qing et al., 2023; Nogawa et al., 2021; Satarug et al., 2022
Glyphosate	Cereals, grains, processed foods	Detectable urinary glyphosate reported in majority (>70%) of samples across multiple biomonitoring studies	ADI 0.5 mg/kg bw/day (EFSA, EPA)	Gillezeau et al., 2019; Zoller et al., 2020; EFSA, 2023
Bisphenol A (BPA)	Canned foods, food contact materials	Continuous low-dose dietary exposure documented; BPA and analogs detected in packaged and plant-based foods	TDI 0.2 ng/kg bw/day (EFSA, 2023)	EFSA, 2023; Chiu et al., 2024; Geueke et al., 2025

Across these exposure profiles, measurable biological effects are consistently observed at exposure levels commonly encountered in the general population. Internal physiological factors, including nutritional status, detoxification capacity, antioxidant defenses, and microbiome integrity, repeatedly shape toxicological outcomes. The key physiological factors influencing toxicological risk under chronic exposure are summarized in Table 2.

Table 2.
Biological Mediation of Toxicological Risk Under Chronic Exposure

Toxicant	**Persistence Profile**	**Key Biological Modulators**	**Evidence From Literature**	**Key Sources**
	Highly bioaccumulative, long biological half-life	Iron and zinc status, renal detoxification capacity	Nutrient deficiencies increase cadmium absorption and nephrotoxicity; cumulative exposure linked to CKD	Genchi et al., 2020; Suhani et al., 2021; Satarug et al., 2022
	Low persistence, high exposure frequency	Gut microbiome integrity, oxidative stress pathways	Altered gut microbiota composition and increased oxidative stress observed under chronic low-dose exposure	Mesnage & Antoniou, 2020; Peillex & Pelletier, 2020; Walsh et al., 2023
	Rapid metabolism, continuous re-exposure	Phase II conjugation efficiency, endocrine sensitivity	Endocrine effects observed at extremely low doses; risk shaped by metabolic and life-stage vulnerability	EFSA, 2023; Chiu et al., 2024; Braunrath et al., 2005

DISCUSSION

Interpreting Chronic Foodborne Exposure Beyond Regulatory Thresholds

The findings of this review indicate that chronic dietary exposure to cadmium, glyphosate, and BPA occurs at levels commonly encountered in the general population and is consistently associated with measurable biological changes. These findings align with contemporary toxicological literature emphasizing that low-dose, cumulative exposure may produce health effects not fully captured by conventional exposure thresholds (Bereda, 2025; Khatri et al., 2025).

Traditional risk assessment frameworks have been effective in preventing acute toxicity. However, they are insufficient to address long-term biological responses arising from repeated exposure and internal accumulation. This limitation is particularly evident for foodborne contaminants with diverse persistence profiles and exposure frequencies, where biological response is shaped not only by dose, but by physiological mediation and cumulative burden.

Cadmium: Cumulative Toxicity and Renal Vulnerability

Cadmium provides one of the most robust examples of chronic toxicological risk arising from dietary exposure. Mechanistic studies demonstrate that cadmium accumulates primarily in renal tissue, where it induces oxidative stress, tubular dysfunction, and progressive loss of renal function (Bouida et al., 2022; Charkiewicz et al., 2023; Genchi et al., 2020).

Benchmark dose analyses and epidemiological studies shows that renal effects may occur at cumulative exposure levels near or below regulatory reference points, challenging the assumption that compliance with tolerable intake guarantees biological safety (Nogawa et al., 2021; Satarug et al., 2022). These findings support the interpretation that cadmium toxicity is driven by long biological half-life and accumulation dynamics rather than acute exposure magnitude alone.

Nutritional and physiological context plays a significant role in shaping cadmium toxicity. Deficiencies in essential minerals and reduced detoxification capacity can increase cadmium absorption and renal retention, therefore heightening susceptibility to chronic kidney disease. These factors highlight the importance of interpreting cadmium risk through both exposure control and biological vulnerability.

Glyphosate: Systemic Effects, Microbiome Interaction, and Scientific Controversy

Glyphosate presents a contrasting exposure profile characterized by low environmental persistence but high dietary frequency. Human exposure synthesis confirms widespread internal exposure through food consumption, as evidenced by biomonitoring data across populations (Gillezeau et al., 2019).

Beyond classical toxicological endpoints, mechanistic studies increasingly implicate glyphosate in oxidative stress, immune modulation, and disruption of gut microbiome composition (Mesnage & Antoniou, 2020; Peillex & Pelletier, 2020; Walsh et al., 2023). These

biological effects provide plausible pathways linking chronic exposure to systemic health outcomes, including metabolic, immune, and inflammatory disturbances.

Interpretation of glyphosate-related risk remains contested within the scientific literature. Zhang et al. (2019) reported associations between glyphosate exposure and increased risk of non-Hodgkin lymphoma in their meta-analysis, raising concerns about potential carcinogenic effects. Mazuryk et al. (2024) further identified evidence of broader systemic toxicity, extending the discussion beyond cancer-related outcomes. In parallel, Glenna and Bruce (2021) examined regulatory decision-making processes and highlighted ongoing tensions between commercial interests, regulatory conclusions, and findings from independent scientific research.

This divergence underscores the importance of integrating mechanistic biology, exposure evidence, and governance transparency when interpreting glyphosate-related health risks.

Biological Modulation and Endogenous Defense Mechanisms

The literature consistently indicates that internal biological systems significantly affect toxicological outcomes among many toxicants. Antioxidant capacity, redox balance, detoxification efficiency, and immune regulation emerge as central determinants of resilience under chronic exposure conditions.

Evidence supporting antioxidant modulation demonstrates that oxidative stress is a shared pathway across cadmium, glyphosate, and BPA exposure. Interventions that support endogenous antioxidant systems have been shown to reduce tissue damage and inflammatory responses in experimental and clinical contexts as mentioned by Kalogerakou & Antoniadou (2024). Hepatoprotective and nephroprotective phytochemicals also illustrate the capacity of biological systems to modulate toxicant-induced injury when physiological defense mechanisms are supported (Shawon et al., 2024; Bhatti et al., 2023).

Emerging literature highlights the importance of gut microbiome as a mediator of toxicant effects. Alterations in microbial composition can influence immune signaling and systemic inflammation, therefore modifying susceptibility to chemical stressors. Probiotic-based approaches have been explored as complementary strategies to support detoxification and reduce internal toxicant burden (Kiousi et al., 2022). In the study by Takahata et al. (2023), botanical interventions were shown to modulate biological responses to chemical stressors, suggesting potential protective effects in high-risk populations, although these findings require cautious interpretation. These studies do not suggest replacing exposure mitigation with supplementation but reinforce the concept that biological response capacity shapes toxicological risk.

Integrating Toxicology, Food Systems, and Public Health

At the food system level, recent syntheses emphasize that chronic chemical exposure arises from interconnected agricultural practices, processing technologies, and regulatory frameworks (Duan et al., 2025; Oliveira et al., 2025). Persistence, mixture effects, and cumulative exposure complicate traditional single-chemical risk assessment approaches,

necessitating broader interpretive frameworks (Khatri et al., 2025). The interaction between regulatory exposure control and internal biological response capacity is conceptually illustrated in Figure 1.

Figure 1. Parallel Strategies in Exposure Mitigation

From a public health perspective, these findings support a dual strategy approach. Regulatory control remains essential to reduce contamination and prevent high-dose exposure, particularly for pesticides and heavy metals (Adjei, 2025). Public health strategies must simultaneously recognize biological variability and support physiological resilience, especially in vulnerable populations exposed to unavoidable dietary contaminants.

The concept of biological alignment offers a framework for integrating these dimensions, positioning toxicological risk as an emergent property of exposure, biology, and governance rather than as a function of exposure alone. A conceptual synthesis integrating governance mechanisms, food system practices, and biological response capacity is summarized in Table 3.

Table 3. Conceptual Synthesis Integrating Governance, Food Systems, and Biological Response Capacity

Governance & Policy	Food System & Industry	Biological Response Capacity
Regulatory threshold setting and periodic revision	Sustainable, low-migration packaging innovation	Nutritional adequacy supporting detoxification pathways
Chemical approval and reassessment frameworks	Agricultural input management and residue reduction	Physical activity as a modulator of metabolic clearance
Environmental monitoring and compliance mechanism	Food processing and formulation decisions	Clinical interventions in high-risk or occupational contexts
Incentives for sustainable materials and practices	Transparency in sourcing and material disclosure	Biomarker monitoring of oxidative stress and biotransformation

Acknowledging that some level of exposure is unavoidable within modern food systems does not remove responsibility for contamination. It actually shifts accountability across governance structures, industry practices, and public health institutions. Effective food

system governance should aim to reduce preventable exposure while also acknowledging the biological realities faced by populations living in contaminated environments. Public health strategies based only on avoidance narratives risk widening inequities, particularly for groups with limited access to alternative food sources or protective resources, as highlighted in recent food policy and public health analyses (Adjei, 2025).

By integrating exposure mitigation with support for biological response capacity, public health policy can better align regulatory goals with human physiological limits. This dual approach emphasizes precaution, transparency, and resilience, positioning food ethics not as an abstract principle but as a practical framework guiding decision-making in the Anthropocene.

Implications for Risk Interpretation and Future Research

The evidence discussed in this chapter suggests that future toxicological assessment should move beyond static exposure thresholds toward dynamic models that incorporate cumulative burden, biological mediation, and population heterogeneity. These advances in analytical chemistry and biomonitoring provide opportunities to better characterize real-world exposure, while mechanistic studies continue to elucidate pathways linking chronic exposure to disease outcomes (Oliveira et al., 2025; Singh et al., 2024).

By integrating toxicological mechanisms, endogenous defense capacity, and ethical governance, biological alignment offers a coherent interpretive lens for understanding health in contaminated environments. This approach does not diminish the importance of regulation but complements it by acknowledging the biological realities of the Anthropocene.

Further progress will depend on longitudinal and systems-based approaches that can capture dynamic interactions among chronic exposure, biological mediation, and health outcomes. Developments in exposomics, high-resolution biomonitoring, and analytical chemistry continue to expand the ability to characterize cumulative and mixture exposures within food systems, where multiple contaminants frequently co-occur (Duan et al., 2025; Oliveira et al., 2025; Khatri et al., 2025). Integrating these exposure data with biomarkers of oxidative stress, endocrine disruption, renal function, and metabolic health will support more comprehensive toxicological risk interpretation beyond static regulatory thresholds.

Vulnerable and high-risk populations, including nutritionally compromised groups, pregnant women, and individuals with pre-existing renal or metabolic conditions require additional attention. Evidence indicates that biological susceptibility varies substantially across life stages and physiological states, suggesting that population-averaged exposure limits may not adequately protect all individuals (Satarug et al., 2022; EFSA, 2023). Future studies should also explore stratified risk assessment models that incorporate physiological variability, cumulative burden, and adaptive capacity.

From a governance perspective, interdisciplinary research linking toxicological evidence with policy analysis remains important. Evaluations of regulatory decision-making processes, industry influence, and transparency mechanisms will help clarify persistent discrepancies between regulatory classifications and independent scientific assessments, particularly for controversial compounds such as glyphosate (Glenna and Bruce, 2021; Zhang

et al., 2019; Mazuryk et al., 2024). These analyses are critical for maintaining public trust and ensuring that food safety policies evolve alongside emerging scientific evidence.

Limitations of the Review and Methodological Considerations

Although this narrative review provides an integrative synthesis of chronic food-related chemical exposure and biological mediation of toxicological risk, several limitations should be acknowledged.

1. Narrative review design and inferential scope

   The narrative review design prioritizes conceptual integration across disciplines rather than quantitative effect estimation. As a result, causal inferences regarding exposure–outcome relationships cannot be established, and effect sizes cannot be directly compared across studies as well. This reflects the complexity of integrative reviews that span environmental toxicology, nutritional biochemistry, physiology, and governance, which limits the precision of risk quantification.

2. Diversity in the reviewed evidence

   The reviewed literature shows substantial heterogeneity in study design, exposure assessment methods, and biological endpoints. Biomonitoring studies differ in analytical techniques, biological matrices, and population characteristics, which may influence reported exposure levels and associated health outcomes. Variability in dietary patterns, agricultural practices, and regulatory frameworks further complicates cross-study comparison, particularly for globally distributed toxicants such as cadmium and glyphosate, as highlighted by exposure syntheses and biomonitoring analyses (Qing et al., 2023; Gillezeau et al., 2019; Zoller et al., 2020).

3. Limitations of human epidemiological evidence

   The available human evidence is derived from cross-sectional or observational studies. Although biomonitoring data consistently demonstrate widespread internal exposure, longitudinal studies linking cumulative exposure trajectories to long-term clinical outcomes remain limited. This constraint is particularly relevant for toxicants with long biological half-lives or delayed disease manifestation, such as cadmium, where renal effects may develop over decades of accumulation (Nogawa et al., 2021; Satarug et al., 2022; IARC, 2017).

Finally, while this review integrates emerging evidence on biological modulation and adaptive capacity, translating these findings into population-level public health strategies remains challenging. Biological resilience is shaped by socioeconomic conditions, nutritional access, healthcare availability, and baseline health status, which vary widely across populations. These contextual factors limit the generalizability of biological mitigation strategies and underscore the need for cautious interpretation of intervention-oriented findings.

CONCLUSION

This review synthesizes evidence demonstrating that modern food systems are characterized by pervasive, chronic exposure to chemical contaminants, including heavy metals, pesticides, and food contact chemicals. Biomonitoring and dietary studies consistently confirm that such exposures are widespread and unavoidable for large segments of the population, positioning food as a primary pathway of long-term chemical intake rather than an occasional source of risk (Geueke et al., 2025; Pekmezci, 2025).

Current toxicological and regulatory frameworks have played a critical role in reducing acute toxicity and guiding population-level risk management. Authoritative assessments by international and national agencies continue to provide essential benchmarks for regulatory decision-making (ATSDR, 2020; EFSA, 2023; EPA, 2020). However, the evidence summarized in this review indicates that exposure thresholds alone are insufficient to fully explain health outcomes under chronic, low-dose, and cumulative exposure conditions. This limitation becomes very relevant for toxicants exhibiting long biological half-lives, detoxification-related re-exposure mechanisms, or high-frequency intake through dietary sources, because these characteristics complicate accurate exposure assessment and risk characterization.

From a global toxicology perspective, emerging literature emphasizes that toxicological risk in the Anthropocene must be interpreted as a dynamic interaction between environmental burden, biological systems, and governance structures rather than as a static function of external dose (Bereda, 2025). Discrepancies between regulatory classifications and independent hazard evaluations, including carcinogenic risk assessments, further underscore the need for continuous reassessment, transparency, and precaution in chemical governance (IARC, 2017; EFSA, 2023).

Overall, this review highlights that biological systems actively mediate toxicological outcomes. Internal factors such as detoxification capacity, nutritional status, antioxidant defense, and microbiome integrity shape individual susceptibility to chronic exposure. Evidence that supports biological mitigation strategies, including microbiome-supportive interventions as well as functional nutritional approaches, suggests that physiological resilience can influence health outcomes without substituting for exposure reduction policies (Kiousi et al., 2022; Kalogerakou & Antoniadou, 2024).

These insights have direct implications for public health and food policy. Effective prevention in contaminated environments requires parallel strategies :

1. Continued regulatory control to minimize environmental contamination
2. Population exposure, alongside measures that support biological response capacity, especially in vulnerable or high-risk groups.

This approach aligns exposure governance with human physiological limits instead of relying solely on avoidance narratives that may be unrealistic under current food system conditions.

Recent developments in food contaminant research and analytical chemistry have enhanced the ability to characterize real-world exposure patterns and mixture effects. Therefore, it is able to support more adaptive risk assessment models (Duan et al., 2025; Oliveira et al., 2025). Continued work, however, is still needed to establish integrative frameworks that link exposure science, biological mediation, and ethical governance, enabling policies that reflect environmental complexity alongside human resilience.

In conclusion, safeguarding human health in the Anthropocene era requires moving beyond exposure purity as the sole benchmark of safety. By integrating toxicological evidence, regulatory oversight, and biological response capacity, the concept of biological alignment provides a coherent foundation for resilient and ethically grounded food systems and public health strategies in an increasingly contaminated world.

ACKNOWLEDGMENTS

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this article.

AUTHORS' CONTRIBUTIONS

AAM: Conceptualization ; Writing – original draft preparation.
DW: Conceptualization ; Writing – review and editing.
CR: Conceptualization ; Writing – review and editing.

ETHICAL STATEMENT

This study was conducted in accordance with established ethical standards for scientific research. As this research is based on a narrative review of previously published literature and does not involve direct interaction with human participants or the use of animals, ethical approval from an institutional review board or ethics committee was not required. No personal, identifiable, or confidential data were collected or processed in the course of this study. All sources were obtained from publicly accessible scientific databases and cited appropriately to ensure academic integrity.

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Preserving Heritage: Supporting Local Home Industry Performance through Sustainable Design of Smoked Fish Facilities in Semarang

Sub-Theme: *Design for Sustainability*

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ABSTRACT

Traditional fish smoking in Bandarharjo, Semarang, is a longstanding coastal cultural practice; however, current facilities generate excessive smoke and waste, lack hygiene, and pose environmental and health risks to nearby settlements. This study aims to develop a sustainable smoked fish production module that preserves traditional methods while improving environmental responsibility, food safety, and craftsmen welfare. A qualitative approach was applied through field observations, online research on waste management strategies, and precedent studies of similar facilities. The proposed design integrates a condensation pipe system to reduce air pollution by converting a significant portion of smoke into Grade III liquid smoke, which can be reused as a natural preservative. Each smoking module incorporates cross-ventilation and improved thermal comfort while maintaining the traditional use of palm kernel shells and corncobs as fuel. The spatial layout is reorganized into distinct dry, wet, smoking, and drying zones to enhance hygiene, improve workflow, and reduce fire risks, referencing the 2020 accident. Although the waste-processing system requires further technical development, the proposal establishes a strategic foundation for an environmentally responsible smoked fish facility rooted in cultural heritage.

Keywords: *environmental health, smoked fish; sustainable facility design.*

INTRODUCTION

The fish smoking industrial center plays a significant role in supporting the local economy of Bandarharjo, Semarang City. As of 2019 (, smoked fish products from this area were distributed to several cities, including Jakarta, Solo, and Yogyakarta, with raw materials primarily supplied from East Java. Despite its economic potential, the location of the industry along the Semarang River presents major spatial and environmental challenges. Traditional fish smoking methods, characterized by simple equipment and limited sanitation control, contribute to air pollution, poor hygiene conditions, and inefficient production.

The thesis addresses the planning of a modular fish smoking facility on a larger-scale production site, emphasizing operational efficiency, environmental control, and long-term maintainability with design principals:

1. Spatial organization and processing flow are treated as key architectural determinants of production success, based on established principles of processing building planning and spatial layout in fish smoking industries (ISBN: 978-602-0960-12-8; ISBN: 978-602-0960-29-6).
2. The design applies standardized material criteria for fish smoking facilities, ensuring hygiene, durability, and ease of cleaning, as supported by food-industry material standards (ISSN (P) 0853-2877; ISSN (E) 2598-327X).
3. Integrated waste management is embedded within the architectural module through clear spatial separation of waste streams, allowing efficient handling, treatment, and maintenance.
4. The waste system is deliberately restrained to three primary categories—smoke waste, wet waste, and dry waste—to maintain simplicity, control, and scalability.
5. Smoke by-products are explored as a potential resource through the development of liquid smoke using low pyrolysis processes, based on chemical engineering research on biomass-derived liquid smoke production (Karolus, Journal Teknik Kimia, 2013).

MATERIALS AND METHOD

This architectural research into fish smoking facilities adopts a qualitative methodology, aimed at describing and analyzing the application of building designs that prioritize hygiene standards and the mitigation of environmental pollution. The study focuses on evaluating waste management and type of waste that could be recycled.

Research Workflow

The implementation stages of this study are structured as follows:

1. Data Acquisition: Conducted site surveys and empirical data collection to establish baseline conditions.
2. User Assessment: Performed a deep dive into artisan needs to align design with local socioeconomic realities.
3. Site Programming: Executed site analysis to define spatial requirements and constraints.
4. Innovation Synthesis: Identified and integrated technical solutions for sustainable waste management.
5. Design Development: Created a specialized production module and a comprehensive masterplan with integrated waste systems.

Research Precedent Selection Rationale

The selection of Bandarharjo, Semarang, as the primary research site is driven by its established role as a fish-smoking industrial hub and the critical safety events that occurred there in 2020. A major fire accident during that year exposed deep-seated vulnerabilities, primarily caused by disorganized spatial planning and an unsustainable intensity of smoking operations.

The current facility is precariously located on land designated for green open space, and its proximity to high-density residential areas exacerbates environmental degradation. This results in severe air quality disruption through heavy smoke concentrations, alongside the unregulated disposal of solid and liquid processing waste, posing a direct threat to the health and sustainability of the surrounding coastal community.

Selected Site Rationale

Figure 1. Designed site position over the existing smoking houses

According to the Regional Spatial Plan (RTRW), the new site is designated as land for trade and services. The site manage to fit the whole production industry at 8.367m2. River Width: 4.8 m

1. Inspection Road Line: 15 m
2. Building Setback (GSB): 5 m
3. Total River Setback: 20 m
4. Total Site Area: 8,367 m²
5. Net Site Area (Excluding Setbacks): 5,451 m²
6. Maximum Building Coverage (KDB 60%): 5,020 m²
7. Minimum Greenery Coefficient (KDH 10%): 836.7 m²
8. Floor Area Ratio (KLB 1.5): Max 12,550 m²
9. Green Open Space (RTH 20%): 1,673 m²
10. Maximum Height: 2 Floors
11. Zoning: Commercial and Service Zone (Zona Perdagangan dan Jasa)

Data and Analysis

1. Legal Regulation

Based on Semarang City Regional Regulation No. 14 of 2011 concerning the Spatial Plan (RTRW) 2011–2031, river buffer zones are designated as protected areas with strict zoning controls. Permitted activities include green open spaces, limited nature-based tourism, installation of public utility networks, and limited structures supporting river management or recreational functions, provided they do not disrupt river performance or water quality. The construction of permanent buildings and activities that may degrade river quality are

prohibited. The minimum river buffer width is set at 3 meters from the outer edge of the embankment in urban areas and 5 meters in non-urban areas.

According to Article 116 of the General Zoning Regulations concerning spatial structure, wastewater management networks and areas are subject to specific controls. The utilization of waste for energy development is permitted, while the construction of public buildings above wastewater networks is prohibited. Limited development of facilities to support wastewater management is allowed. In response to these regulations, a simple wastewater treatment facility is proposed to address industrial waste discharged into the Semarang River.

2. **Support Paper**

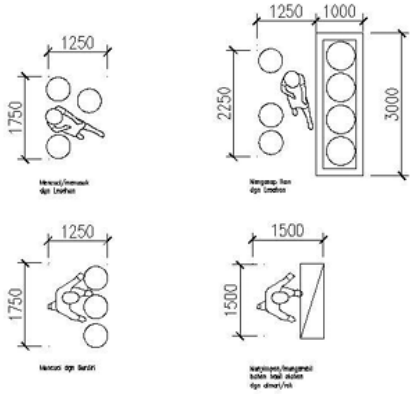


Figure 2: Analysis standard dimension of fish smoking spatial program

RESULTS AND DISCUSSION

Key Finding: Air Quality Solution

The proposed design addresses chronic air quality degradation through the integration of a novel condensation pipe system embedded within the roofing structure of each smoking module. This intervention leverages thermodynamic principles to intercept emissions at the source. Based on empirical literature and research assumptions, the system is estimated to sequester and recycle approximately most of smoke particulates, representing a significant reduction in localized atmospheric pollution.

Picture 3.Typical Small Floorplan Fish Smoking Module (Existing)

Source: ISBN : 978-602-0960-12-8

The working conditions in the fish smoking area remain inadequate. This is primarily due to the integration of the smoking area with fuel storage spaces, such as coconut shells and combustion residues. As a result, the workspace is continuously exposed to smoke and dust, leading to poor air quality. These conditions not only reduce worker comfort and safety but also compromise hygiene standards in the fish smoking production process.

Considering the limitation of available land, this study prioritizes land-use efficiency as a key design approach. Therefore, the proposed model focuses exclusively on the small-scale fish smoking type, developed into a modular system capable of accommodating six small smoking units within a single integrated structure.

The proposed modular design accommodates 6–8 fish-smoking units within a 1.5-storey industrial facility, organized to ensure efficient production flow and compliance with hygiene standards. The layout integrates supporting facilities such as sanitary toilets with hand-washing stations, cold storage (4 × 4 m), dry storage (8 × 4 m), and preparation rooms (8 × 4 m on both sides of the module) to maintain product safety and operational cleanliness. The smoking area (12 × 4 m) is positioned linearly at the core of the building to support controlled processing and minimize cross-contamination. The upper floor functions as a transitional clean zone for dry fish holding prior to smoking, fish drying areas (3 × 16 m on both sides), and a dedicated liquid smoke condensation waste processing area (2 × 16 m) with a direct connection to a centralized liquid smoke waste storage system, reinforcing an integrated waste management approach within an industrial-scale, hygienic fish-smoking facility.

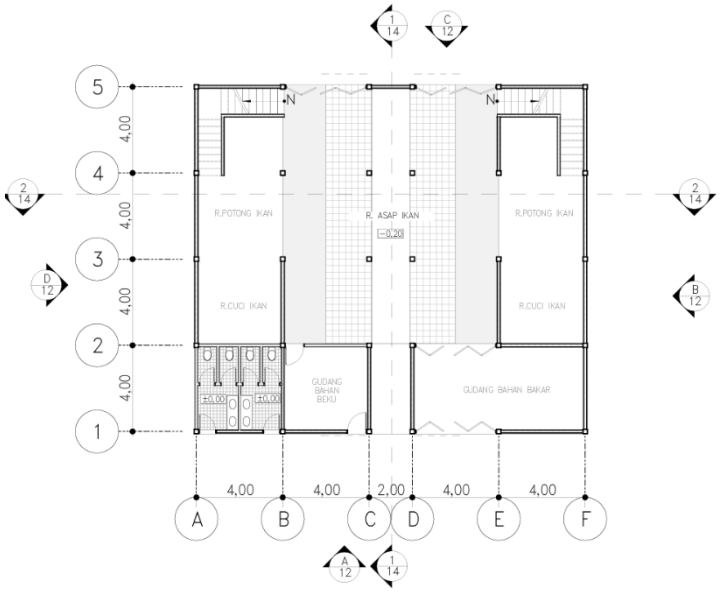


Figure 4. Ground Floor of the Designed Smoking Module

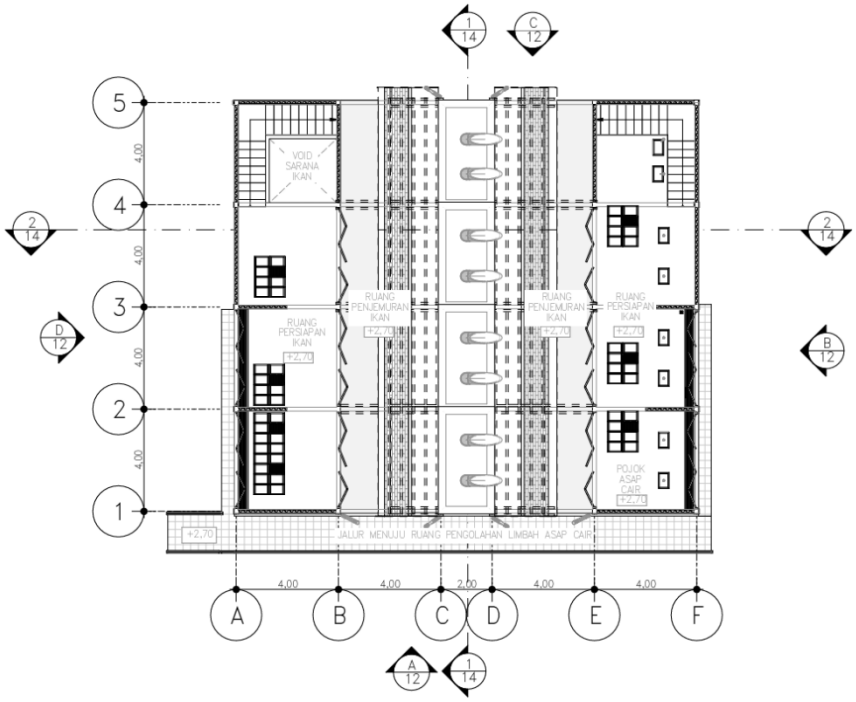


Figure 5. Mezanine Floor of the Designed Smoking Module

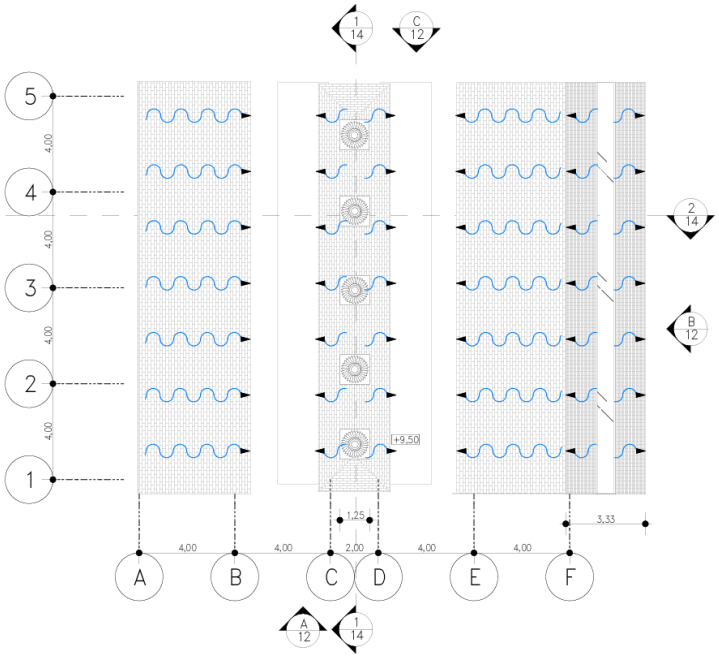


Figure 6. Pipe Layout of the Designed Smoking Module

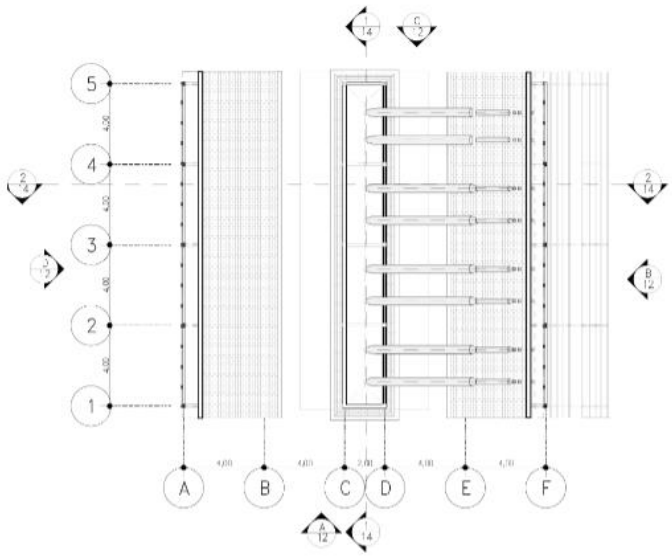


Figure 7. Roof Plan of the Designed Smoking Module

With surrounding module walls limited to a height of 160 cm and incorporating multiple openings, the design provides additional natural ventilation to support a more comfortable and well-aerated smoking environment. The design applies material standards directly in accordance with established recommendations for food industry facilities (Rahayu, et al., 2015). Non-slip ceramic flooring is used in wet and dirty areas to prevent accidents and facilitate cleaning, while smooth, non-porous wall finishes are applied to reduce moisture absorption and bacterial growth. Work surfaces and processing areas utilize materials that are heat-resistant, easy to sanitize, and durable under continuous use. Ventilation-related components and smoking areas employ fire- and heat-resistant materials to ensure safety and operational efficiency.

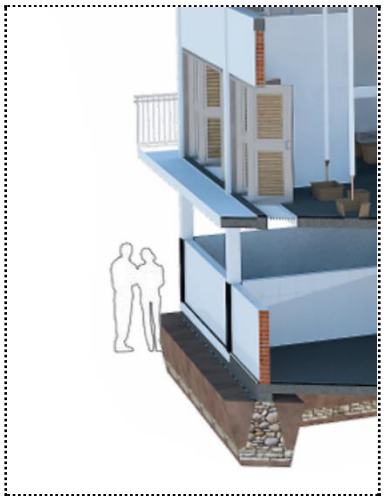
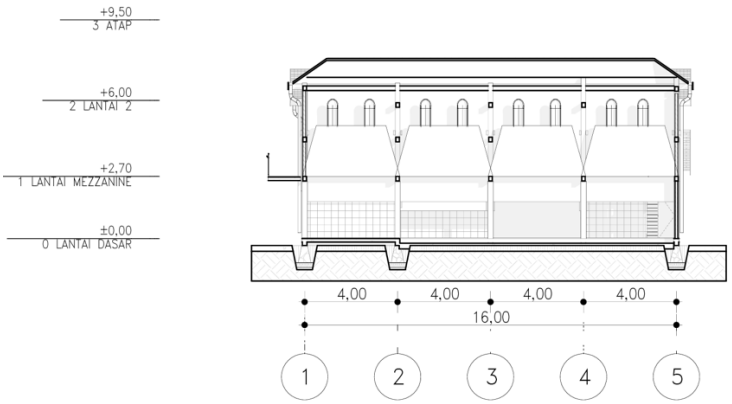


Figure 8. Section 2 of Designed Smoking Module



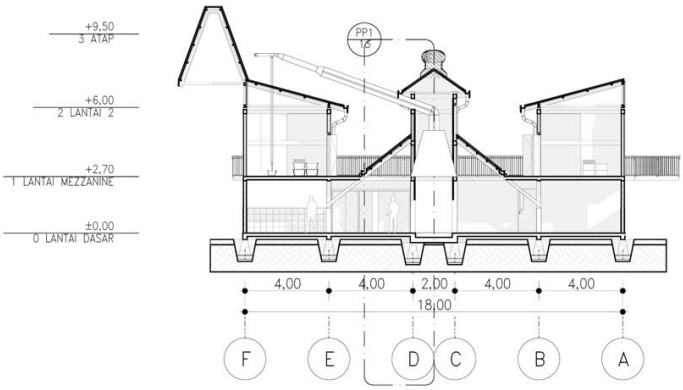
Picture 9. Section 1 of Designed Smoking Module

Thermodynamics of the Smoking Process

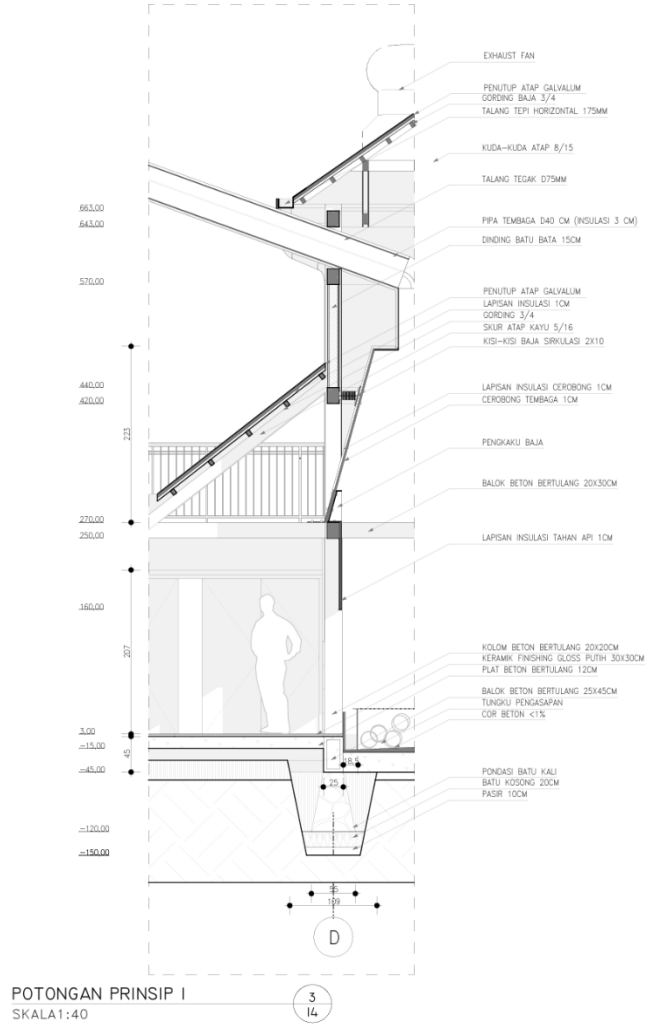
In the study *"Design of Fish Smoking Spaces Based on Processing Flow: A Case Study in Bandarharjo, Semarang City"* by Baju Arie Wibawa and M. Agung Wahyudi (2015), a recommendation is made to further develop the design study by incorporating more comprehensive design aspects. In particular, the authors highlight the need for detailed design proposals related to smoke chimney systems, which play a crucial role in reducing the environmental impacts generated by fish smoking activities. Therefore, a study that specifically and thoroughly addresses chimney design remains highly necessary. Therefore, this study introduces a core innovation in the form of an integrated condensation pipe system applied directly to each smoking module to control smoke emissions.

The recommended requirement states that chimney height should reach 2–2.5 times the height of surrounding buildings and be equipped with internal filters to reduce smoke emissions. In the proposed design, the chimney height is set at 3.5 meters above a 9.5-meter-high building, while the average height of surrounding buildings is approximately 3 meters. Due to land limitations and the intention to process smoke emissions through an integrated treatment system, this dimensional requirement is not fully met. However, the incorporation of smoke condensation and treatment systems becomes a key design emphasis, positioning smoke waste processing as a core environmental innovation within the industrial site.

The technical logic of the filtration system utilizes the internal kinetic energy generated by the smoking process. The continuous density, pressure differentials, and high operational pace drive smoke upward into insulated conduits, where rapid cooling facilitates the conversion of vapor into Grade III liquid smoke. To compensate for the intense thermal load and prevent heat accumulation in the upper plenum, each module is equipped with four strategic exhaust fans to ensure continuous airflow and thermal regulation.

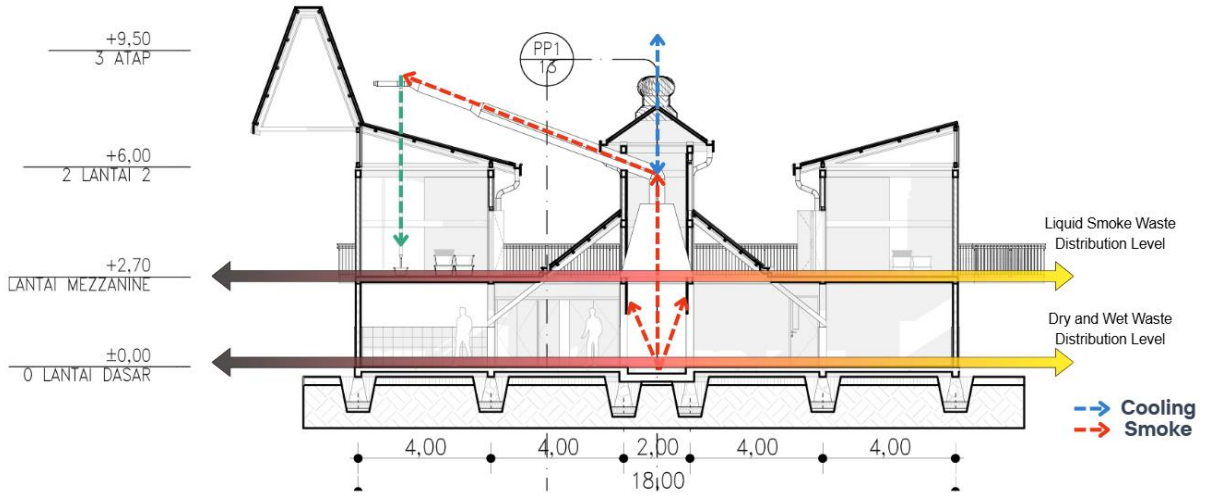


Picture 10. Section 2 of Designed Smoking Module



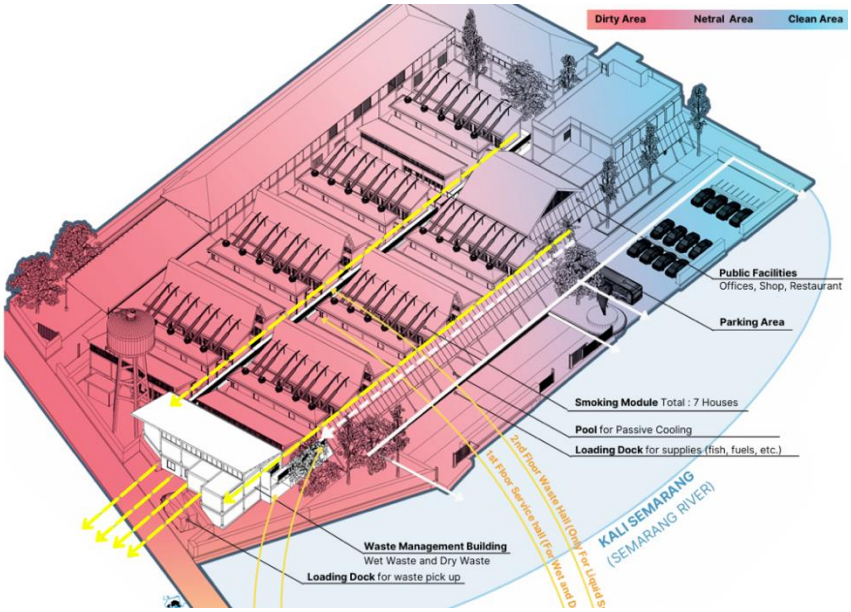
Picture 11. Principal Section of Designed Smoking Chimney

Key Finding: Waste Stream Segregation



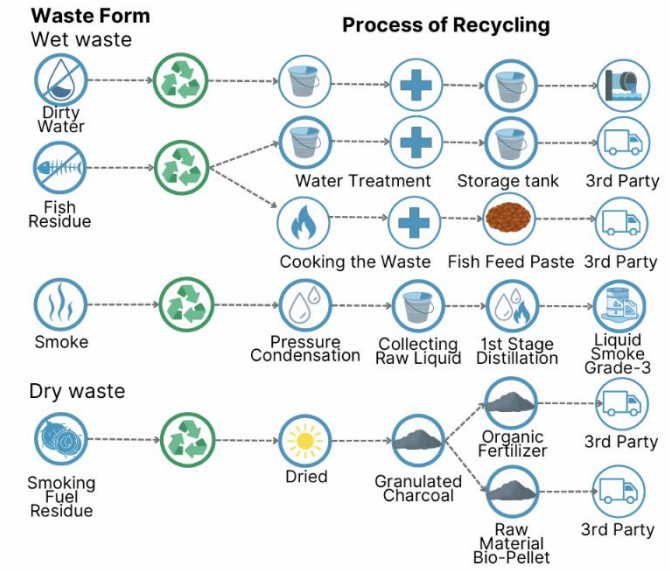
Picture 12. Waste Distribution Diagram on Section 2 Module

To maximize operational efficiency and hygiene, the facility adopts a vertical zoning strategy. The ground floor is dedicated to primary processing activities—including washing, cutting, cleaning, and seasoning—allowing for the centralized management of wet and dry organic waste. The upper level is reserved for sun-drying and smoking, facilitating a direct gravity-fed or pressurized distribution line for liquid smoke collection, thereby preventing cross-contamination between raw processing and finished goods.



Picture 13. Waste Distribution Diagram on Masterplan

The masterplan centralizes all waste streams into a dedicated waste management facility, ensuring that the industrial zone remains free of hazardous accumulation. This facility acts as a logistical node, featuring a specialized loading dock designed for the sanitary extraction of waste by third-party contractors. This systematic approach ensures that the production site maintains its hygiene standards while facilitating external waste processing.



Picture 14. Waste Type and Process Diagram

CONCLUSION

In conclusion, the study successfully synthesizes cultural heritage preservation with modern environmental and occupational health standards. The redesign of the Bandarharjo Fish Smoking Center through a modular industrial architecture approach can significantly improve production efficiency, hygiene standards, and environmental performance within the constraints of limited land availability. By organizing spaces according to the fish smoking process flow and separating wet–dirty, dry–clean, and dry–dirty zones, the proposed design minimizes cross-contamination and supports food safety requirements. The application of appropriate materials, ventilation systems, and standardized spatial layouts ensures a healthier working environment and easier maintenance. Furthermore, the integration of smoke condensation and waste management systems transforms previously harmful by-products into managed resources, highlighting the potential of small-scale traditional industries to adopt sustainable practices. Overall, this research provides a practical design reference for upgrading traditional fish smoking facilities into hygienic, efficient, and environmentally responsible production centers.

SUPPORTING INFORMATION

Table 1. Material and Element Room Condition in Food Industry (Setyawan, et al., 2016)

Spatial Element	Standard	Design Recommendation
Floor	• Waterproof • Heat-resistant • Durable	Concrete plaster or ceramic flooring with a specific slope in washing areas to facilitate drainage
Wall	• Waterproof • Flat surface • Light-colored • Non-toxic • Not easily peeling • Durable	1. Brick walls coated with stain-resistant paint in light colors 2. Ceramic wall finish applied to the lower part of the wall up to a height of 1.5 m
Ceiling	• Lightweight • Waterproof • Not prone to leakage	Gypsum GRC board ceiling installed following the roof slope to create a higher interior space
Ventilation	• Equipped with exhaust or filter system	Ventilation using exhaust equipment to remove hot air from the interior space, combined with additional openings to allow fresh air intake

Table 2. Building Area for 7 Modules in Masterplan

Building Area Calculation Summary

No	Floor	Effective Area (Non-Circulation) (m^2)	Circulation Area (m^2)	Total Area (m^2)	Notes
Mass 1 (Fish Smoking)					
1	Ground Floor	298.94	30.00		7 modules
2	Mezzanine Floor	138.92	17.60	**3,398.22**	

Out of 8.004 m2 of total building area

Table 3. Designed Proposal Area Information Area

Specification	*Allowable Limits (Zoning Regulations)*	*Designed Proposal (Proposed Plan)*
Site Area (Lot Area)	*8,367 m²*	*N/A*
Building Coverage (Site Coverage)	*Max 60% (5,020 m²)*	*4,358 m² (86.8% compliance)*
Greenery Area (Green Space)	*Min 10% (836.7 m²)*	*1,145.4 m²*
Floor Area Ratio (FAR)	*Max 1.5 (12,550 m²)*	*8,004 m² (63.7% compliance)*
Open Space (RTH)	*N/A*	*N/A*
Building Volume	*N/A*	*43,580 m³*

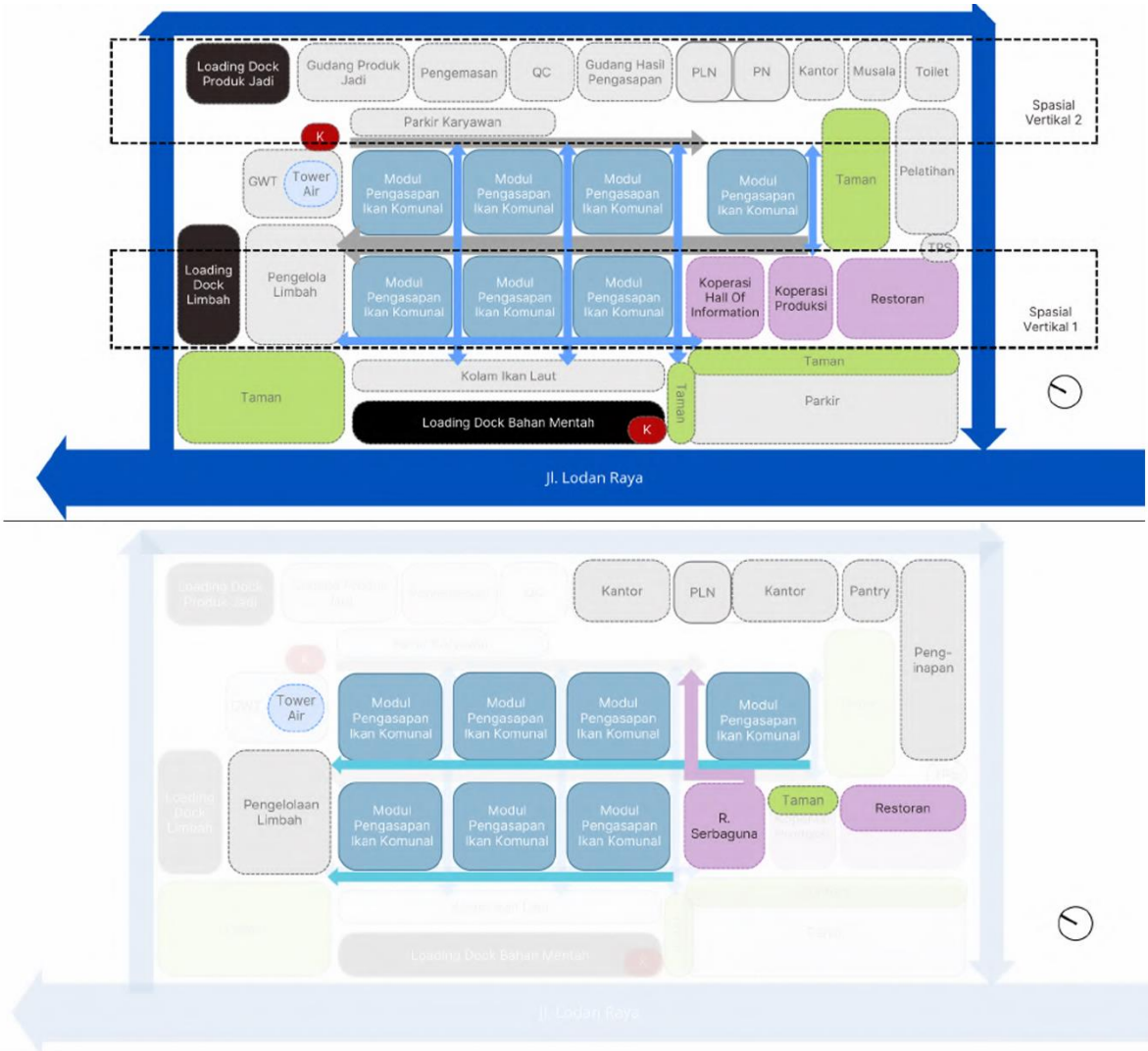


Diagram 1. First and Mezzanine Floor Masterplan Spatial Diagram

CONFLICT OF INTEREST

While the proposed design is rooted in established architectural and environmental theory, it is categorized as a preliminary strategic foundation. The efficacy of the smoke-to-liquid recycling system has not yet undergone rigorous mechanical validation or certification. Consequently, the projected outcomes remain theoretical, necessitating further engineering development and site-specific testing to confirm operational efficiency.

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Analysis of the Role of Green Accounting, Green Innovation, and Green Human Capital on Sustainability Disclosure based on Principles for Sustainable Insurance with Risk based Capital Moderation

Sub-Theme: *ESG and Sustainability Reporting*

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ABSTRACT

This study examines the effects of green accounting, green innovation, and green human capital on sustainability disclosure based on Principles of Sustainable Insurance in an object general insurance company with risk-based capital as a moderating variable and return on assets (ROA) and return on equity (ROE) as control variables, grounded in signaling theory. Using a quantitative approach, secondary data were collected from annual and sustainability reports of general insurance firms and analyzed using panel data regression analysis. The empirical results indicate that green accounting and green human capital have a positive effect on sustainability disclosure, while green innovation does not exhibit a positive effect. Risk-based capital strengthens the relationship between green accounting and sustainability disclosure but does not moderate the relationship between green innovation and sustainability disclosure. This study is subject to limitations related to data consistency, semi-subjective measurement indicators, and sector-specific sampling. Nevertheless, the findings provide empirical evidence that supports the development of sustainability disclosure practices and regulatory frameworks in the general insurance sector.

Keywords: *green accounting; green human capital; green innovation; insurance; risk-based capital; sustainability disclosure; sustainable insurance principles;*

INTRODUCTION

Sustainability within a company is increasingly important because it is closely related to the existence of the business. Sustainability has become a global issue, so that currently the long-term goal of a company is no longer merely generating profit, but rather focuses on the company's ability to maintain its existence in the business world (Astuti & Ahmar, 2025). Companies with the most sustainability implementations are financial companies. In the financial sector, business sustainability is closely related to the reputation and trust of customers in the company. Financial sector companies that experience business unsustainability will develop a bad reputation among customers, which can reduce customer trust in the company (Endiana et al., 2020). Insurance companies, as part of the financial sector, also have a responsibility for business sustainability. They must prioritize sustainability

in every aspect of their operations, as they are on the front lines of addressing social risks and long-term economic challenges (Gunardi et al., 2021). Insurance companies rely on their ability to measure and manage risk. Insurance companies primarily manage client funds by investing client premiums to provide protection against potential risks for the insured (Orisu et al., 2021)**.** Insurance companies have greater control than other businesses, as they assume the risks posed by clients/policyholders. To support the sustainability of insurance companies, the OJK as its independent regulator has begun requiring sustainability reporting and *Environmental, Social, Governance* (ESG) factors from these companies, namely the 2017 regulation Number 51. Insurance companies that are committed to sustainability are more trusted by customers and stakeholders, and can increase customer loyalty and attract a younger generation who are more environmentally conscious (Jahnert et al., 2025). Another implementation of the OJK regulation regarding business sustainability, insurance companies have issued green products. to support business sustainability, such as environmentally friendly property insurance, electric/hybrid vehicle insurance, renewable energy insurance, and insurance for carbon emission reduction projects.

Sustainability disclosure requires standards to meet the information needs of stakeholders. The use of *the Principles for Sustainable Insurance* (PSI), issued by the United Nations Environment Programme Finance Initiative (UNEP FI), as a sustainability disclosure standard specifically designed to address the characteristics of the insurance industry, which relies heavily on risk management and is highly exposed to climate change risks, is one of the differentiators of this research (Carmo *et al.,* 2022). UNEP FI is a partnership between UNEP and the global financial sector that aims to advance sustainable finance practices through the integration of environmental, social, and governance (ESG) principles into the operations of financial institutions, including insurance companies, and for the UNEP FI insurance sector (Silva *et al.,* 2025). Unlike the *Global Reporting Initiative* (GRI) standards, which are universal and applicable to all sectors, their focus is more general and emphasizes reporting on broad economic, social, and environmental impacts, UNEP FI's PSI provides much more specific guidelines for underwriting processes, insurance investment portfolio management, disaster risk assessment, and climate adaptation-mitigation strategies relevant to insurance companies. PSI also incorporates climate and social risk governance elements directly into core insurance business processes.

The implementation of Green Accounting, Green Innovation, and Green Human Resources through Sustainability Disclosure in Indonesia, especially insurance companies, is not yet optimal, despite the existence of several regulations. Based on POJK Number 51 of 2017 concerning the Implementation of Sustainable Finance for Financial Services Institutions, Issuers, and Public Companies, companies are required to implement Green Accounting to be able to prepare sustainability reports accurately. POJK Number 8 of 2024 concerning Insurance Products and Insurance Product Marketing Channels also supports innovation in insurance products so that companies are required to implement Green Innovation and report it in Sustainability Disclosure. POJK Number 34 of 2024 concerning Development of Human Resource Quality in Insurance Companies, Guarantee Institutions, and Pension Funds also requires the implementation of Green Human Resources and reporting it in Sustainability Disclosure.

There are inconsistencies in the research results of several researchers on related topics, namely research Frijat et al. (2025); Temirovich & Abdulkhakovich (2025)**;** Oktaviani

et al. (2024);Riyanti & Murwaningsari (2023) found that Green Accounting has a positive effect on Sustainability Disclosure. However, there is research that states that Green Accounting does not have a positive effect on Sustainability Disclosure, namely in researchPesak & Miran (2024); Rangkuti & Kumalasari (2023). Green Innovation has a positive influence on Sustainability Disclosure in research Khanchel et al. (2023); Siregar et al. (2023); Srouji et al. (2023). However, Green Innovation does not have a positive effect on Sustainability Disclosure in the study. Putri & Aji (2025). Green Human Resources have a positive influence on Sustainability Disclosure in research Magau (2025); Riyanti & Murwaningsari (2023); Nikolaou et al. (2024); However Bananuka et al. (2023), Green Human Resources does not affect Sustainability Disclosure in the study Nurmalasari & Vinezha (2024). *Risk Based Capital* has a positive effect on Sustainability Disclosure in the study.Kazemi et al. (2025) And Lim et al. (2021).

This study used a sample of insurance companies that were members of the Indonesian General Insurance Association for the 2021-2024 period. This study combined the independent variables of Green Accounting, Green Innovation, and Green Human Resources into a single study. The study Srouji et al. (2023)used only the independent variable Green Innovation, and the independent variable Green Human Resources.Riyanti & Murwaningsari (2023) This study only uses the independent variables Green Accounting and Green Human Resources. This study also adds the moderating variable *Risk-Based Capital.* and control variables ROA and ROE.

This research uses Signal Theory. Spence (1973) introduces signaling theory in the context of information economics, particularly in relation to the labor market. The essence of signaling theory is that there is an information imbalance between two parties: internal parties who have information (such as company management) and external parties who need that information (such as investors, creditors, and other stakeholders). Bird & Smith (2005)explains that to reduce uncertainty, those with more complete information can send signals to others. These signals can be actions, policies, or information disclosures intended to indicate the quality, condition, or prospects of an entity. In the corporate context, disclosure of information through Sustainability Disclosure demonstrates to the market that the company follows responsible business practices in terms of governance, environment, and social (ESG). (Scott & O'Brien, 2020).According to signaling theory, companies with good performance or competitive advantages tend to be more motivated to disclose information more openly and completely. This is done to differentiate them from less successful companies. Such disclosure is expected to strengthen the company's reputation, attract investors concerned with sustainability, and increase market confidence (Subroto & Endaryati, 2024).

By adopting Green Accounting practices, companies demonstrate transparency in reporting their environmental impact. Green Accounting is seen as a signal that a company cares about the environment and has an accounting system that takes ecological impact into account (Astuti & Ahmar, 2025). This implementation demonstrates to stakeholders that the company is environmentally responsible and transparent and complies with applicable environmental regulations (Rana et al., 2025). Conversely, the Green Innovation initiative demonstrates the company's commitment to creating environmentally friendly products and processes. Green Innovation signals the company's ability to innovate sustainably, improve energy efficiency, or reduce carbon emissions. This implementation demonstrates that the company is not solely pursuing profit but is committed to sustainability (Singh et al., 2024).

Investments in Green Human Resources, such as sustainability-related training and skills development, also demonstrate a company's commitment to building a corporate culture that supports long-term sustainability goals. This disclosure serves as a signal that the company has competent human resources to implement sustainability strategies (Bahri & Aprilianti, 2023). Signaling theory supports the understanding of how businesses implement practices such as Green Accounting, Green Innovation, and Green Human Resources as positive signals conveyed through Sustainability Disclosure, demonstrating non-financial added value and commitment to sustainability.

Based on signaling theory, sustainability disclosure can be considered a positive signal to investors. The more comprehensive, transparent, and high-quality the sustainability disclosure, the stronger the market signal that the company is committed to responsible business practices. (Goh, 2023).

Hypothesis Development

The implementation of Green Accounting serves as a signal that a company has a high level of environmental awareness and responsibility (Kusmawati & Anisah, 2025). This strengthens the quality of Sustainability Disclosure, as the information disclosed becomes more relevant, measurable, and integrated with financial reporting. Thus, companies are able to build positive perceptions from stakeholders such as regulators, consumers, and investors, who are increasingly paying attention to sustainability issues. Research Temirovich & Abdulkhakovich (2025)shows that the implementation and reporting of Green Accounting has a positive effect on improving the quality of Sustainability Disclosure , which reflects transparency and accountability in managing environmental aspects. The results of this study agree withFrijat et al. (2025); Oktaviani et al. (2024)And Khan & Gupta (2024)which states that the higher the level of Green Accounting disclosure in a company, the better its Sustainability Disclosure. Based on the explanation above, the first hypothesis in this study is:

H1: Green Accounting has a positive effect on Sustainability Disclosure.

In the context of capital markets and sustainable corporate governance, the implementation of Green Innovation demonstrates to stakeholders that the company is committed to sustainability and environmental responsibility (Kurniawati & Widiayana, 2024). Based on signaling theory, companies can use Green Innovation practices as a means to communicate values, strategies, and environmental concerns to external parties transparently. One form of conveying this signal is through Sustainability Disclosure which includes disclosure of information related to the company's environmental initiatives, policies, and performance. Research Srouji et al. (2023); Khanchel et al. (2023)and Siregar et al. (2023) proves that Green Innovation has a positive effect on improving the quality of Sustainability Disclosure, which strengthens the company's transparency and accountability towards environmental issues. The better the Green Innovation, the better the company's Sustainability Disclosure (Baranova et al., 2025). Based on this explanation, the second hypothesis in this study is:

H2: Green Innovation has a positive effect on Sustainability Disclosure.

The implementation of Green Human Resources encourages improved Sustainability Disclosure because employees play an active role in the process of reporting and transparently disclosing environmental initiatives and performance. This also increases the

credibility of the information conveyed to stakeholders Amin & Herawaty (2024). And Widyastuti et al. (2021)shows that Green Human Resources have a positive effect on improving the quality of Sustainability Disclosure because HR involvement and competence are key factors in conveying corporate sustainability information. The more Green Human Resources a company has, the better its Sustainability Disclosure. Considering these explanations, the third hypothesis of this study is:

H3: Green Human Resources have a positive effect on Sustainability Disclosure

The higher the RBC value, the greater the company's capacity to absorb risks and finance strategic initiatives, including investments in environmental and sustainability reporting systems. This means that companies with a high RBC tend to have more sufficient resources to support the comprehensive and systematic implementation of Green Accounting. Therefore, RBC is used as a moderating variable to strengthen the influence of Green Accounting on Sustainability Disclosure. When the RBC is high, the positive impact of Green Accounting on Sustainability Disclosure is stronger. Conversely, when the RBC is low, the relationship becomes weaker. According to researchKazemi et al. (2025) And Lim et al. (2021) Risk Based Capital strengthens the positive influence of Green Accounting on Sustainability Disclosure. Based on this explanation, the fourth hypothesis in this study is:

H4: Risk Based Capital strengthens the influence of Green Accounting on Sustainability Disclosure.

Green Innovation is a crucial element supporting the quality and comprehensiveness of Sustainability Disclosure, particularly in environmental disclosure . Companies with a high RBC have greater confidence in taking risks and innovating in the environmental sector, supported by a strong capital structure. Therefore, RBC is expected to strengthen the influence of Green Innovation on Sustainability Disclosure. This means that companies with high capital capacity will be better able to maximize the positive impact of Green Innovation in sustainability reporting, both in terms of information quality, transparency, and environmental accountability. These results agree and align with research Kazemi et al. (2025)andLim et al. (2021) which states that Risk-Based Capital strengthens the influence of Green Innovation on Sustainability Disclosure. Based on the explanation above, the fifth hypothesis in this study is:

H5: Risk Based Capital strengthens the influence of Green Innovation on Sustainability Disclosure.

A company's success in utilizing Green Human Resources is largely determined by its internal capacity, particularly in the financial aspects of insurance companies, as assessed by Risk-Based Capital (RBC). With adequate capital support, companies are able to optimally develop Green Human Resources through intensive training, a reward system for green initiatives, and the integration of sustainability values into HR management. Based on this explanation, Risk-Based Capital is suspected of strengthening the influence of Green Human Resources on Sustainability Disclosure. In other words, the contribution of Green Human Resources in driving business sustainability reporting is comparable to RBC. According to researchKazemi et al. (2025) And Lim et al. (2021), Risk Based Capital strengthens the positive influence of Green Human Resources on Sustainability Disclosure. Based on the explanation above, the sixth hypothesis in this study is:

H6: Risk Based Capital strengthens the influence of Green Human Resources on Sustainability Disclosure.

Framework Conceptual

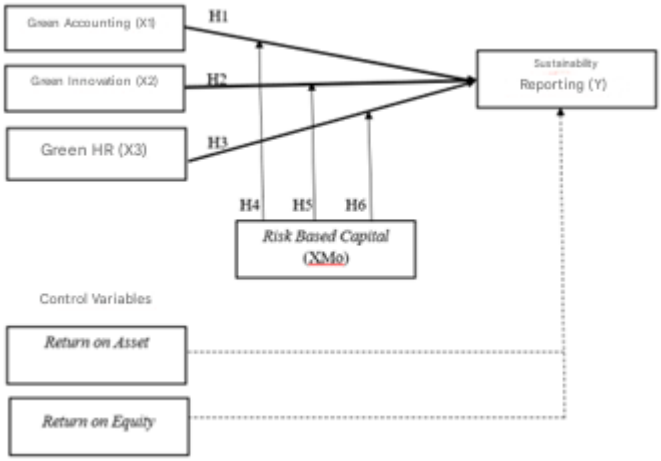

Figure 1.1 Framework Conceptual

MATERIALS AND METHOD

Research Design

This study uses a quantitative approach to explore the relationship between Green Accounting, Green Innovation, and Green Human Resources, strengthened by the moderation of *Risk-Based Capital* . The dependent variable in this study is Sustainability Disclosure (Oktaviani et al., 2024). The independent variables in this study are Green Accounting, Green Innovation, and Green Human Resources . The moderating variable in this study is *Risk-Based Capital* . This type of hypothesis testing is known as causality testing, and its purpose is to determine whether the dependent variable or the independent variable is influenced by the independent variable. This study uses panel data regression, which combines time series with cross-sectional data, to account for the temporal dimension. Secondary data collected from annual reports, sustainability reports, and information from each company's website for the past four years (2021–2024) were used in this study. Quantitative analysis was then conducted to draw conclusions from the study. The research subjects were general insurance companies registered as members of the Indonesian General Insurance Association from 2021 to 2024. The study used *purposive sampling* and *balanced sampling techniques* in the process of determining and selecting the sample of companies to be used in the study.

Table 2.1 Measurement Variables

Numbers.	Variables	Formula	Scale
1.	Disclosure Sustainability	*UNEP FI Scoring* : 0 = No disclosure 1 = Qualitative information 2 = Qualitative and numerical information 3 = Qualitative information, numbers, and diagrams (pictures) Sustainability Disclosure = Implemented indicators 78 (indicators total)x 100% Source :Labini et al. (2025)	Ratio
2.	Green Accounting	Green Accounting = Implemented indicators 3 (indicators total)x 100% Source:Goddess(2020)	Ratio
3.	Green Innovation	Green Innovation = Implemented indicators 12 (indicators total)x 100% Source :Srouji et al. (2023)	Ratio
4.	Green Human Resources	Green Human Resources = Implemented indicators 5 (indicators total)x 100% Source :Yusoff *et al* (2020)	Ratio
5.	*Risk-Based Capital*	*Risk Based Capital = Equity Minimum Solvency Level Limit x100%* Source :Lim et al. (2021)	Ratio
6.	ROA	*Return on Assets = Net Profit / Assets Total* Source :Chandler (1977)	Ratio
7.	ROE	*Return on Equity = Net Profit / Equity Total* Source:Chandler (1977)	Ratio

Panel Data Regression and Moderated Regression Analysis (MRA). Panel data regression is used to test the influence of independent variables on dependent variables.

$$Y = a + \beta 1X1 + \beta 2X2 + \beta 3X3 + \beta 4XMo + \beta 5X1*XMo + \beta 6X2*Xmo + \beta 7X3*Xmo + e$$

RESULTS AND DISCUSSION

The sample used in this study was all insurance companies registered with the Indonesian General Insurance Association (AAUI) for the period 2021 to 2024. Based on the criteria outlined in the research method, it was found that 75 general insurance companies registered with the Indonesian General Insurance Association (AAUI) for the period 2021-2024 were selected. However, several sample criteria were not met, resulting in a sample size of 66 companies. The total sample size for this study was 264 companies.

Table 3.1 Results of Descriptive Statistical Tests

Variables	N	Min	Max	Mean	Standard Deviation
X1_Green Accounting	264	0.333	1,000	0.667	0.214
X2_Green Innovation	264	0.250	1,000	0.697	0.153
X3_Green Human Resources	264	0.200	1,000	0.633	0.203
XMo_Risk Based Capital	264	0.396	34,832	3,806	3,830
XC1_Return on Asset	264	0.001	0.253	0.039	0.036
XC2_Return on Equity	264	0.001	4,324	0.145	0.313
Y_Disclosure Sustainability	264	0.141	0.740	0.444	0.116

The Sustainability Disclosure variable shows that the company only disclosed 14.1% of the total Sustainability Disclosure items. Meanwhile, the maximum value shows that there are insurance companies that have disclosed 74% of the items in the sustainability disclosure indicator. The general standard deviation of the companies in the research sample has disclosed around 44% of the total Sustainability Disclosure items. The Green Accounting variable has a minimum value of 33%, meaning the majority only disclosed one of the three indicators related to Green Accounting practices. The indicator least disclosed by insurance companies from 2021-2024 was *Green Marketing & Promotion Cost,* which is the cost associated with promoting green activities such as marketing and promotions that are environmentally friendly, energy efficient, and produce low carbon emissions. The Green Accounting cost indicator most frequently disclosed by insurance companies was *Environmental Operational Cost,* the cost incurred for operational activities that have a direct impact on environmental management, such as waste management, emission reduction, and energy efficiency. Green Innovation Variables Only 25% of the Green Innovation indicators were disclosed or implemented by the company. The least disclosed Green Innovation indicator was a separate page for green reporting in the annual report. The most disclosed Green Innovation indicator by this insurance company was the use of information on green marketing integration, such as the phrase "Plant Trees, Save the Environment" and other Green Innovation slogans.

Variables Green Human Resources own minimum value of 20% of indicator Green Human Resources used in research . Indicators The least Green Human Resources expressed company insurance is employee own sufficient capacity in matter attention to environment seen in mandatory training and seminars followed employees (He *et al.,* 2023). The most frequently cited indicator of Green Human Resources is the CEO's full support for environmental initiatives within the company. This can be seen in *the Management Overview* in the annual report and the sustainability report. Most companies have levels of sustainable human resource development that are not significantly different from the average, although some companies have significantly higher or lower levels (Chen *et al.,* 2023). 5. The *Risk-Based Capital* variable has a minimum value of 39.6% . This figure means the company only has capital equivalent to 39.6% of the total minimum capital required by regulators. This value does not meet the 120% requirement for the insurance industry in Indonesia, indicating a relatively weak capital position compared to other companies in the sample. The maximum

value is 3,483% . This indicates that the company has a capital capacity approximately twenty-nine times the minimum required (Lim *et al.,* 2020). *6. The Return on Assets* variable has a minimum value of 0.001 or 1% . This value reflects a very low level of efficiency in generating profits from the company's total assets, even approaching the break-even point. The maximum value of *the Return on Assets* variable is 0.253 or 25.3% . This indicates that the company is able to generate a net profit of 25.3% of its total assets, indicating high efficiency and profitability. The average (mean) ROA of the entire sample is 0.039 or 3.9%. 7. Variables *Return on Equity* own minimum value as big as 0.001 or 1% . This value reflect that company the only capable produce profit amounting to 1% of its total equity , indicating efficiency low finances in managing owner's capital . The maximum ROE value is 4,324 or 43.2% . This figure show that company capable produce profit clean approximately 43% of total equity , which reflects efficiency and performance excellent finances (Azwin *et al.,* 2024).

Table 3.2 Normality Test Results

Regression Model	Asymp. Sig	Conclusion
Regression Model Multiple	0.200	Normally Distributed

A normality test was conducted to determine whether the variables used in the study were normally distributed. This study used a statistical tool, the Kolmogorov-Smirnov test (KS test), to test the normality of the residual values. The research model can be said to have a normal residual distribution if the *probability value* or Asymp.Sig. (2-tailed) is greater than 5%. Based on Table 4.2, which displays the results of the normality test, it can be seen that the Asymp. Sig. (2-tailed) value is 0.200. This value is greater than 0.05. Therefore, it can be concluded that the distribution of residual values in the studied model is normal and H0 is accepted. Multicollinearity test aims to examine the relationship between independent variables. A good regression model is one in which there is no correlation between the independent variables. can seen from mark *Variance Inflation Factor* (VIF). The value used as a criterion is a VIF value smaller than 10.

Table 3.3 Multicollinearity Test Results

Variables	*Tolerance*	VIF	Conclusion
Green Accounting	0.914	1,094	n't any multicollinearity
Green Innovation	0.767	1,304	n't any multicollinearity
Green Human Resources	0.795	1,257	n't any multicollinearity
Risk-Based Capital	0.280	3,574	n't any multicollinearity
Return on Asset	0.924	1,082	n't any multicollinearity
Return on Equity	0.927	1,079	n't any multicollinearity
X1_Xmo	0.511	1,956	n't any multicollinearity

Variables	*Tolerance*	VIF	Conclusion
X2_Xmo	0.741	1,349	n't any multicollinearity
X3_Xmo	0.404	2,475	n't any multicollinearity

Test results show all variables own VIF value is higher small of 10. The test results also show that all variables have a *tolerance value* greater than 0.01. This means that in the research model there is no correlation between the independent variables.

Table 3.4 Heteroscedasticity Test Results

Variables	Sig	Conclusion
Green Accounting	0.992	n't any heteroscedasticity
Green Innovation	0.330	n't any heteroscedasticity
Green Human Resources	0.239	n't any heteroscedasticity
Risk-Based Capital	0.792	n't any heteroscedasticity
Return on Asset	0.848	n't any heteroscedasticity
Return on Equity	0.219	n't any heteroscedasticity
X1_Xmo	0.975	n't any heteroscedasticity
X2_Xmo	0.125	n't any heteroscedasticity
X3_Xmo	0.491	n't any heteroscedasticity

The heteroscedasticity test aims to determine whether there is unequal *variance* in the residuals from one observation to another in the regression model. A good regression model is one that does not exhibit heteroscedasticity. This heteroscedasticity test is performed using the Park test, which regresses *the absolute residuals* against each independent variable. An autocorrelation test in a linear regression model must be performed if the data is *time series* . Autocorrelation essentially means that a value in a particular sample or observation is significantly influenced by the value of the previous observation. The statistical tool used to determine the correlation between residuals in this study is the Durbin-Watson test.

Table 3.5 Autocorrelation Test Results

N	dL	dU	4-dU	4-dL	DW	Conclusion
264	1,669	1,804	2,196	2,331	2,041	n't any autocorrelation

The Durbin Watson test decision-making uses the condition if dU < d < 4-dU. If it meets these conditions, then there is no positive or negative autocorrelation in the research sample. Based on the Durbin Watson table k = 9 and n = 264, dU = 1.804 is found , so 1.804 < 2.041 < 2.196 . Therefore, it can be concluded that there is no autocorrelation in the equation above.

Table 3.6 Results of the Determination Coefficient Test

Model	Adjusted ^{R2}	% Adjusted ^{R2}
Regression Model Multiple	0.582	58.2%

Based on the determination coefficient test conducted, the *adjusted R square value was obtained* as 0.582 or 58.2%. The F-test is used to determine whether independent variables simultaneously have a significant effect on the dependent variable. The confidence level used in this study is 0.05, so a sig. value smaller than the probability value of 0.05 indicates a simultaneous influence of the independent variables on the dependent variable.

Table 3.7 Results of Simultaneous Significance Test

Model	F	Sig.	Conclusion
Regression Model Multiple	30,853	0.0000	Significant

Based on table 4.7 above, the F value is 30.853 with a probability value of 0.0000 and less than the significance value of 0.05. From this probability value, it can be concluded that Green Accounting, Green Innovation, and Green Human Resources, moderated by *Risk-Based Capital* and controlled by *Return on Assets* and *Return on Equity,* have a simultaneous effect on Sustainability Disclosure. in sample companies.

A partial test is conducted to partially examine the effect of the independent variable on the dependent variable. This test is conducted using multiple regression analysis with a 95% confidence level or an alpha value of 5%. The following are the results of the partial test using the t-test.

Result

Table 3.8 t-Test Results

Variables	**Prediction Direction**		**Significant *(One-Tails)***	**Conclusion**
Green Accounting	Positive	0.241	0.001	H1 accepted
Green Innovation	Positive	0.087	0.175	H2 is rejected
Green Human Resources	Positive	0.161	0.019	H3 accepted
Green Accounting * *Risk Based Capital*	Strengthen	0.132	0.001	H4 accepted
Green Innovation * *Risk Based Capital*	Strengthen	0.046	0.215	H5 is rejected
Green Human Resources * Risk *Based Capital*	Strengthen	0.058	0.110	H6 is rejected

These results can be written in the following regression equation model:

Y = 0.241AH + 0.087IH + 0.161SDMH + 0.132AH*RBC + 0.046IH*RBC + 0.058SDMH*RBC

Based on the Hypothesis Test Results table 4.8 above, it can be concluded that hypotheses H2, H5, and H6 are rejected because they have probability values greater than

the significance value of 0.05. This means that Green Innovation cannot have a positive effect on Sustainability Disclosure. *Risk-Based Capital* is unable to strengthen the positive effect of Green Innovation and Green Human Resources on Sustainability Disclosure. Hypotheses H1, H3, and H4 are accepted because they have probability values smaller than the significance value of 0.05. This means that Green Accounting and Green Human Resources have a positive effect on Sustainability Disclosure. *The Risk-Based Capital ratio* is able to strengthen the positive effect of Green Accounting. towards Sustainability Disclosure.

Hypothesis Test Results

The results of the first hypothesis testing in this study indicate that Green Accounting has a positive and significant effect on Sustainability Disclosure in general insurance companies affiliated with the Indonesian General Insurance Association (AAUI) during the 2021–2024 period. This finding indicates that the higher the adoption and implementation of Green Accounting in a company, the better the quality of the resulting Sustainability Disclosure (Zelazna, 2020). Green Accounting includes recording and reporting environmental costs, recognizing environmental assets and liabilities, and measuring ecological impacts within the company's financial accounting framework, which is divided into three categories: *environmental operational costs, green marketing and promotion costs, and environmental development and research costs* . This practice is not merely administrative but is an integrated part of the reporting system that demonstrates the company's real commitment to sustainability. This research aligns with Signaling Theory, which states that companies strive to send signals to external parties, such as investors, regulators, and the general public, to reduce information asymmetry and foster positive perceptions of company performance (Yilmaz, 2021). In this case, Green Accounting acts as a signal that the company is not only concerned with financial performance but also oriented towards environmental risk management and long-term sustainability. Measurable and documented environmental information through Green Accounting serves as the main foundation for preparing credible and meaningful Sustainability Disclosures. Based on Signaling Theory, the implementation of Green Accounting serves as a credible initial signal regarding the company's commitment to sustainability. This signal is then reinforced and communicated widely through transparent, measurable, and consistent Sustainability Disclosures. Thus, insurance companies that implement Green Accounting well have a greater opportunity to gain *stakeholder trust* and strengthen their strategic position in facing increasingly complex business challenges in the green economy era. This research is in line with the results of other research.Baranova et al. (2025); Pertiwi et al. (2023); and Riyanti & Murwaningsari (2023)which shows a positive relationship between Green Accounting and Sustainability Disclosure.

The results of testing the second hypothesis in this study indicate that Green Innovation negatively impacts Sustainability Disclosure in insurance companies affiliated with the Indonesian General Insurance Association (AAUI) during the 2021–2024 period. This study's findings demonstrate a relationship inconsistent with most previous theories and empirical findings, which generally state that environmentally friendly innovation or Green Innovation contributes positively to improving the quality and comprehensiveness of Sustainability Disclosure (Toke and Kalpande, 2023). Green Innovation, which encompasses the development of environmentally friendly products, processes, and technologies, is theoretically believed to strengthen a company's sustainability position. These results indicate that the adoption of Green Innovation in the insurance sector in Indonesia has not been widely

implemented because the services offered tend not to be directly related to environmental damage or pollution. Insurance services do not directly produce waste from their operational activities that threaten environmental sustainability, therefore insurance companies do not place much emphasis on Green Innovation. Furthermore, the Green Innovations undertaken by these insurance companies have the potential to be ineffectively integrated into the Sustainability Disclosure system and appear to reflect the company's failure to communicate Green Innovation initiatives as a positive signal to *stakeholders* through Sustainability Disclosure (Shah and Bhatt, 2022). Signaling Theory states that companies use various mechanisms, including Sustainability Disclosure, to convey positive signals about their commitments, values, and future prospects to the market and stakeholders. The Green Innovations undertaken by these companies are not clearly documented or reported in Sustainability Disclosure, so these initiatives fail to shape positive public perceptions. The absence of sufficient information regarding Green Innovations can raise doubts and the perception that the company is not truly committed to sustainability, ultimately reducing the credibility of Sustainability Disclosure . Based on the results of this study, Green Innovations undertaken by insurance companies are still in their early stages or are internally technical and have not been developed as part of a comprehensive sustainability strategy. Consequently, the impact of these innovations is not yet strong enough to be reflected in Sustainability Disclosure (Rahi *et al.,* 2024) . Companies may also not see any urgency or pressure from regulators or the market to explicitly report on their environmental innovations, so sustainability reporting remains normative and has not yet incorporated Green Innovation aspects in depth. The results of this study provide a signal that there is a need for increased integration between Green Innovation strategies and Sustainability Disclosure in Indonesian insurance companies and insurance companies in Indonesia also need to increase the adaptation of Green Innovation in their operational activities. This study is in contrast to research Kholifatunnisa & Setyorini (2025); Siregar et al. (2023); andMarietza & Nadia (2021) who found that Green Innovation has a positive effect on improving the quality of Sustainability Disclosure .

The results of the third hypothesis testing in this study indicate that Green Human Resources have a positive and significant effect on Sustainability Disclosure in general insurance companies that are members of the Indonesian General Insurance Association (AAUI) during the period 2021 to 2024. This finding indicates that companies that actively develop the quality of Human Resources (HR) with insight, competence, and concern for environmental issues through training, recruiting environmental experts, and strengthening a sustainability-oriented organizational culture tend to produce more informative, transparent, and relevant sustainability reporting. In the context of the insurance industry, strengthening Green Human Resources is crucial considering that this sector is highly dependent on human capacity in managing risks, making strategic decisions, and responding to regulatory and social pressures related to *Environmental, Social, and Governance* (ESG) . The results of this study are in line with Signaling Theory which states that organizations will strive to send signals that demonstrate the company's quality and values to external parties, especially in conditions where there is information asymmetry between management and stakeholders. Green Human Resources become an internal signal that reflects the company's values, orientation, and long-term commitment to sustainability (Rahaman *et al.,* 2024). This is because human resources who understand the importance of environmental issues will encourage management to report green initiatives more proactively and strategically.

Furthermore, Green Human Resources also act as facilitators for other sustainability initiatives, such as Green Innovation and Green Accounting, as human competencies are key to designing, implementing, and evaluating these programs. Based on Signaling Theory, the presence of environmentally conscious human resources is clear evidence that a company is not merely carrying out social responsibility formally, but truly embedding sustainability into its organizational DNA (Pahlavan *et al.,* 2023). This serves as a credible signal that can increase stakeholder trust in the quality of the Sustainability Disclosure presented. This research is in line with research ; Magau (2025); Amin & Herawaty (2024)andAlkaf et al. (2023) shows that Green Human Resources have a positive influence on improving the quality of Sustainability Disclosure.

The results of the fourth hypothesis testing in this study found that *Risk-Based Capital* (RBC) can strengthen the influence of Green Accounting on Sustainability Disclosure. The higher a company's RBC level, the stronger the impact of Green Accounting implementation in promoting the quality and transparency of sustainability reporting. These research findings align with Signaling Theory, which states that companies will strive to send positive signals to the market and stakeholders through information that reflects positive internal conditions. Green Accounting and RBC are two mutually reinforcing signals (Nzama *et al.,* 2022). The implementation of Green Accounting signals that a company cares about its environmental impact, while a high RBC indicates a company's financial health and ability to manage risks effectively. When these two signals appear simultaneously, the credibility of a company's Sustainability Disclosure is strengthened in the eyes of investors, regulators, and the public. Companies with a high RBC have a better capital structure and financial resilience in facing operational and environmental risks. This condition allows companies to consistently implement quality Green Accounting practices such as recording emissions, energy use, waste management, and measuring other environmental impacts without being hampered by financial constraints. In other words, RBC creates fiscal and organizational space for companies to make Green Accounting a strategic part of business activities, not just symbolic reporting (Buric *et al.,* 2022). The implementation of Green Accounting tends to be more conservative than general accounting, requiring greater funding in terms of capital, profitability, and cash flow. Therefore, insurance companies with a higher RBC are more suitable for implementing Green Accounting. This strengthens the positive signal to the market that the company has a long-term commitment to sustainability. The results also show that the interaction coefficient between Green Accounting and RBC is positive and significant. This proves that RBC can act as a moderating variable that strengthens the relationship between Green Accounting practices and the quality of Sustainability Disclosure (Musa *et al.,* 2021). The signal generated from the combination of Green Accounting and a high RBC is considered more convincing than if a company relies solely on one or the other. Signaling Theory states that companies not only convey their intentions *through* Green Accounting but also demonstrate their capacity *through* a strong RBC. Furthermore, considering the role of the control variables *Return on Assets* (ROA) and *Return on Equity* (ROE), the regression results still show a significant moderating effect of RBC. This means that the influence of RBC as a moderator is consistent, even after considering the company's financial performance. This strengthens the interpretation that the signal provided by RBC is not merely a reflection of profitability, but rather an indication of risk management and financial stability that support the credibility of sustainability reporting. This research aligns with researchAmin & Herawaty

(2024) And Widyastuti et al. (2021), *Risk Based Capital* is able to strengthen the positive influence of Green Accounting on Sustainability Disclosure.

The study's findings indicate that *Risk-Based Capital* (RBC) is unable to strengthen the positive influence of Green Innovation on Sustainability Disclosure in general insurance companies in Indonesia. The presence of RBC does not provide a significant moderating effect and does not increase the positive influence between Green Innovation and Sustainability Disclosure (Mondal *et al.,* 2024). This finding indicates that although companies have high capital adequacy, it is not used to strengthen their commitment to disclosing sustainability information. RBC continues to function primarily as a tool to comply with mandatory solvency regulations, rather than as a factor that encourages companies to make broader sustainability disclosures. In the insurance sector, RBC is positioned as a primary indicator of financial stability and the company's ability to face claims risks. Therefore, general insurance companies tend to place greater emphasis on meeting the minimum RBC threshold set by the Financial Services Authority (OJK) to maintain operational continuity and regulatory compliance. This study also considers ROA (*Return on Assets*) and ROE (*Return on Equity*) as control variables to ensure that the results are not influenced by fluctuations in company profitability. ROA and ROE were used to control for the possibility that companies with higher financial performance are more likely to disclose sustainability information (Latifah and Soewarno, 2023). However, even with the inclusion of these two control variables, the study results still show that RBC does not moderate the influence of green innovation on sustainability disclosure. This confirms that capital adequacy, even after controlling for differences in profitability between companies, is not a factor that encourages companies to disclose sustainability information more intensively. Company profitability is unable to change the function of RBC, which is more oriented towards risk stability than sustainability transparency. This study's findings contradict Signaling Theory, which states that companies with strong financial capacity tend to send positive signals to stakeholders through the delivery of broader and more transparent information. However, the study results show that RBC does not act as an external signal that encourages companies to increase sustainability disclosure (Huong *et al.,* 2024). This indicates that in the general insurance industry in Indonesia, RBC is perceived solely as an internal indicator, rather than as a tool to build a company's image in the eyes of investors and the public.

Although more profitable companies have greater resources to support green innovation and sustainability reporting, RBC still does not moderate the relationship (Horich *et al.,* 2020). This suggests that profitability and capital adequacy serve different functions in the context of sustainability reporting. ROA and ROE may reflect a company's ability to generate profits, but RBC is a measure of capital readiness for risk, not a measure of a company's ability or willingness to expand sustainability disclosure. Overall, the findings of this study provide insight that RBC cannot function as an external signal in the context of sustainability reporting, despite signaling theory predicting otherwise. General insurance companies in Indonesia appear to separate financial compliance and sustainability strategy, thus RBC is not included in strategic considerations to strengthen the influence of Green Innovation on Sustainability Disclosure. These results also indicate that other factors such as regulatory pressure on ESG, investor demand, or corporate culture may be more influential in determining the level of sustainability disclosure than capital adequacy. This research contrasts with researchAmin & Herawaty (2024) and Widyastuti et al. (2021) who found that

Risk Based Capital strengthens the positive influence of Green Innovation on Sustainability Disclosure.

The results of this study indicate that the moderating variable *Risk-Based Capital* (RBC) is unable to strengthen the positive relationship between Green Human Resources and Sustainability Disclosure in general insurance companies in Indonesia. This is indicated by the interaction coefficient between Human Resources and RBC, which is positive but very small, followed by a significance value far above the tolerance limit of 0.05. Thus, RBC does not function as a variable that enhances or strengthens the ability of Green Human Resources to encourage sustainability disclosure practices in insurance companies. Green Human Resources reflects an organization's ability to manage employees oriented towards sustainability values, such as environmental competence, awareness of environmentally friendly practices, and the ability to integrate green principles into business processes (Gull *et al.,* 2022). Much of the literature considers Green Human Resources to be an important driver in strengthening a company's commitment to implementing sustainability policies more systematically. However, the results of this study indicate that although Green Human Resources has the potential to contribute to sustainability disclosure, the presence of RBC as an indicator of financial health does not significantly strengthen this relationship.

Research findings indicate that this is not the case. Even if a company is in a healthy financial position, this does not automatically encourage an increased role for Green Human Resources in Sustainability Disclosure practices. This insignificance can be explained by several factors that may be present in the context of the general insurance industry in Indonesia (Giang *et al.,* 2021). First, insurance companies tend to view RBC as a regulatory obligation to measure capital strength and the company's ability to meet policy risks, rather than as a strategic indicator to drive sustainability activities. Most companies focus more on meeting the Financial Services Authority (OJK) requirement to maintain a minimum RBC level of 120% rather than utilizing it as a tool to strengthen sustainability reporting practices. As a result, even if the RBC is high, it is not used as a basis for expanding or enhancing the contribution of Green Human Resources in the disclosure process. Second, general insurance companies may have developed Green Human Resources through training or internal programs, but have not fully integrated these competencies into their sustainability reporting systems. In many cases, sustainability efforts focus more on compliance *and* reputational aspects. Therefore, even when Green Human Resources (HR) is available, its contribution to Sustainability Disclosure is still suboptimal (Erbetta *et al.,* 2023). Based on signaling theory, companies with strong capital can use sustainability reporting as a tool to demonstrate credibility, stability, and long-term commitment to sustainable business practices. Thus, companies are expected to not only strengthen the impact of Green HR practices but also increase the intensity and quality of sustainability disclosure. However, in the context of this study, this signaling mechanism did not work. High RBC did not encourage companies to provide positive signals through sustainability reporting practices. This indicates that general insurance companies in Indonesia primarily use RBC as an internal, financial-based risk indicator, rather than as an external signal of sustainability commitment (Deb *et al.,* 2023). Thus, RBC does not play a strong enough role in strengthening the relationship between Green HR and sustainability disclosure, contradicting the predictions of signaling theory. Furthermore, this study also considered control variables in the form of *Return on Assets* (ROA) and *Return on Equity* (ROE), which were used to ensure that the relationship between the variables was not influenced by the company's financial performance. However, even

though ROA and ROE were controlled in the research model, RBC still did not show a significant moderating role. This strengthens the conclusion that the strength of a company's capital is not directly related to the effectiveness of Green HR in improving sustainability reporting. From an industry perspective, general insurance companies generally face more dominant regulatory pressures than market pressures regarding sustainability reporting. Therefore, even though companies have strong capital, the priority of capital use is more focused on maintaining solvency and meeting operational standards rather than strengthening sustainability capacity. This asymmetry between financial strength and sustainability capacity is why RBC does not play a role as a reinforcing factor in this study. Overall, this study shows that strong financial conditions reflected through RBC do not necessarily encourage an increase in the effectiveness of Green HR in influencing sustainability disclosure. This finding contradicts signaling theory and shows that sustainability reporting in general insurance companies in Indonesia is still more influenced by other factors, such as regulatory compliance, organizational culture, and understanding of sustainability strategies, than by indicators of capital health. This research is in line with research Amin & Herawaty (2024) and Widyastuti et al. (2021) which found that *Risk Based Capital* is unable to strengthen the positive influence of Green Human Resources on Sustainability Disclosure.

CONCLUSIONS

This study aims to determine the effect of Green Accounting, Green Innovation, and Green Human Resources on Sustainability Disclosure, with *Risk-Based Capital* as a moderating variable, and *Return on Assets* and *Return on Equity* as control variables. The sample of this study was 66 insurance companies that are members of the Indonesian General Insurance Association (AAUI). in 2021-2024. Based on the testing conducted and the results of the research discussion, the conclusions of the study are:

1. Green Accounting has a positive impact on Sustainability Disclosure.
2. Green Innovation does not have a positive effect on Sustainability Disclosure.
3. Green Human Resources have a positive influence on Sustainability Disclosure.
4. *Risk Based Capital* is able to strengthen the influence of Green Accounting on Sustainability Disclosure.
5. *Risk Based Capital* is unable to strengthen the influence of Green Innovation on Sustainability Disclosure.
6. *Risk Based Capital* is unable to strengthen the influence of Green Human Resources on Sustainability Disclosure.

RESEARCH LIMITATIONS

This study has several limitations that need to be considered in interpreting the results and developing recommendations for further research. The limitations of this study lie in the use of secondary data obtained from annual reports, sustainability reports, and official company websites (Abur *et al.,* 2023). This limitation arises because not all companies consistently disclose information related to Green Accounting, Green Innovation, and Green Human Resources. This can lead to variations in the data that do not fully reflect the company's actual condition. The measurement of the Green Accounting, Green Innovation, and Green Human Resources variables uses an index method based on disclosure items.

The preparation and assessment of this index are semi-subjective because they depend on the researcher's interpretation of the contents of the company's report (Agyemang, 2024).

5.3 Implications and Suggestions

Based on the conclusions and limitations outlined above, several implications can be conveyed to several parties, *For Academics,* this research contributes to the development of signaling theory in the field of Sustainability Disclosure, particularly regarding the role of internal company factors such as Green Accounting, Green Innovation, and Green Human Resources in driving Sustainability Disclosure practices. These findings strengthen the use of signaling theory. on Sustainability Disclosure in further research (Frijat *et al.,* 2024). This research also contributes to new indicators that can be used to measure Sustainability Disclosure, namely *the Principles for Sustainable Insurance* (PSI), published by the United Nations Environment Programme Finance Initiative (UNEP FI).

For Companies For company management, especially those operating in the financial and insurance sectors, this study demonstrates the importance of developing strategies and policies that support the implementation of green strategies Green Accounting through systematic and transparent recording of environmental activities and costs. Green Innovation to encourage resource efficiency and the development of environmentally friendly products/services (Dewa *et al.,* 2020). Green Human Resources by increasing HR capacity through training and an environmentally conscious organizational culture.

For Regulators For regulators and policy makers, such as the Financial Services Authority (OJK) or the Ministry of Environment and Forestry, the results of this study can be used as a basis for encouraging more comprehensive sustainability reporting regulations and accommodating aspects of Green Accounting, Green Innovation, and Green Resources, integrating RBC assessments in company sustainability evaluations, especially in the financial sector, developing guidelines for Green Human Resources training and certification . to increase HR competencies in supporting sustainable development goals (SDGs).

For the Community This research also has social and environmental implications. The implementation of Green Accounting, Green Innovation, and Green Human Resources practices will contribute to increased corporate social and environmental responsibility. In the long term, this will support the achievement of economic, social, and environmental sustainability**,** while strengthening the company's reputation in the eyes of the public and investors.

CONFLICT OF INTEREST

Companies in fulfilling transmission requirements require quite large costs, this can certainly disrupt the management's goal of obtaining the greatest possible profit by eliminating unnecessary costs for business continuity, this makes some companies reluctant to disclose the total costs in the transmission report because the transmission coverage is directly proportional to the costs incurred by the company.

AUTHOR CONTRIBUTIONS

This research contributes to the development of signaling theory in the field of Sustainability Disclosure, particularly related to the role of internal company factors such as Green

Accounting, Green Innovation, and Green Human Resources in driving Sustainability Disclosure practices. The findings related to this strengthen the use of signaling theory in Sustainability Disclosure. This research also contributes related to new indicators that can be used to measure Sustainability Disclosure, namely the Principles for Sustainable Insurance (PSI) published by the United Nations Environment Programme Finance Initiative (UNEP FI).

ETHICAL STATEMENT

This research is original and truly my own work, and is not the work of another person using my name, and is not the result of imitation or plagiarism of another person's work. This research has never been published before.

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Does Sustainability Report Disclosure, Leverage, Earning Quality and Firm Value Has an Effect on Audit Report Lag? Roa as Moderated Variable

Sub-Theme: *ESG and Sustainability Reporting*

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ABSTRACT

This study investigates the effects of sustainability reporting disclosure, leverage, earnings quality, and firm value on audit report lag (ARL), with Return on Assets (ROA) serving as a moderating variable. The study is theoretically grounded in signaling theory and compliance theory. The sample consists of energy companies operating in Indonesia over the 2020–2024 period. A quantitative research design is employed, utilizing secondary data obtained from annual reports and sustainability reports. The data are analyzed using panel data regression techniques. The empirical findings reveal that sustainability reporting disclosure, earnings quality, and firm value do not have a significant effect on ARL, whereas leverage exhibits a positive and statistically significant effect on ARL. Furthermore, ROA is found to strengthen the relationship between leverage and ARL; however, it does not moderate the relationships between sustainability reporting disclosure, earnings quality, or firm value and ARL. The findings provide robust empirical evidence underscoring the importance of adopting global reporting standards, such as the IPIECA framework, within Indonesia's energy sector. The adoption of such standards may contribute to the alignment of firms' financial performance with regulatory frameworks, thereby enhancing coordination between corporations and policymakers in the Indonesian energy industry.

Keywords: *Audit Report Lag (ARL), Earnings Quality, Firm Value*, *Leverage*, *Sutainability Report Disclosure*

INTRODUCTION

Based on regulations established by the BEI number KEP-00066/BEI/09-2022, all public companies are required to publish interim financial reports and annual financial reports that have undergone an audit process. Meanwhile, the OJK also states in its regulation Number 14/POJK.04/2022 through articles 2 (two) and 4 (four) that the obligation to report finances periodically applies to all companies registered with the OJK. Al Hasan (2025) reports that there are 128 companies that have failed to submit their annual financial reports for the reporting period ending December 31, 2024, to the IDX, including one company listed in the energy sector. Decision makers require accurate and relevant information, therefore,

timeliness is a fundamental principle in the presentation and submission of financial reports (Ahmad & Kamarudin, 2003; Dong, Robinson & Xu, 2018; Abdillah et al., 2019; Apadore & Noor, 2013). For this reason, this study focuses on companies listed in the energy sector in Indonesia as the object of research. The energy sector in Indonesia can influence financial statement delays because this sector has a complex system structure, has high risks, and can affect the global economy (Julianti et al., 2025).

Audit Reporting Lag (ARL) has a concept as described by Wang et al. (2024) defined as the time span between the closing date of the financial reporting period and the date the auditor's report is signed. Long audit times and delayed opinions can have a negative effect on a company's financial statements and affect the credibility and quality of the company (Alhamwadeh et al., 2024 and Sulimany, 2024). In making corporate decisions, the factor of delayed financial reporting will affect investors and stakeholders (Febriani and Gunawan, 2023). A high leverage ratio tends to cause auditors to require a longer period of time to complete the financial statement audit process. According to Al-Ajmi (2008) and Shlash (2024), the leverage ratio has a significant impact on auditor delays in delivering audit opinions. There is a difference with the results of a study conducted by Conover et al. (2007) on companies in a number of countries, which indicates that high leverage does not affect the duration of publication of company financial reports. This statement is reinforced by the findings of Shodikin, et. al (2024) research, which shows that leverage does not affect auditor delays in submitting audited financial reports.

The results of research conducted by Asthana (2014) indicate that delays in the publication of audited financial reports by companies are an indication that these companies have poor profit quality. Audit reports will be completed quickly without any delays when companies submit higher profit disclosures beyond the auditor's tolerance threshold (Salterio, 2012). Research by Jeon and Chang (2017) reinforces the statement that ARL time is getting shorter when companies have higher profit transparency. The opinion from the research by Arzaq et al. (2022) states that earnings quality affects the time auditors take to shorten their reporting time. This opinion contradicts the results of research by Regina (2021) and Ayundah (2024), who argue that earnings quality is not a reference for the timeliness of submitting financial reports that have undergone the audit process. The audit completion process by auditors requires a more substantial allocation of time to complete the audit process when a company has below-standard profit quality and affects the publication of financial reports (Nandika & Sunarto, 2022). The value of a company will be considered poor when its financial statements are published late (Asante-Appiah, 2020). According to research by Kurnia et al. (2024), firm value can influence the publication of audit reports. There are significant implications of late audit financial reports for firm value. This factor will signal inefficiency and internal problems in the financial reports. This study produced findings that differed from those of Akeem et al. (2020) because he revealed that firm value did not affect the audit process.

Sustainability reports serve as one of the indicators of company performance in Indonesia, in line with the findings of a number of studies showing that sustainability reporting practices have increased progressively from year to year (Gunawan et al., 2022). In the context of sustainability report disclosure, this study focuses on companies operating in the energy sector in Indonesia. In preparing sustainability reports, companies in Indonesia generally still refer to the Global Reporting Initiative (GRI) standards used as a reference by

all company sectors listed on the IDX and OJK. For this reason, this study applies content analysis methods in assessing sustainability report disclosure by referring to the International Petroleum Industry Environmental Conservation Association (IPIECA) Standard performance framework as a basis for assessment. The IPIECA standard is a guideline, reference, and specific measurement tool for creating sustainability reports for companies operating in the oil and gas industry. This approach is considered relevant for measuring sustainability report disclosures and distinguishes it from previous studies conducted by Oktaviani et al., (2023) and Mandilas (2023), which used the GRI standard. According to Maryanti et al., (2022), research that uses measurements appropriate to the type of company sector is needed to produce more relevant and comprehensive information. This study is in line with the Indonesian regulatory framework that allows companies to report sustainability initiatives through annual reports based on POJK 51/POJK.03/2017 (Jingga and Gunawan, 2025).

It is acknowledged that it is very rare to find companies that use IPIECA standards in their reports. Findings in Indonesia show that, in practice, many companies still use a combination of GRI guidelines and IPIECA standards in compiling their sustainability reports. For example, PT Pertamina (Persero) and Indika Energy combine GRI and IPIECA standards in their sustainability reports. This difference motivated researchers to use measurements that are more relevant to energy companies through disclosure, not only from sustainability reports but also from annual reports. For this reason, in this study, in addition to sustainability reports, researchers also used annual reports as samples in content analysis. Sustainability reports can provide positive signals to companies because they can contribute to improving the timeliness of financial reporting (Jang et al., 2016). Even though companies publish sustainability reports, this does not have an impact on the determining factors that affect the occurrence of ARL (Oktaviani et al., 2023). The moderating variable implemented in this study is Return on Assets (ROA), which aims to increase the impact that occurs between variables on ARL. The control variables applied in this study include company size and the size of the Public Accounting Firm (PAF). Based on the description above, this study was designed to test and measure the influence of the identified variables on ARL.

Signaling Theory

Signaling theory is a conceptual framework that explains internal efforts within a company to convey information to investors regarding management's perspective on the company's future plans and performance (Brigham and Houston, 2006). Management's interaction with shareholders is something that needs to be considered because management tends to accelerate or delay the information conveyed to shareholders (Hendi and Sitorus, 2023). Krisyadi and Noviyanti (2022) revealed that the duration required by management to publish financial reports can convey different signals to investors. Therefore, companies are expected to carry out the audit process by paying attention to the duration set by the auditor in finalizing the audit opinion and submitting audited financial statements on schedule. If the audit report is submitted late, it will cause uncertainty for the company and may lead to negative assumptions among investors (Arzaq et al., 2021). This trust can reduce auditor skepticism, reduce additional audit procedures, and ultimately shorten audit reporting delays (Alsheikh & Alsheikh, 2025).

Compliance Theory

Compliance is the goal of individuals, groups, or entities to carry out or not carry out something in accordance with established regulations (Stanley Milgram, 1963). The concept of compliance is used in this study to describe the impact of the dependent variable, ARL, to refer to the auditor's task of ensuring that the audited company has complied with all applicable regulations, standards, and provisions (Sihombing and Florencia, 2024). Compliance follows the details, standards, or laws that have been made, generally published by the competent authorities or organizations in certain fields. According to sociology, there are two basic concepts in compliance literature that can be described as instrumental and normative (Kurniawan and Gunawan, 2022). From a normative perspective, compliance theory is essential in the application of accounting and auditing. Corporate compliance in submitting financial reports is a crucial aspect in fulfilling the compliance principles that require information disclosure according to the schedule set and regulations passed by the OJK (Agustine and Darmawati, 2024). From a normative perspective, this compliance theory can be applied through Financial Services Authority Regulation (POJK) No. 14/POJK.04/2022, which coordinates the procedures and provisions for the submission of periodic financial reports by Issuers or Public Companies. From this point of view, compliance theory can explain the variables used to prove that listed companies have complied with applicable regulations.

Sustainability Report Disclosure and Audit Report Lag

The disclosure of sustainability reports has become increasingly urgent as an instrument for identifying effective strategies in resolving governance, economic, social, and environmental issues. As a result, a number of companies have made adjustments and alignments in disclosing sustainability reports (Gulluscio et al., 2020; Ludwig & Sassen, 2022; Kumar 2022). This argument is supported empirically by the results of previous studies conducted in Saudi Arabia and companies affiliated with the Gulf, which found that ARL can be reduced by a company when they disclose sustainability information and have a high score (Qasem et al., 2023 and Al-Absi et al., 2024).

Research presented by Alseikh and Alseikkh (2025) shows that sustainability reports reflect management practices based on the principles of transparency and accountability, thereby strengthening stakeholder confidence and reducing auditor skepticism. In addition, these practices also serve as a positive signal mechanism for auditors and all stakeholders, demonstrating the implementation of strong corporate governance and ethical practices, in line with the signaling theory perspective. Based on these statements, the hypotheses developed in this study are formulated as follows:

H1: Sustainability reports have a significant negative effect on Audit Report Lag

Leverage and Audit Report Lag

The findings presented by Doloksaribu et al., 2025 show that the leverage ratio has a significant positive effect on ARL, considering that an increase in a company's debt level

implies a more complex audit and requires more extensive processing time. The results of research by Karina and Kusmawardhani (2023) reveal that companies engaged in energy have an average leverage ratio of 41.6% in managing their assets through debt. Findings revealed by Abdullatif et al. (2025) with a research background in Jordan show that leverage has a positive effect on ARL. Based on these statements, the hypotheses developed in this study are formulated as follows:

H2: Leverage has a significant positive effect on Audit Report Lag

Earning Quality and ARL

According to Aurely et al. (2021), audit activities tend to be completed in a shorter time in companies with high earnings quality, while companies with low earnings quality require the implementation of more complex audit procedures, so that the requires a longer completion time. This view is consistent with the findings of Arzaq et al. (2022) and Oh et al. (2022), who concluded that delays in the publication of financial reports have a negative impact on a company's earnings quality. Sadewo and Saputra (2024) found in their study that delays in audit reports can be reduced by improving earnings quality. By publishing company financial information as soon as possible or delaying the disclosure of accounting information for as long as possible (Fakhfakh and Jarboui, 2022). Based on these statements, the hypotheses developed in this study are formulated as follows:

H3: Earnings quality has a significant negative effect on Audit Report Lag

Firm Value and Audit Report Lag

Financial reports that are presented in a timely manner, are accurate, and comply with applicable regulations have relevant and useful information value for decision-making by stakeholders. The absence of timeliness in the publication of financial reports can have negative consequences for firm value (Blankley et al., 2014) and damage the company's reputation (Asante-Appiah, 2020). Research findings by Kurnia et al. (2024) and Omer et al. (2020) state that there is a negative correlation between ARL and firm value. Based on these statements, the hypotheses developed in this study are formulated as follows:

H4: Firm value has a significant negative effect on Audit Report Lag

A study in China reveals that companies that implement sustainability report disclosure have a positive impact on audit efficiency, thereby reducing financial statement delays (Wang & Wang, 2023). According to (Gaol & Duha, 2021), companies with high ROA potentially require longer audit durations, as an increase in ROA expands the scope of audit procedures that must be performed. Thus, companies that generate higher profitability tend to select good quality auditors in an effort to obtain a more accurate assessment of their financial performance (Sobhan et al. 2025). Based on these statements, the hypotheses developed in this study are formulated as follows:

H5: ROA can strengthen the effect of sustainability report disclosure on Audit Report Lag

Based on the debt covenant hypothesis, which is part of positive accounting theory, there is a correlation between a company's debt level and its implications for profit generation. The use of debt to support a company's operational activities enables the achievement of high profit levels without causing delays in the submission of audit reports (Pratiwi & Suwarno. 2024). If a company records a high level of leverage, management has the potential to implement certain accounting policies to shift profit recognition from future periods to the current period, which in turn can affect the ROA ratio. Based on these statements, the hypotheses developed in this study are formulated as follows:

H6: ROA can strengthen the effect of leverage on Audit Report Lag

Auditors play a crucial role in determining opinions on company financial statements and are required to carry out high-quality audit processes that can accurately identify material misstatements in the presentation of financial statements (Sorialam et al., 2022). Companies that publish favorable information, such as large profits, will tend not to delay the reporting of financial statements (Megayanti and Budiartha, 2016). Companies that record high profit levels have the potential to publish financial statements on time and expect a relatively short audit delay period. Based on these statements, the hypotheses developed in this study are formulated as follows:

H7: ROA can strengthen the effect of earning quality on Audit Report Lag

Delays in publishing financial reports will have a negative impact on firm value (Givoly, et. al (2022); Blankley, et.al (2014)). Investors will signal to delay investing until the company's earnings are announced, and the stock price response to earlier earnings reports is more important than that to later published reports (Givoly, et. al (2022); Beaver, et. al (1980)). When a company has a good ROA ratio, it means that the company's stock market value will also be good and will affect the brevity of the audit time. Companies with good ROA ratios and good firm values reflect a healthy company condition. Based on these statements, the hypotheses developed in this study are formulated as follows:

H8: ROA can strengthen the influence of firm value on Audit Report Lag

RESEARCH METHOD

Sampel

The sample in this study was obtained using purposive sampling with certain criteria. The criteria for sample selection in this study are as follows:

1. Energy companies listed on the IDX for the period 2021–2024.
2. Companies with consistent and complete annual financial reports during the 2021–2024 period to ensure that the data used has the same number of observations for all variables.
3. Companies with consistent and complete annual sustainability reports for the period 2021–2024 so that the processed data can be assessed in the analysis content.

This study uses secondary data as a data collection technique, namely information obtained from companies. The data sources used come from the Indonesia Stock Exchange (IDX) website through its official website, www.idx.co.id, and each company's website. The

first analysis method applied in this study is content analysis, which is a research technique used to examine and interpret the content of documents or texts (Sitasari, 2022). In the context of this study, the analysis was conducted on company sustainability reports to determine the value of the ratios disclosed in the sustainability reports. This study also applied panel data regression analysis to examine the relationship between independent variables, dependent variables, moderating variables, and control variables.

Variable Measurement

The variables analyzed included sustainability report disclosure, leverage, earning quality, and firm value as independent variables, ROA as a moderating variable, and Audit Report Lag as the dependent variable. This study also included control variables to improve the accuracy of the model and strengthen the validity of the regression results. The control variables used are firm size and PAF Size.

Table 1. Variable Measurement

Variable	Operational definition	Symbol	Measurement
Dependent variable			
Audit Report Lag	ARL or financial reporting lag is defined as the time interval between the end of a company's fiscal year and the date of signing of the audit report by the auditor (Abouelela et al., 2025).	ARL	= Date Of Audit Report - Company Year-End Books* Explanation: The end of the company's fiscal year in this study is set at December 31, as eflected in the company's annual financial statements.
Independent Variable			
Sustainability Report Disclosure	This variable is measured using content analysis with assessments following the standard framework of the International Petroleum Industry Environmental Conservation Association (IPIECA) for companies listed in the energy sector.	SR	Disclosure research through content analysis with the following criteria: 0 : No Disclosure 1 : Qualitative Information 2 : Qualitative Information and Number 3 : Qualitative Information, number and diagram (picture) $SR\ Rasio = \frac{\sum Sustainability\ Report}{\sum IPIECA\ Standards \times maximum\ disclosure\ value} \times 100\%$
Leverage	Based on previous studies (Putriningsih et al., 2025; Anggraini , and Budi, 2025), the measurement of leverage ratio in this study uses the Debt to Equity Ratio (DER) indicator.	LEV	$DER = \frac{Total\ Debt}{Total\ Asset} \times 100\%$
Earning Quality	Abdelghany (2005) explains that the determining factor of profit quality requires a division between net cash from operating activities and the company's net profit; the lower the ratio value, the higher the profit quality.	EQ	$EQ = \frac{Operating\ Cash\ Flow}{EBIT} \times 100\%$
Firm Value	Tobin's Q is defined as the ratio of a company's market value to its net investment.	FV	$Tobin's\ Q = \frac{MVE+BVD}{TA} \times 100\%$ Explanation MVE : Market Value Equity BVD : Book value of debt TA : Total Asset
Moderating Variables			
Return on Assets	According to Brigham and Houston (2017:148), ROA is the ratio between net income and total assets used to measure the rate of return on all company assets.	ROA	$ROA = \frac{Net\ Income}{Total\ Asset} \times 100\%$

Control Variables			
Company Size	Based on Brigham and Houston (2018), company size can be categorized as through various indicators, including revenue, total assets, and total equity.	SIZE	$Firm\ Size = Log\ (Total\ Assets)$
PAF Size	Public accounting firms (PAF) in Indonesia are classified into Big Four and Non-Big Four.	KAP Size	This variable is measured using a dummy variable. Companies audited by the Big Four will be rated 1, while companies audited by non-Big Four firms will be rated 0.

Research Model

The data analysis methods employed in this study include both descriptive and inferential statistical analyses. Hypothesis testing is carried out using two methods: Panel Data Regression and Moderated Regression Analysis (MRA). Panel data regression is used to test the influence of independent variables on dependent variables. Moreover, moderated regression analysis was employed to investigate the influence of additional independent variables on the relationship between the independent and dependent variables.

ARL = α + α1SR + α2LEV + α3EQ + α4FV + α5ROA + α6SIZE + α7KAP_SIZE + α8SRROA + α9LEVROA + α10FVROA + α11EQROA + eit

RESULT AND DISCUSSION

The sample selection process in this study was conducted using purposive sampling, where samples were selected regularly based on predetermined criteria. This study used a sample of companies in the energy sector listed on the Indonesia Stock Exchange. During the observation period of 2021-2024, a total of 55 companies were sampled, with a total of 220 observations.

Descriptive Statistics

The results of the descriptive statistical analysis for each variable are shown in the following table:

Table 2. Descriptive Statistics Result

	ARL	SR	LEV	EQ	FV	ROA	KAPSIZE	SIZE
Mean	90.19545	0.335568	0.502048	2.016574	1.803405	0.081340	0.336364	1.13E+09
Median	87.00000	0.319444	0.490356	0.988587	1.034946	0.054482	0.000000	2.49E+08
Maximum	255.0000	0.913889	2.418443	106.2587	26.15849	0.616346	1.000000	1.08E+10
Minimum	34.00000	0.022222	0.020567	-10.93908	0.263849	-0.451982	0.000000	4528366.
Std. Dev.	27.85060	0.201875	0.349607	7.890628	2.800834	0.148759	0.473542	1.92E+09
Observations	220	220	220	220	220	220	220	220

Based on the table, it can be seen that ARL has an average delay in publishing audit reports of 90 days, with a minimum value of 34 days and a maximum of 255 days in publishing its financial reports. The data from the table shows that the company is quite compliant in publishing financial reports when viewed from the average value of published audit reports. The average sustainability report disclosure rate is 33.56%, with a maximum value of 91%

and a minimum value of 2%. This indicates that there are several companies that disclose detailed sustainability reports, while others do not. Companies have an average leverage ratio of 50%, with a maximum value of 241% and a minimum value of 2%. This indicates that there are companies with very high levels of debt in financing their operations through debt.

Earning quality shows an average of 202%, but there are extreme values with a maximum of 106.26% and a minimum of -10.93%, indicating that the distribution is highly abnormal and there are many outliers. The data shows that there are significant differences in the quality of the companies' profits. The average firm value is 180%, but there is a large difference between the minimum of 26.38% and the maximum of 261.58%, indicating significant differences in firm values in the sample.

The average ROA of the company is 8.1% with a range of -45.2% to 61.6%, indicating that the company is losing money as seen from the very wide range of values. The average PAF size is 33.6%, which means that the sample was audited by a large PAF (Big Four). A maximum value of 1 indicates that some companies were audited by a Big-4 PAF, while a minimum value of 0 indicates that some companies were audited by a non-Big-4 PAF. The average company size is around IDR 1.13 trillion, but there is a large difference between small and large companies (ranging from IDR 4 million to IDR 10.8 trillion). This clarifies the significant difference in company size in the sample.

Estimation Model Selection

This test is conducted to determine the most suitable estimation approach for analyzing panel data. Table 3 presents the results of the model selection test using the Chow test, the Hausman test, and the Lagrange Multiplier (LM) Test for the estimation model. The Chow test is used to choose between the Common Effect Model (CEM) or the Fixed Effect Model (FEM). The Hausman test is performed to determine the appropriate model between the FEM or the Random Effect Model (REM). The LM test is performed to determine the appropriate model between CEM or REM.

Table 3. Model Estimation Test Results

Test	Statistic	d.f.	Prob
Uji Chow (Cross-Section F)	2.423143	(54,154)	0.0000
Uji Hausman (Cross-section random)	16.379199	11	0.1276
Uji LM (Breusch-Pagan)	14.64186	19.49961	34.14147
	(0.0001)	(0.0000)	(0.0000)

The Chow test results show that the Cross-section F value is 2.423 and the probability is 0.0000. Because the p-value is < 0.05, H_0 is rejected, which means that the FEM is more appropriate to use than the CEM. The Hausman test results show a Chi-Square value of 16.38 with a p-value of 0.1276 (> 0.05). Because the probability value is greater than 0.05, H_0 is not rejected, which means that the REM is more appropriate to use than the FEM. The LM Test results show that the test values for cross-section, time, and both are 14.64, 19.50, and 34.14, respectively, with p-values < 0.05 for all three. It can be seen that for all p-values, the results are significant (0.0000–0.0001), so the null hypothesis (no individual or time effects) is rejected. This means that the panel model is more appropriate than the ordinary regression

model (OLS) because there are significant individual and time effects. Therefore, in this LM, the selected model is REM, which is the best model for balanced panel regression. For this reason, REM is used for balanced panel regression in this study.

Multicollinearity Test

Table 4. Multicollinearity Test Results

Variable	Coefficient Variance	Uncentered VIF	Centered VIF
C	25.49500	7.462226	NA
SR	151.8384	6.807389	1.802935
LEV	33.99121	3.718157	1.210490
EQ	0.056110	1.084675	1.017890
FV	0.480375	1.555246	1.097968
ROA	202.9218	1.701330	1.308372
KAP_SIZE	20.47182	2.015482	1.337547
SIZE	1.57E-18	2.272679	1.689338

The results of the multicollinearity test based on the Variance Inflation Factor (VIF) value show that all centered VIFs are below 10. Since all VIF values are < 10, it can be concluded that there is no multicollinearity problem among the independent variables in the model.

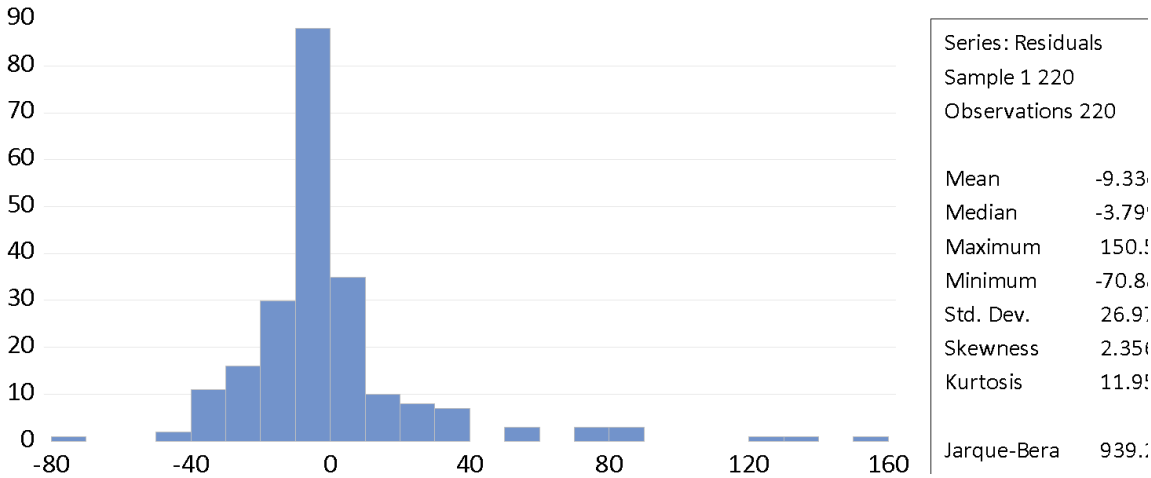
Heteroscedasticity Test

Table 5. Heteroscedasticity Test Results

	Value	df	Probability
Likelihood ratio	**16.72136**	**55**	**1.0000**

The results of the panel heteroscedasticity test *(Panel Period Heteroscedasticity LR Test)* show a Likelihood Ratio value of 16.721 with a p-value of 1.0000. Because the p-value > 0.05, the null hypothesis is not rejected, which means there is no heteroscedasticity in the model.

Normality Test



The normality test results show that the probability value obtained is 0.000000, indicating that the data is not normally distributed because the value is < 0.05. , the data is still normally distributed because the sample size is greater than 30. This is in accordance with the statement in the central limit theorem, where data with a large sample size, especially those greater than 30 (n > 30), is considered to be normally distributed (Dielman, 1961).

RESULTS AND DISCUSSION

Results

The results of the hypothesis testing, which include regression testing and moderated regression analysis using fixed-effects models, are presented in Table 6 below.

Tabel 6. Hypothesis Testing Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.	Conclusion
SR	-1,353625	15.49923	-0,087335	0,9305	H_1 rejected
LEV	20,20188	7,400593	2,729765	0,0069	H_2 accepted
EQ	-0,007198	0,216365	-0,033268	0,9735	H_3 rejected
FV	-0,880147	0,724289	-1,215188	0,2257	H_4 rejected
Adjusted R-squared					**0,027724**
Prob(F-statistic)					**0.110225**
Moderasi					
ROA	74,99415	47,72898	1,571250	0,1176	Moderation rejected
ROA*SR	-81,27337	78,05633	-1,041214	0,2990	H5 rejected
ROA*LEV	-32,72400	52,70494	-0,620891	0,5354	H6 rejected

ROA*EQ	-41,73292	18,00435	-2,317936	0,0214	H7 accepted
ROA*FV	-2,460445	3,987241	-0,617080	0,5379	H8 rejected

From Table 6, it is known that SR does not affect ARL with a Prob value of 0.9305 > 0.05, meaning that H1 is rejected. Lev affects ARL with a Prob value of 0.0069 < 0.05, meaning that H2 is accepted. EQ does not affect ARL with a Prob value of 0.9735, meaning that H3 is rejected. FV does not affect ARL with a Prob value of 0.2257, meaning that H4 is rejected. ROA as a moderating variable does not affect ARL with a Prob value of 0.1176 > 0.05, meaning that ROA is unable to moderate ARL, so the hypothesis is rejected.

The interaction between ROA and sustainability report disclosure has no effect on ARL with a Prob value of 0.2990 > 0.05, meaning that H5 is rejected. The interaction between ROA and leverage has no effect on ARL with a Prob value of 0.5354 > 0.05, meaning that H6 is rejected. The interaction between ROA and earning quality affects ARL with a Prob value of 0.0214 < 0.05, meaning that H7 is accepted. The interaction between ROA and firm value does not affect ARL with a Prob value of 0.5379 > 0.05, meaning that H8 is accepted.

The coefficient of determination (Adjusted R-squared) is Adj R^2 = 0.03. The analysis results show that the coefficient of determination (Adj R^2) is 3%. This indicates that the independent variables in the model have a very small contribution in explaining the variation of the dependent variable. In other words, 3% of the change in the dependent variable cannot be explained by the independent variables in this study. Meanwhile, 97% of the change is caused by other factors outside the model. Based on Table 4.8, the Prob (F-statistics) value is 0.110225 > 0.05, so it can be concluded that all independent variables together are unable to influence the dependent variable, namely ARL, as a whole.

Discussion

Research Results on the Effect of Sustainability Report Disclosure on Audit Report Lag

These findings indicate that in the context of the research sample, there is no evidence that companies with consistent sustainability disclosure have a significantly different ARL compared to other companies. However, if we refer to the coefficient table of -1.35, there is a negative interaction between the sustainability report disclosure variable and ARL. These results are in line with signaling theory, which emphasizes that prioritizing sustainability report disclosure can enhance higher ethical principles, thereby prioritizing transparency in meeting stakeholder information needs (Sulimany, H.G.H., 2025; Ali et al., 2025; Alnor, 2024; Aydoğmuş et al., 2022; Diab and Eissa, 2024; Wu et al., 2024).

Through POJK 51/2017 regulation, it is hoped that companies in Indonesia will be more compliant in disclosing their sustainability performance. However, this regulation is often only used to fulfill compliance without any administrative sanctions or incentives from policymakers for business actors. As a result, the regulation is often considered only a minimum form of compliance with the rules without providing clear added value to companies in the eyes of investors (Kurnia et al., 2020). These results imply that a commitment to sustainability

reporting indicates good governance, which can motivate companies to disclose their financial records in a timely manner and increase investor confidence (Sulimany, H.G.H., 2025).

Research Findings on the Effect of Leverage on Audit Report Lag

These findings show that companies that finance their operations through debt will publish their financial reports late. This also supports the signaling theory, which states that companies with high debt levels will delay the publication of their financial reports. Research conducted by Koleangan et al. (2022) states that when a company's leverage ratio is high, they will tend to be late in publishing their financial reports and vice versa. Findings by Sudjono et al (2022) state that leverage is a reflection of a company's financial risk level. The complexity of audit procedures requires auditors to be careful in evaluating the repayment of a company's short-term and long-term debt (Doloksaribu, 2025). This means that there are still many companies in Indonesia that use debt for their operational financing, especially companies in the energy sector. This phenomenon requires auditors to spend additional time conducting audits, as they must ensure that the information presented in the financial statements is free from material errors and reflects the actual quality of the financial statements.

Research Results on Earning Quality and Audit Report Lag

These findings prove that if a company has good earning quality, it will reduce the time required to issue audited financial statements. Research conducted by Afzali et al. (2025) states that companies that experience a decline in earning quality will have a negative impact on the reliability and credibility of their financial statements. One of the criteria in this study is energy companies in Indonesia, so there are implications and policies to improve earning quality in performing sustainable performance, which will have an effect on increasing accountability, reducing asymmetry, and increasing investor confidence (Sulimany, H.G.H., 2025). Therefore, it is expected that companies listed on the IDX will comply with POJK 51 of 2017 and POJK 14 of 2022 regulations to maintain good profit quality by actively disclosing sustainability reports to reduce ARL.

Research Results on Firm value and Audit Report Lag

Companies with high firm values will slow down ARL, because auditors do not need to spend a long time conducting their audits. Conversely, according to Appiah (2020), companies with poor firm values will experience higher audit quality because auditors work harder in compiling their financial reports. The negative impact of late audit reports with poor firm values can be described from several perspectives:

1. Delays in audit reports can indicate inefficiencies or problems in the company's financial reporting process, which could potentially cause concern among investors about the reliability of financial information.

2. Prolonged delays in audit reports can be interpreted as an indicator of fundamental problems in the company's operations or governance, such as poor internal controls or management inefficiencies.

3. Companies that fail to provide audited financial reports on time may face closer scrutiny from regulators and stakeholders, leading to potential legal and reputational risks (Kurnia, et al. 2024).

Research Findings ROA Can Strengthen the Influence of Sustainability Report Disclosure on Audit Report Lag

Companies view profitability as good news, so they have shorter financial reporting intervals to signal their outstanding performance to the public (Sulimany, H.G.H., 2025). Current users of financial reports have placed significant weight on companies' non-financial performance, such as their commitment to ESG and other sustainable practices, for investment decisions (Almulhim and Aljughaiman, 2023; Kong et al., 2023; Wu et al., 2024).

This finding not only enriches the existing literature on sustainability reporting disclosure and audit efficiency but also provides practical guidance for managers and policymakers to emphasize the importance of improving corporate ESG performance in order to enhance audit efficiency (Zhang, L., & Guo, C. (2024)). Furthermore, the strong correlation between the ROA variable and sustainability report disclosure can reduce audit time so that companies can report their finances on time. This reduction in audit time makes companies aware of the need to comply with existing regulations related to financial reporting and sustainability reporting (Alsheikh & Alsheikh, 2025).

Research Results ROA Can Strengthen the Influence of Leverage on Audit Report Lag

ROA is assessed based on total assets, while leverage is assessed based on total debt. Therefore, this does not guarantee that companies with high ROA and low leverage can publish their financial reports on time (Al-Faruqi et al., 2021). This is inconsistent with the signaling theory, which states that there is a misalignment when ROA functions as a moderating variable in this relationship (Nurvilawati, et al., 2024). Research conducted by Srbinoska (2021) states that companies with debts do not reduce financial reporting delays because low leverage alone does not represent a protective mechanism that supports timely financial reporting. Meanwhile, research conducted by Endri et al (2024) supports the signaling theory statement that companies with high ROA will accelerate ARL by increasing the company's net profit each year.

Research Results ROA Can Strengthen the Influence of Earning Quality on Audit Report Lag

This indicates that companies with high ROA values will have good earning quality and ultimately reduce financial reporting delays. This study supports the argument regarding signaling theory, that companies with high ROA and good earning quality will immediately publish their financial reports on time (Alseikh & Alseikh, 2025). When earnings quality is good, financial statement transparency increases and audit risk decreases (Oh & Jeon, 2022). Company management is expected to improve the company's earnings quality so that positive information about the company's performance will encourage investors to make investment decisions (Sorialam et al., 2022). Delays in publishing financial statements on time can have a negative impact on the quality of the company. Investors delay trading stocks until the income statement is announced, and the stock price response to an earlier income statement

is more important than the stock price response to a delayed income statement (Oh & Jeon, 2022).

Research Findings: ROA Can Strengthen the Influence of Firm value on Audit Report Lag

This study indicates that companies with high ROA values may not necessarily influence the company's Tobin's Q value to reduce ARL. Research conducted by Kurnia et al. (2024) shows that longer audit reporting delays are associated with lower firm values. Audit reporting delays may indicate inefficiencies or problems in a company's financial reporting process, which could potentially raise investor concerns about the reliability of financial information. Previous research states that higher profitability reduces audit delays because well-performing companies will publish their achievements as soon as possible (Khoufi & Khoufi, 2018). Companies that fail to provide audited financial reports on time may face stricter scrutiny from regulators and stakeholders, potentially leading to legal and reputational risks. This is in line with compliance theory, which states that there will be risks of fines and legal action if companies are late in publishing their financial reports.

CONCLUSION

The general conclusion of the study confirms that the disclosure of sustainability reports, ROA moderates earning quality, and ARL can enable auditors to complete audits on time so that delays can be avoided. The results show that when a company is performing well internally and externally, the risk of ARL will decrease. Conversely, when a company is performing poorly, as indicated by a high leverage ratio, low earning quality, and poor firm value, the risk of ARL will increase. This is because auditors need a long time to conduct their audits in order to avoid errors in the audit process.

Limitation and Suggestion

This study has several limitations that still need to be considered, namely, this study uses content analysis in determining sustainability performance scores, so it contains elements of subjectivity. For this reason, the sample analyzed may contain bias, because not all companies publish sustainability reports or annual reports. This limitation makes the research sample small, because the number of companies is still minimal, so it does not represent the population as a whole. The researchers used the IPIECA standard in disclosing sustainability reports, even though in Indonesia it is still very rare for companies in the energy sector to refer to this standard. This difference in measurement standards has resulted in incomplete disclosures in sustainability reports, as the majority of companies in Indonesia prepare their sustainability reports using the GRI standard. Despite the limitations of this study, the findings still contribute to the development of literature and practices in the field of sustainability and corporate governance. Future research should use a broader approach in identifying sustainability reports without bias in sustainability so that the research results are more accurate and representative.

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CONFLICT OF INTEREST

I declare that this paper has no financial, professional, or personal interests that could influence the sector researched in this paper.

AUTHOR CONTRIBUTIONS

I hope that the results of this study will be useful to readers and contribute to future research.

ETHICAL STATEMENT

I welcome constructive suggestions and criticism for future research. My paper is original and entirely my own and is not the work of others attributed to me.

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Greenwashing as a Mediating Variable in the Effect of ESG Disclosure on Firm Value

Sub-Theme: *ESG and Sustainability Reporting*

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ABSTRACT

This study examines the relationship between environmental, social, and governance disclosure and corporate value, using greenwashing as a mediating mechanism. Motivated by inconsistencies in empirical evidence on the economic impact of sustainability disclosure, this study seeks to elucidate how disclosure credibility affects market valuation. The study takes a quantitative explanatory approach, utilizing panel data from publicly traded corporations in environmentally and socially sensitive sectors. A disclosure index measures sustainability disclosure, market-based valuation proxies' corporate value, and structured content analysis identifies greenwashing. Panel regression and mediation analysis are used to evaluate the proposed associations. The data show that social and governance transparency positively influence corporate value, however environmental disclosure has a negative impact. Greenwashing has been found to strongly moderate the relationship between governance disclosure and business value, implying that effective governance minimizes false sustainability marketing while increasing disclosure credibility. These findings reveal that sustainability disclosure does not always generate economic benefit, and that governance is critical in establishing credible sustainability reporting. The study adds to the sustainability and corporate finance literature by focusing on greenwashing as an economic mechanism that influences how sustainability information is transformed into firm value.

Keywords: *Environmental Disclosure, Firm Value, Governance Disclosure, Governance Social Disclosure, Greenwashing*

INTRODUCTION

Sustainability has been a major concern in the business world as companies face increased pressure from climate change, environmental deterioration, and social inequity. As a result, businesses are expected to generate profit while fulfilling their environmental, social, and governance responsibilities. As a result, Environmental, Social, and Governance (ESG) disclosure has emerged as a critical source of non-financial information for investors, regulators, and other stakeholders evaluating corporate sustainability, risk management, and long-term value creation (Freshtriana & Kim, 2025; Triyani et al., 2020).

In capital markets, firm value indicates investors' expectations for a company's future prospects and sustainability. Traditional financial information alone is frequently insufficient to convey long-term environmental and social concerns, necessitating further dependence on ESG disclosure as a supplement to financial reporting (Li et al., 2017; Baker et al., 2024). However, the economic significance of ESG disclosure is unknown, especially when sustainability data lacks consistency, comparability, and reliability. Distortions in disclosure practices can reduce the impact of ESG disclosure on business value (Luque-Vílchez et al., 2023).

In this setting, greenwashing has emerged as a practice in which companies make overstated, ambiguous, or difficult-to-verify sustainability claims, potentially distorting actual sustainability results. Such tactics may damage the credibility of ESG disclosure and have an impact on how markets view sustainability data (Hu et al., 2024). This is especially important in emerging markets, such as Indonesia, where sustainability reporting regulations have expanded since the issuance of Financial Services Authority *(Otoritas Jasa Keuangan)* Regulation No. 51 of 2017, but disclosure quality remains uneven across firms and sectors (Agni & Anis, 2024).

Research findings on the relationship between ESG disclosure and business value is inconclusive. Some studies show that ESG disclosure improves transparency, investor confidence, and long-term value creation, while others show insignificant or even negative effects across sectors and institutions (Aydoğmuş et al., 2022; Yeye & Egbunike, 2023; Abu Hussain et al., 2024). These inconsistencies suggest that ESG disclosure does not always result in increased company value, and that market responses to sustainability information may be influenced by contextual factors such as disclosure credibility, sectoral characteristics, and investor interpretation. The conflicting findings underline the importance of looking beyond direct ESG-firm value linkages to uncover fundamental mechanisms that may explain how capital markets process and evaluate ESG information.

Despite the rising quantity of studies on greenwashing and company value, significant gaps remain in the current literature. Freshtriana and Kim (2025) present empirical evidence that greenwashing can increase firm value, implying that capital markets may respond positively to symbolic sustainability narratives. However, their analysis is primarily concerned with the direct impact of greenwashing on business value and does not explicitly investigate the underlying ESG disclosure process that may give birth to such practices. In contrast, Hu et al. (2024) emphasize greenwashing as a result of low-quality or opportunistic ESG disclosure and its function in degrading disclosure credibility, but they do not empirically evaluate how greenwashing interacts with firm value within a unified framework.

Therefore, the purpose of this study is to examine the relationship between ESG disclosure and business value, with a focus on greenwashing as a mediating variable. The goals of this research are to (1) examine the impact of environmental, social, and governance disclosure on firm value, (2) assess the effects of ESG disclosure on greenwashing practices, and (3) determine whether greenwashing mediates the relationship between ESG disclosure and firm value. By addressing these aims, the study hopes to provide a better understanding of how ESG disclosure contributes to company value generation in the face of credibility challenges.

MATERIALS AND METHOD

Materials or Respondents

This study makes use of secondary panel data from publicly traded companies in the energy and consumer non-cyclicals sectors on the Indonesia Stock Exchange (IDX) from 2021 to 2024. The sample consists of companies that have routinely submitted annual and sustainability reports with adequate Environmental, Social, and Governance (ESG) disclosures. Data were sourced from audited financial records, corporate sustainability reports, and the official IDX website (www.idx.co.id). Purposive sampling was used to ensure the data was complete and consistent across firms and years. The final sample includes enterprises that (1) were continually listed during the observation period, (2) published ESG-related information, and (3) provided all of the necessary financial and market data for analysis.

Instrumentation

ESG disclosure and greenwashing indicators were identified through structured content analysis of sustainability reports using predefined coding criteria. Financial and market variables were compiled using spreadsheet software prior to statistical processing. Computer-assisted text screening tools were used to support consistency in content analysis, while final classifications followed conceptual definitions established in the research framework.

Procedure

ESG disclosure was assessed using an index based on the Global Reporting Initiative (GRI) Standards, with each disclosure item scoring "1" if disclosed and "0" otherwise. Dimension-specific ESG ratings were calculated using the ratio of disclosed items to total applicable items. Tobin's Q was used as a proxy for firm value. Greenwashing was assessed using the 7 Sins of Greenwashing methodology. Each detected category was awarded a value of "1," while non-identified categories were allocated "0," resulting in a greenwashing score ranging from 0 to 7 for each firm-year observation.

Data Analysis

Descriptive statistics were calculated to summarize data characteristics. Hypothesis testing was performed using panel regression analysis with firm value as the dependent variable, ESG dimensions as independent variables, and greenwashing as a mediating variable. Control variables included profitability, leverage, and firm size. Classical assumption tests were performed on suitable models, including normality, heteroskedasticity, and multicollinearity. The panel regression framework was used to conduct mediation analysis, which focused on indirect effects.

Hypothesis

Environmental disclosure demonstrates a company's commitment to addressing environmental risks and impacts. From a signalling standpoint, transparent environmental disclosure may reduce information asymmetry and boost investor confidence, hence

improving corporate value. Firms that disclose environmental initiatives are regarded to be more prepared to manage long-term environmental risks and regulatory demands, thereby increasing market valuation.

H1: Environmental disclosure has a positive effect on firm value.

Social disclosure captures a firm's engagement with employees, customers, and communities. Strong social performance can enhance corporate reputation, improve stakeholder relationships, and support operational stability. These factors are expected to contribute positively to firm value by signalling long-term sustainability and responsible management.

H2: Social disclosure has a positive effect on firm value.

Governance disclosure represents the quality of corporate oversight, transparency, and accountability. Effective governance mechanisms reduce agency problems and enhance managerial discipline, which can lead to improved decision-making and risk management. As a result, governance disclosure is expected to have a positive impact on firm value.

H3: Governance disclosure has a positive effect on firm value.

Greenwashing occurs when firms exaggerate or misrepresent sustainability practices, potentially misleading investors. Such practices may undermine the credibility of sustainability information and distort market perceptions. When greenwashing is identified, it can reduce investor trust and negatively affect firm value.

H4: Greenwashing disclosure has a positive effect on firm value.

Beyond direct relationships, this study examines whether greenwashing functions as an intervening mechanism in the relationship between ESG disclosure and firm value. Rather than formulating separate hypotheses, the indirect effect of Environmental, Social, and Governance disclosure on firm value through greenwashing is evaluated using the Sobel test. This approach allows the study to assess whether greenwashing significantly transmits the influence of ESG disclosure to firm value by affecting the credibility of sustainability information.

RESULTS AND DISCUSSION

This study used a balanced panel of 108 firm-year observations from energy and consumer non-cyclicals companies listed on the Indonesia Stock Exchange from 2021 to 2024. Table 1 shows the descriptive statistics. Overall, ESG disclosure levels (ENV, SOC, and GOV) are relatively uniform, indicating consistent disclosure procedures driven by standardized reporting. Firm value (FV) and greenwashing (GWI) show greater variability, indicating disparities in market valuation and sustainability communication techniques among enterprises.

Table 1.

Variable	Mean	Median	Max	Min	Std. Dev.	Obs
ENV	0.2086	0.2200	0.3100	0.1300	0.0563	108
SOC	0.2461	0.2450	0.3500	0.1600	0.0578	108
GOV	0.1137	0.1200	0.1300	0.0800	0.0583	108
FV	1.6583	1.0250	8.4100	0.7100	1.4839	108
GWI	3.9166	4.0000	6.0000	1.0000	1.2834	108
ROA	4.8037	0.4600	14.9170	0.0270	7.5853	108
LEV	1.2759	0.8665	3.5310	0.8620	0.7615	108
SIZE	9.4174	9.5450	12.1470	7.5070	1.2987	108

Panel model selection using the Chow, Hausman, and Lagrange Multiplier tests indicates that the Fixed Effect Model (FEM) is the most appropriate specification for the firm value model. Diagnostic tests confirm the absence of multicollinearity and heteroskedasticity, supporting the reliability of the regression estimates.

ESG Disclosure, Greenwashing, and Firm Value

The results show that the effects of ESG disclosure on business value differ by dimension. Environmental disclosure has a negative and statistically significant link with corporate value, implying that investors may view environmental measures as costly or compliance-driven, especially in ecologically sensitive industries. Previous research (Aydoğmuş et al., 2022; Yeye & Egbunike, 2023) have found that environmental investments may result in short-term financial constraints that are not immediately accounted for by the market. As a result, environmental disclosure may not necessarily lead to a higher market valuation in the short term.

In contrast, Social and Governance disclosures exhibit positive and significant effects on firm value. These results align with earlier evidence showing that social responsibility and governance quality enhance stakeholder trust, operational stability, and managerial oversight, thereby strengthening firm value (Abu Hussain et al., 2024; Li et al., 2017). Firms with stronger social engagement and governance frameworks appear more capable of signalling long-term sustainability and risk management to investors, leading to favourable market responses.

Greenwashing has also been shown to have a major impact on firm value. The findings show that greenwashing has a negative impact on firm value, implying that inaccurate or inflated sustainability statements impair investor trust when disclosure veracity is questioned. This study lends support to the concept that greenwashing is an informational distortion that reduces the economic benefits of sustainability disclosure. According to past research, greenwashing can reduce firm value by heightening scepticism about non-financial information and compounding perceived reputational risk (Freshtriana & Kim, 2025; Hu et al., 2024). These findings support the notion that financial markets increasingly penalize companies when their sustainability narratives are deemed to be symbolic rather than substantive.

ESG Disclosure and Greenwashing

Further analysis reveals that ESG disclosure does not uniformly constrain greenwashing practices. Governance disclosure has a negative and statistically significant effect on greenwashing, indicating that stronger governance mechanisms reduce the likelihood of misleading sustainability communication. This finding supports prior arguments that governance quality plays a central role in ensuring disclosure credibility and limiting opportunistic sustainability narratives (Hu et al., 2024; Luque-Vílchez et al., 2023).

Social disclosure shows only a weak negative association with greenwashing, while Environmental disclosure does not exhibit a statistically significant effect. These results suggest that environmental disclosure alone is insufficient to prevent symbolic sustainability practices in the absence of effective governance controls, reinforcing concerns that ESG reporting may be used strategically when oversight mechanisms are weak (Hu et al., 2024).

Mediation Analysis

The mediation analysis demonstrates that greenwashing significantly mediates the relationship between Governance disclosure and firm value. Stronger governance reduces greenwashing practices, which in turn enhances firm value by improving the credibility of sustainability information. This result extends the findings of Freshtriana and Kim (2025), who document a direct relationship between greenwashing and firm value, by showing that governance operates as a mechanism that conditions how greenwashing influences market valuation.

However, greenwashing does not mediate the relationships between Environmental or Social disclosure and firm value. These dimensions appear to affect firm value primarily through direct channels rather than through information distortion mechanisms. This suggests that governance is the dominant ESG dimension in safeguarding disclosure credibility and translating sustainability information into economic value.

CONCLUSION

This study examines the relationship between Environmental, Social, and Governance (ESG) disclosure and business value is examined using greenwashing as a mediating mechanism. The data show that ESG disclosure does not serve as a universal value-enhancing technique. Instead, its economic impact is determined by the specific ESG feature, the credibility of sustainability communication, and the sectoral context in which businesses operate.

The findings reveal that Social and Governance disclosures have a positive relationship with corporate value, demonstrating that investors consistently prioritize stakeholder participation and effective oversight mechanisms. In contrast, environmental disclosure does not always increase corporate value. This is especially true in ecologically demanding sectors like energy, where environmental activities are frequently viewed as compliance-driven expenditures or cost burdens rather than immediate sources of economic

return. In the consumer non-cyclicals sector, where reputational stability and operational continuity are critical, Social and Governance dimensions appear more salient in shaping investor perceptions.

Importantly, the study reveals that greenwashing plays a selective mediating role. Strong Governance reduces greenwashing practices and indirectly enhances firm value by improving the credibility of ESG disclosures. This mechanism is especially relevant in sectors with high regulatory pressure and public exposure, such as energy and consumer non-cyclicals, where the risk of symbolic sustainability communication is more pronounced. Governance thus emerges as the central channel through which ESG disclosure quality is translated into market value. These findings add to the ESG and corporate finance literature by emphasizing the need of sectoral sensitivity in assessing sustainability disclosures. The findings demonstrate that the value relevance of ESG is determined not just by disclosure intensity, but also by disclosure credibility and institutional context. Greenwashing is demonstrated to be an economic mechanism capable of altering market interpretation of ESG data, rather than an ethical concern.

From a practical perspective, companies operating in the energy and consumer non-cyclicals sectors should place greater emphasis on robust governance mechanisms to ensure that sustainability disclosures are grounded in substantive actions rather than symbolic claims. For investors, the results underscore the importance of assessing ESG information carefully, particularly governance quality, as an indicator of disclosure credibility. Regulators may also benefit from implementing sector-specific reporting guidelines and stronger enforcement measures to reduce greenwashing practices and improve the informational quality of sustainability disclosures in capital markets.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and research design. Data collection, content analysis, and empirical analysis were performed by the authors. All authors participated in drafting, reviewing, and revising the manuscript, and approved the final version for publication.

ETHICAL STATEMENT

This study is based exclusively on secondary data obtained from publicly available sources, including annual reports and sustainability reports of publicly listed companies. The research did not involve human participants, animals, or sensitive personal data. Therefore, ethical approval and informed consent were not required for this study.

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Applying Kevin Lynch's City Image Elements for Urban Heritage Branding: The Case of Semarang Chinatown

Sub-Theme: *Environmental Policy and Governance*

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ABSTRACT

Semarang Chinatown, established in 1679, is one of the most prominent cultural heritage districts in the city. Over time, however, the area has experienced a decline in spatial quality and reduced attractiveness as a cultural tourism destination. In response, the Semarang City Government launched a revitalization program in 2024 to enhance physical conditions and integrate the district into the Semarang Lama tourism corridor. This study provides a preliminary assessment by applying Kevin Lynch's urban image framework as the foundation for developing a heritage based branding concept titled "Semarang Chinatown: Spirit of Heritage and Culinary." Using a qualitative approach that combines field observations, literature review, and imageability analysis, the research identifies significant spatial potentials. These include distinctive pedestrian paths, clear heritage and commercial edges, strategic connections to the Old Town tourism route, a coherent district character shaped by traditional shophouses, and iconic landmarks such as historic temples and culinary heritage sites. Despite these strengths, challenges remain in establishing a consistent visual identity and improving spatial connectivity. The findings emphasize the importance of urban image elements in supporting heritage revitalization, strengthening urban image elements, and promoting sustainable development aligned with SDGs 11.

Keywords: *Cultural tourism, heritage, revitalization, sustainable development, urban image elements.*

INTRODUCTION

Historic urban heritage districts play a critical role in shaping the cultural identity and collective memory of cities, particularly in rapidly transforming urban contexts. Semarang Chinatown (Kawasan Pecinan Semarang), established in 1679, represents one of the most prominent ethnic heritage districts in Semarang City, characterized by historic shophouse architecture, religious landmarks, traditional trading activities, and a strong culinary culture (Lestari et al., 2021; Kurniati et al., 2020). Despite its cultural significance, the district has experienced a gradual decline in spatial quality and visual coherence, manifested in fragmented pedestrian environments, inconsistent facade treatments, and weakened

connectivity between heritage assets. Previous studies indicate that public perception of Semarang Chinatown tends to focus on a limited number of iconic sites or cultural events, while the broader spatial and experiential qualities of the district remain underrecognized (Soetjipto & Satyagraha, 2020). In response to these challenges, the Semarang City Government initiated a city-led revitalization program in 2024 aimed at improving physical infrastructure and integrating Chinatown into the broader Semarang Lama tourism corridor. However, while this initiative has contributed to material and infrastructural upgrades, it has focused primarily on physical interventions with limited consideration for how spatial structure and experiential legibility shape the district's collective image and long-term sustainability as a heritage destination (Sasnita & Lindarto, 2025).

Within urban studies, the concept of urban image provides a foundational framework for understanding how urban environments are perceived, navigated, and remembered. Kevin Lynch's theory of imageability identifies five key spatial elements such as paths, edges, districts, nodes, and landmarks that function as cognitive anchors shaping orientation, emotional attachment, and everyday urban experience (Lynch, 1960). Subsequent scholarship has emphasized that urban image is not merely a physical construct, but a socio-spatial phenomenon shaped by cultural practices, historical continuity, and governance decisions (Dovey & Pafka, 2020; Shirvani Dastgerdi & de Luca, 2019). In parallel, city branding literature increasingly argues that effective and authentic place branding must be grounded in tangible spatial experience rather than symbolic or promotional narratives alone. Walkable heritage paths, recognizable landmarks, cohesive districts, and active public nodes constitute the experiential foundation through which place identity is communicated, remembered, and emotionally internalized (Zenker & Braun, 2017; Gathen et al., 2020; Scannell & Gifford, 2017). From this perspective, Lynch's city image elements provide more than a theory of perception; they offer an operational bridge for diagnosing the congruence between spatial form, lived experience, and branding narratives within heritage districts.

The integration of urban image and heritage branding becomes particularly critical within the framework of sustainable urban development, as articulated in the United Nations Sustainable Development Goals (SDGs). Sustainable Development Goal 11 emphasizes the safeguarding of cultural heritage (Target 11.4) and the provision of inclusive, safe, and accessible public spaces (Target 11.7), both of which are inherently spatial and perceptual in nature (UNESCO, 2016; UN-Habitat, 2020). Heritage landmarks that function as clear visual anchors contribute to cultural continuity, while legible paths and socially active nodes enhance accessibility, safety, and everyday usability. Nevertheless, a significant research gap remains. Although urban image theory, heritage conservation, city branding, and SDG oriented urban policy have each been widely discussed, these domains are frequently addressed in isolation. Urban image studies often prioritize perception and legibility, heritage research focuses on conservation values, and branding scholarship emphasizes narrative construction and competitiveness, with limited integration into a unified spatial-analytical framework applicable for policy evaluation particularly in rapidly transforming cities of the Global South such as Indonesia (Shirvani Dastgerdi & de Luca, 2019; Gathen et al., 2020; Manoharan et al., 2025; Follmann et al., 2023; UNESCO, 2017). Moreover, prevalent methodologies relying on surveys or secondary data often fail to capture the dynamic interaction between physical form and lived experience, which is essential for understanding heritage imageability and spatial legibility in everyday urban life (Carmona, 2019; Montello, 2018).

Positioned within this gap, this study applies Kevin Lynch's city image framework as a spatial analytical lens to examine Semarang Chinatown in the context of ongoing revitalization. Rather than proposing a theoretical innovation, the study seeks to operationalize and test the applicability of Lynch's image elements within a heritage district undergoing policy intervention. Accordingly, this research is guided by the following questions: (1) How are Kevin Lynch's urban image elements such as paths, edges, districts, nodes, and landmarks configured and performed within Semarang Chinatown based on systematic qualitative field observation? (2) To what extent do these spatial elements support or constrain the coherence of the heritage-based branding concept "Semarang Chinatown: Spirit of Heritage and Culinary"? (3) How can urban image analysis provide a practical spatial reading that relates observed conditions to SDG 11 targets, particularly cultural heritage protection (Target 11.4) and inclusive public space provision (Target 11.7)?

By applying and contextualizing Lynch's framework within Semarang Chinatown, this study offers an empirically grounded assessment of the district's spatial legibility. Its contribution is primarily contextual and operational: it demonstrates how an established urban design framework can be used as a diagnostic tool to interpret the relationship between spatial form, heritage branding narratives, and sustainability objectives in a revitalizing heritage district. The findings aim to inform local policy discussions on sustainable heritage governance rather than advance a new theoretical model.

MATERIALS AND METHOD

Research Design and Study Area

This study adopts an exploratory single case study design employing a qualitative spatial analysis approach to examine the urban image structure of a heritage district. The research is intentionally bounded to enable in-depth, place-specific analysis of spatial form, activity patterns, and experiential qualities through direct field observation.

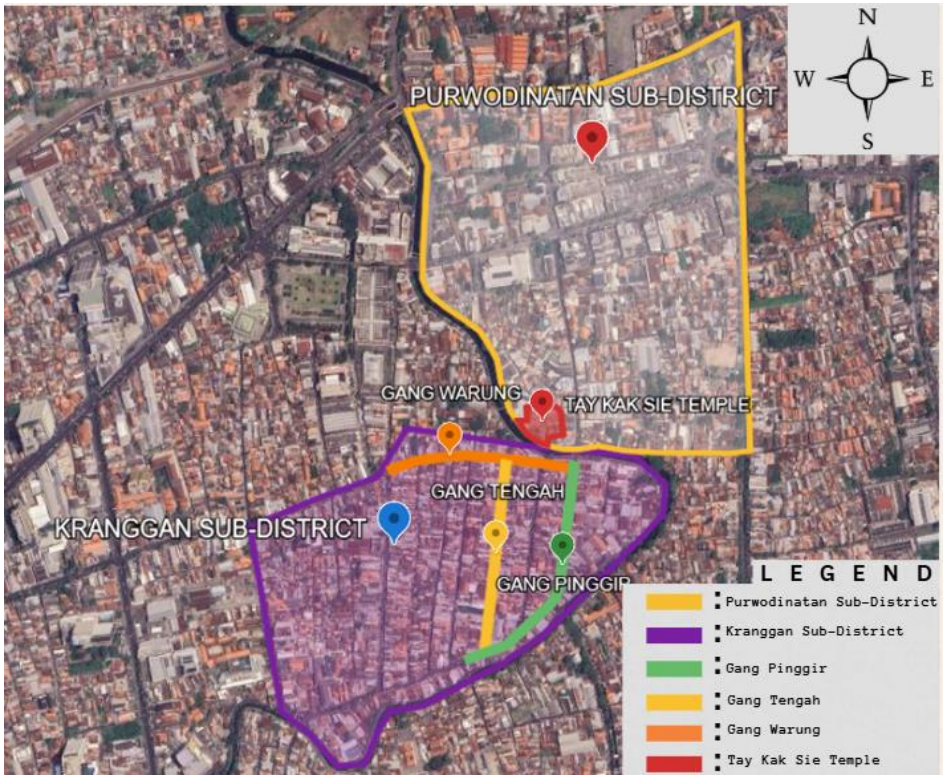

Figure 1. Study Area

The case study focuses on Semarang Chinatown (Kawasan Pecinan Semarang), located in Semarang Tengah District, Central Java, Indonesia, covering parts of Kranggan and Purwodinatan sub-districts. Spatial analysis was concentrated on the core heritage area of Semarang Chinatown, where traditional commercial activities, culinary functions, and cultural practices are most intensively expressed. Field observation focused on three primary internal circulation corridors such as Jalan Gang Warung, Jalan Gang Pinggir, and Jalan Gang Tengah which function as the main paths structuring movement and everyday activities within the district. These corridors were selected because they represent the dominant spatial sequences through which residents and visitors perceive and navigate the Chinatown area.

In addition, to corridor based observation, Klenteng Tay Kak Sie was identified as the principal landmark for analysis based on its high visual visibility, strong cultural significance, and role as a primary spatial anchor within Semarang Chinatown. As the most recognizable heritage structure in the district, the temple plays a central role in shaping spatial orientation and collective image. By clearly delimiting the study area, observation corridors, and key landmark, this research establishes a focused and systematic spatial observation framework. These boundaries directly align with Kevin Lynch's city image elements such as paths, edges, districts, nodes, and landmarks to ensuring that the analysis remains methodologically coherent and spatially grounded within the defined heritage context.

Data Collection

Identification Primary data were obtained through systematic non-participant field observation supported by photographic documentation and structured field notes. Observations were conducted over a concentrated 2 weeks fieldwork phase between October and November 2025, covering multiple weekdays and weekends, as well as daytime and

nighttime periods. This temporal coverage allowed the study to capture variations in pedestrian movement, activity intensity, and spatial perception across different times of use, following principles of human scale urban observation (Gehl & Svarre, 2013).

Photographic documentation was used not merely as passive illustration but as visual evidence to record spatial conditions, activity patterns, and aesthetic qualities observed in the field. The photographs supported later analytical verification by enabling crosschecking between field notes and observable physical attributes such as visual clutter, facade consistency, pedestrian continuity, and landmark visibility. Structured field notes were recorded using an observation protocol sheet organized according to Kevin Lynch's five city image elements: paths, edges, districts, nodes, and landmarks (Lynch, 1960). The protocol included specific prompts for each element for example, for *paths*: sidewalk continuity, pavement condition, degree of visual clutter, and pedestrian density; and for *edges*: clarity of spatial transitions and changes in land-use or architectural character ensuring consistency and comparability across observation locations.

Key observation corridors included Jalan Gang Warung, Jalan Gang Pinggir, and Jalan Gang Tengah, which function as the primary internal circulation routes and concentrate heritage buildings, culinary activities, and everyday social interactions. In addition, Klenteng Tay Kak Sie was observed as the principal landmark due to its strong visibility and cultural significance. Secondary data consisted of policy and planning documents, including the Semarang Chinatown Revitalization Plan (2024), relevant municipal spatial plans, and peer reviewed academic literature. These sources were used to contextualize field observations and to support triangulation between observed spatial conditions, official policy objectives, and heritage branding narratives.

Analytical Framework: Operationalizing Lynch's City Image Elements

This study employs Kevin Lynch's city image framework as the core analytical instrument to examine the spatial legibility and image structure of Semarang Chinatown. In order to ensure methodological clarity, transparency, and replicability, each of Lynch's five city image elementssuch as paths, edges, districts, nodes, and landmarks was operationalized through specific, observable indicators that translate cognitive mapping theory into a systematic field-based assessment (Lynch, 1960).

The analytical framework was designed to explicitly link cognitive functions in urban perception with measurable spatial attributes. As summarized in Table 1, each city image element is associated with (1) its core function in cognitive mapping, and (2) a set of operational indicators used as a guide for structured field observation. This approach transforms abstract perceptual concepts into a practical observation protocol, enabling consistent documentation of spatial conditions across different locations within the study area. The operational indicators were applied during field observation to capture key aspects of spatial experience, including movement continuity, boundary clarity, visual coherence, activity concentration, and symbolic legibility. For example, *paths* were assessed based on connectivity, pedestrian priority, and visual order; *edges* were evaluated through perceptibility, continuity, and contrast; while *districts* were examined in terms of thematic coherence, functional dominance, and atmospheric identity. *Nodes* were analyzed as focal points of activity convergence and social

interaction, whereas *landmarks* were evaluated based on visual dominance, symbolic singularity, and navigational utility.

Table 1. City Image Element Observational Indicators

No	City Image Element (Lynch, 1960)	Core Function in Cognitive Mapping	Observational Indicators (Guide for Field Notes)	Key References for Application
1	Paths	Channels for movement and sequence.	1. Connectivity & Continuity: Direct linkage between major nodes/landmarks; unbroken sidewalk flow. 2. Pedestrian Priority: Dedicated width, even pavement, absence of vehicular conflict. 3. Visual Order: Minimal clutter (signage, utilities); clear sightlines and intuitive navigation.	Gehl & Svarre, 2013; Carmona, 2019
2	Edges	Linear boundaries demarcating districts.	1. Perceptibility: Presence of a clear physical or visual barrier/transition (gateway, change in streetscape). 2. Continuity: Consistency of the edge condition (e.g., building facade line). 3. Contrast: Evident difference in activity, scale, or form across the boundary.	Lynch, 1960; Shirvani Dastgerdi & de Luca, 2019
3	Districts	Medium to large areas with recognizable character.	1. Thematic Coherence: Uniformity in architectural style, scale, and street furniture. 2. Activity Concentration: Predominance of a defining function (e.g., trade, culinary, worship). 3. Atmospheric Identity: Distinct sensory quality (sounds, smells, pacing).	Lynch, 1960; Zenker & Braun, 2017
4	Nodes	Strategic foci of intersection and gathering.	1. Intensity of Use: Convergence of pedestrian flows and density of stationary activity. 2. Social Function: Type of place (intersection, market square, seating cluster). 3. Holding Power: Evidence of lingering (people eating, chatting, waiting).	Lynch, 1960; Carmona, 2019
5	Landmarks	External point as references for orientation.	1. Visual Dominance: High visibility from key approaches; unique silhouette. 2. Symbolic Singularity: Clear cultural/historical significance; iconic status. 3. Navigational Utility: Common use as a directional reference in speech or wayfinding.	Lynch, 1960; Gathen et al., 2020

During analysis, observations recorded for each indicator were qualitatively interpreted to assess the relative strength and clarity of each city image element. Rather than relying on subjective impression alone, this structured framework allowed the researchers to identify whether each element functioned effectively (*strong*), partially (*moderate*), or inadequately (*weak*) in supporting spatial legibility and place recognition, based on direct field evidence. By operationalizing Lynch's city image elements in this manner, the analytical framework provides a spatially grounded diagnostic tool that bridges urban perception theory with empirical observation. This framework forms the methodological foundation for subsequent analysis comparing observed spatial conditions with the district's heritage branding narrative and broader urban sustainability objectives.

Data Analysis

Data analysis followed a two stage qualitative spatial analysis designed to systematically interpret field observations through Lynch's framework and relate them to branding narratives and SDG 11 targets.

Stage 1: Thematic Coding and Preliminary Rating

Field notes and photographic records were thematically coded into the five city image elements. Observed attributes were evaluated against the operational indicators in Table 1. Each element was then given a preliminary qualitative rating (strong, moderate, or weak) based on the cumulative evidence for its clarity, continuity, and functional effectiveness, resulting in a consolidated spatial profile of the study area.

Stage 2: Interpretive Synthesis Against Branding and SDG 11 Targets

Building on the rated profile from Stage 1, an interpretive synthesis was conducted. This stage assessed whether the condition of each spatial element supported or constrained (1) the "Spirit of Heritage and Culinary" branding narrative and (2) SDG 11 Targets 11.4 (cultural heritage) and 11.7 (inclusive public spaces). Support was interpreted when spatial conditions enhanced legibility, identity, or accessibility aligned with these goals. Constraint was identified where fragmentation, disorder, or conflict diminished experiential or policy coherence.

For example, a path with continuous sidewalks and clear sightlines was seen as supporting the walkable culinary district brand and SDG 11.7, while a cluttered, discontinuous path was interpreted as a constraint. Similarly, a highly visible and culturally legible landmark was viewed as supportive of heritage branding and SDG 11.4, whereas an obscured landmark was considered a constraint.

Triangulation and Validation

To ensure robustness, observational findings were triangulated with secondary policy documents (e.g., the 2024 Revitalization Plan). Discrepancies between observed spatial conditions and stated policy goals were analyzed as empirical evidence of implementation gaps, strengthening the analytical validity.

Through this procedure, the study translates raw spatial data into a diagnostic assessment, providing a clear, evidence-based link between urban form, heritage branding, and sustainable development objectives.

RESULTS AND DISCUSSION

Urban Image Structure of Semarang Chinatown

Based on the systematic application of the operational indicators outlined in Table 1, the urban image structure of Semarang Chinatown reveals a distinct imbalance among Lynch's city image elements. Field observations, coded and evaluated using evidence based criteria, indicate that landmarks and activity nodes exhibit strong imageability, while paths and edges remain weak and fragmented, affecting overall spatial legibility.

Figure 2- 5. Weak edge articulation: The lack of a defined gateway or consistent facade treatment blurs the boundary between Semarang Chinatown (left) and the adjacent modern commercial area (right).

Figure 6. Social intensity of an informal node: A vibrant culinary cluster on Jalan Gang Tengah demonstrating high pedestrian convergence and stationary activity.

The primary internal paths such as Jalan Gang Warung, Jalan Gang Pinggir, and Jalan Gang Tengah have functioned as the main movement corridors and host dense culinary and commercial activities. However, when assessed against indicators of continuity, pedestrian priority, and visual order, these paths demonstrate limited performance as image forming elements. Discontinuous sidewalks, uneven pavement conditions, and high degrees of visual clutter caused by unregulated signage, overhead utilities, and informal parking disrupt clear sightlines and pedestrian comfort. As a result, the sequential experience between heritage destinations is fragmented, weakening the cognitive continuity of movement through the district.

Similarly, edges surrounding Semarang Chinatown show weak spatial articulation. Observations indicate an absence of perceptible gateways, facade consistency, or transition markers along boundaries with adjacent urban areas, particularly toward modern commercial zones. This weak edge condition blurs the spatial distinction between Chinatown and its surroundings, reducing its recognizability as a coherent heritage district.

In contrast, nodes such as culinary clusters and market intersections that demonstrate strong experiential intensity. These locations concentrate pedestrian flows and social interaction, functioning as informal but effective focal points of everyday urban life. Their strength lies less in formal design and more in the density and continuity of activity.

Landmarks, most notably Klenteng Tay Kak Sie, emerge as the strongest urban image elements. Evaluated through indicators of visibility, symbolic significance, and navigational utility, the temple functions as a dominant visual and cultural anchor. Its clear silhouette, strategic location, and collective recognition reinforce spatial orientation and serve as a primary reference point for both residents and visitors.

Conceptual Implications: Figure Ground Imbalance and Object Based Heritage Identity

The observed configuration has strong landmarks and nodes contrasted with weak paths and edges that suggests a deeper conceptual condition within Semarang Chinatown's urban image. This pattern reflects an imbalance in the figure ground relationship, a foundational concept in urban design theory.

In this context, landmarks such as Klenteng Tay Kak Sie operate as highly legible figures as distinct objects that dominate perception while the surrounding ground, represented by connective paths, edges, and district fabric, remains weak and visually fragmented. As a result, heritage identity is concentrated in isolated objects rather than embedded within a continuous spatial system. This condition aligns with what can be described as an object based heritage identity, where meaning and recognition are anchored to specific iconic sites. In contrast, a system-based heritage district would exhibit strong spatial continuity, where paths, edges, and districts collectively reinforce identity through the experience of movement and transition. In Semarang Chinatown, the weakness of the ground limits the ability of the spatial system to support and extend the symbolic power of its landmarks. Consequently, heritage perception becomes episodic rather than experiential that centered on arrival at specific destinations rather than sustained through a coherent spatial journey.

Implications for Heritage Branding and SDG 11

This figure ground imbalance has direct implications for the effectiveness of heritage branding. While the branding narrative frames Semarang Chinatown as a heritage culinary district, the spatial system does not consistently support this narrative at the experiential level. Strong landmarks and vibrant culinary nodes communicate cultural value locally, but fragmented paths and weak edges disrupt the continuity required for a cohesive branding experience. From the perspective of SDG 11, the findings indicate a dual condition. The strong visibility and cultural significance of landmarks contribute positively to Target 11.4, which emphasizes safeguarding cultural heritage. However, the limited pedestrian quality and unclear spatial boundaries constrain progress toward Target 11.7, particularly in terms of providing inclusive,

accessible, and comfortable public spaces. Based on this analysis, a strategic implication emerges: heritage branding in Semarang Chinatown should prioritize strengthening the spatial ground particularly pedestrian paths and district edges so that iconic landmarks function within an integrated system rather than as isolated objects. Such an approach would enhance both branding coherence and alignment with SDG 11 objectives.

Synthesis

By applying Kevin Lynch's city image framework as an operational spatial analytical tool, this study demonstrates how the urban image of Semarang Chinatown is currently shaped by strong symbolic figures embedded within a weak connective ground. This finding directly addresses the research objective of linking urban image analysis with heritage branding and sustainability agendas. The results confirm that while Semarang Chinatown possesses substantial cultural and symbolic capital, its branding potential is constrained by uneven spatial legibility. The study contributes by showing that heritage based branding effectiveness depends not only on the presence of iconic landmarks, but on the systemic performance of urban image elements as a whole. In doing so, it reinforces the value of imageability analysis as a policy relevant instrument for guiding heritage revitalization toward more coherent, inclusive, and sustainable urban outcomes.

CONCLUSION

This study applies Kevin Lynch's city image framework as a practical analytical lens to examine the spatial foundations of heritage branding in Semarang Chinatown. The findings reveal a figure ground imbalance, where strong landmarks and activity nodes contrast with weak paths and edges, resulting in an object-based heritage identity rather than a coherent spatial system. While key landmarks support SDG 11.4 on cultural heritage protection, fragmented pedestrian connectivity constrains progress toward SDG 11.7 concerning inclusive public spaces. The study demonstrates the contextual usefulness of Lynch's framework as a diagnostic tool for assessing alignment between spatial form, branding narratives, and sustainability objectives.

However, several limitations should be noted. The research is based on a single-case exploratory design and relies primarily on qualitative field observation, limiting generalizability and quantitative validation. In addition, findings reflect spatial conditions within a specific revitalization phase. Future research may incorporate comparative case studies, user perception surveys, or GIS based spatial analysis to strengthen methodological rigor and examine long-term spatial transformation.

SUPPORTING INFORMATION

This study is supported by additional visual documentation, including georeferenced maps of the study area, a full set of observational photographs categorized by Lynch's image elements, and the structured field note protocol. These materials are available from the corresponding author upon reasonable request.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise, related to this work.

AUTHOR CONTRIBUTIONS

- Tesalonika Ananta Tara: Fieldwork, data collection, formal analysis, writing original draft.
- Angela Valencia Destiana Sutedja: Conceptualization, Methodology, supervision, validation, writing review & editing, project administration.
- All authors agreed to the final version of this manuscript.

ETHICAL STATEMENT

This study involved non-participant observation of public spaces and analysis of publicly available documents. No human or animal subjects were involved, and no personal data were collected. The research adhered to ethical principles of non-intrusive observation and was conducted in accordance with the ethical guidelines of Soegijapranata Catholic University for academic research.

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The Effect of Corporate Social Responsibility on Firm Value with Profitability as a Mediating Variable

Sub-Theme: *Environmental Policy and Governance*

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ABSTRACT:

This study examines the effect of corporate social responsibility on firm value, with profitability measured by return on assets as a mediating variable. The study uses secondary data from twenty-five mining companies listed on the Indonesia Stock Exchange during the period 2022 to 2024. Corporate social responsibility is measured using five indicators based on the Global Reporting Initiative standards. Firm value is proxied by Tobin's Q. Data were analyzed using Partial Least Squares Structural Equation Modeling. The results indicate that corporate social responsibility has a positive and statistically significant effect on profitability, while corporate social responsibility does not show a significant direct effect on firm value. Profitability does not mediate the relationship between corporate social responsibility and firm value. The findings suggest that, in the mining sector, corporate social responsibility contributes more to internal financial performance than to market valuation.

Keywords: Corporate Social Responsibility, Profitability, Firm Value, Return On Assets, Tobin's Q.

INTRODUCTION

Corporate Social Responsibility (CSR) has become increasingly significant in Indonesia, especially in the mining sector, which faces substantial social and environmental challenges. Despite its growing adoption, CSR is often misunderstood, perceived merely as a formality or social activity rather than a strategic business practice. CSR encompasses a company's obligations toward economic, social, and environmental sustainability (Triple Bottom Line) and, when strategically implemented, can improve both business performance and sustainability.

Regulations such as Law No. 40 of 2007 and Financial Services Authority Regulation (POJK) No. 51/POJK.03/2017 mandate CSR reporting in Indonesia, yet implementation quality varies. Market demand for transparency has grown, encouraging companies to adopt CSR for reputation and investor relations. However, empirical findings on CSR's impact on firm value remain mixed. Some studies report positive effects, while others find no significant relationship.

This inconsistency suggests potential mediation by internal factors like profitability. Profitability reflects operational efficiency and investor perceptions. This study examines the

influence of CSR on firm value, mediated by profitability, focusing on mining companies listed on the IDX.

MATERIALS AND METHOD

Stakeholder Theory

Freeman (1984) posits that firms must account not only to shareholders but also to a wider group of stakeholders affected by their activities. Corporate success depends not solely on financial returns but also on fulfilling social and environmental responsibilities. CSR operationalizes this responsibility.

Signaling Theory

Signaling Theory (Spence, 1973) suggests CSR disclosures can signal company quality and sustainability commitment to investors and the public, thereby enhancing trust and market valuation (Brine et al., 2008). Voluntary CSR disclosure is perceived more positively than mandatory compliance.

Definitions

- Corporate Social Responsibility (CSR): Commitment to sustainable development balancing economic, social, and environmental interests (WBCSD, 2000).
- Firm Value: Market evaluation of company performance, measured by Tobin's Q (Chung & Pruitt, 1994).
- Profitability: Efficiency in generating profit from assets, measured by Return on Assets (ROA).

Empirical Studies

Studies on CSR's effect on firm value show mixed results (Katiya et al., 2011; Putu Elia et al., 2018; Evelyn et al., 2015). Profitability may mediate CSR's effect on firm value, though evidence is inconsistent (Mananggar, 2015; Nurlaila & Sofyani, 2021).

Hypotheses

- H1: CSR affects firm value.
- H2: CSR affects profitability.
- H3: Profitability affects firm value.
- H4: CSR affects firm value through profitability.

Population and Sample

The population consists of all mining sector companies listed on the Indonesian Stock Exchage. Purposive sampling selected twenty-five companies that continuously published annual report and disclosed corporate social responsibilty information for the 2022 to 2024 period.

Operational Definitions

1. **Corporate Social Responsibility (CSR)**

CSR is the independent variable representing the company's responsibility toward its stakeholders. The measurement of CSR refers to the Global Reporting Initiative (GRI) Standards with five reflective indicators:

- Environment (GRI 300)
- Employment (GRI 401, 403, 404)
- Community (GRI 413)
- Product Responsibility (GRI 416, 417)
- Governance and Ethics (GRI 102, 205)

CSR is measured using the Corporate Social Responsibility Index (CSRI) based on content analysis, and the score is calculated using the following formula:

$$\mathbf{CSRI} = \sum \frac{Xi}{n}$$

Where:

CSRI = Corporate Social Responsibility Indeks
n = Total number of disclosure indicators (in this study, n = 5)
Xi = 1 if the indicator is disclosed; 0 if not disclosed

2. **Firm Value**

This dependent variable is measured using Tobin's Q, the ratio of market value to the book value of assets:

$$\mathbf{Q} = \frac{\text{MVE} + \text{TL}}{\text{TA}}$$

Where:

MVE (Market Value of Equity) = Year-end closing share price × number of outstanding shares
TL = Total Liabilities
TA = Total Assets

Interpretation:

Q > 1: Overvalued
Q < 1: Undervalued
Q = 1: Fairly valued

3. Profitability (ROA)

As the mediating variable, profitability is measured using Return on Assets (ROA):

$$\textbf{ROA} = \frac{\text{Operating Profit after tax}}{\text{Total Assets}} \times 100\%$$

ROA reflects the company's efficiency in generating profits from its total assets.

Data Collection

Secondary data were obtained from company annual reports and financial statements available on the Indonesia Stock Exchange website and company websites for the years 2022 to 2024.

Data Analysis Technique

Analysis was conducted using Partial Least Squares Structural Equation Modeling. The analysis included assessment of the measurement model (convergent and discriminant validity, reliability) and evaluation of the structural model (path coefficients, statistical significance via bootstrapping, and R square).

RESULT AND DISCUSSION

The measurement model showed adequate convergent validity and reliability for the corporate social responsibility construct with outer loadings exceeding recommended thresholds and composite reliability above 0.70. The structural model results indicate a significant positive path from corporate social responsibility to profitability (path coefficient = 1.021, t = 5.768, $p < 0.001$). The path from corporate social responsibility to firm value was not statistically significant (path coefficient = 0.351, t = 1.686, p = 0.092). The path from profitability to firm value was also not significant (path coefficient = 0.232, t = 1.455, p = 0.146). The indirect effect of corporate social responsibility on firm value via profitability was not significant. R squared values for firm value and profitability were low, indicating the model explains only a small portion of variance in firm value.

The findings suggest corporate social responsibility disclosures in the mining sector are associated with internal performance improvements, reflected in higher return on assets, but these improvements do not translate into higher market valuation as proxied by Tobin's Q. Industry specific factors such as commodity price volatility, regulatory uncertainty, and external investor priorities may limit the market impact of corporate social responsibility signals.

CONCLUSION

This study investigates the effect of Corporate Social Responsibility (CSR) on firm value, with profitability as a mediating variable, in mining sector companies listed on the Indonesia Stock Exchange (IDX) during 2022–2024. Using Partial Least Squares Structural Equation Modeling

(PLS-SEM), the results indicate that CSR has a positive and significant effect on profitability but no significant direct or indirect effect on firm value.

These findings suggest that CSR contributes more to enhancing internal performance than to influencing market perceptions, as reflected in Tobin's Q. This supports Stakeholder Theory, highlighting the importance of meeting internal stakeholder expectations, but only partially supports Signaling Theory, as the market does not fully interpret CSR disclosures as a positive signal for firm value in the mining sector.

Practical Implications

Companies should integrate corporate social responsibility into core strategy to realize operational benefits and improve profitability. To translate corporate social responsibility into market valuation, firms need substantive disclosures, measurable outcome reporting, and investor engagement.

Policy Implications

Regulators should ensure not only mandatory CSR reporting but also its effective implementation through supervision and enforcement. Investor education on the relevance of CSR information in investment decisions is equally important to foster a more responsive market.

Theoretical Implications

The study reinforces the stakeholder perspective on corporate social responsibility and suggests that the signaling effect of disclosure on market valuation is context dependent.

Limitations and Future Research

Limitations include a sample of twenty-five companies, a three-year observation period, a simple five indicator disclosure scoring method, and absence of control variables such as firm size, leverage, and macroeconomic conditions. Future research should expand sample size and period, include control variables, and consider mixed methods to capture investor perceptions.

Overall, the findings emphasize the strategic value of CSR in improving financial performance and underscore the need for substantive execution and credible disclosure to translate sustainability initiatives into measurable gains in firm value.

SUPPORTING INFORMATION

Additional tables and figures related to the measurement model and full bootstrapping output are available upon request.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

- Lokita Putri Arti: conceptualization, data collection, analysis, and manuscript drafting.
- Christina Juliana: supervision, methodology guidance, manuscript review, and corresponding author.

ETHICAL STATEMENT

This study used publicly available secondary data (company annual reports) and did not involve human participants or animals; therefore, formal ethical approval was not required.

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Navigating Green Transition In Indonesia: Blockchain Policy Recommendation for Tracking Carbon Footprints

Sub-Theme: *Environmental Policy and Governance*

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ABSTRACT

This study discusses the urgent need to implement blockchain technology in Indonesia's carbon trading system to improve transparency, accuracy, and carbon footprint verification. Although Indonesia already has various regulations such as UU No. 4/2023, Presidential Regulation 110/2025, and the Carbon Economic Value framework, there are no explicit provisions governing the use of blockchain as a tool for recording and monitoring emissions. This study fills that gap through normative analysis, a conceptual approach, and comparisons with Singapore and the European Green Deal framework, which has promoted the digitization and integration of blockchain in emissions tracking. Previous studies have only highlighted conventional carbon markets without technological integration. The study's findings indicate that the use of blockchain has the potential to strengthen the credibility of emissions data, reduce manipulation, and support the harmonization of domestic policies with global climate commitments. This study proposes concrete policy recommendations for integrating blockchain into Indonesia's carbon footprint tracking system.

Keywords: Blockchain, Carbon Trading, Environmental Regulations, Government, Indonesia Green Transition

INTRODUCTION

Indonesia is the third most biodiverse country in the world after Brazil and Congo. However, despite this wealth, Indonesia also faces an irony because at one point it was recorded as the country with the highest rate of deforestation in the world (Association, 2024) . Indonesia has vast tropical forests with significant carbon sequestration capabilities, making it an ideal candidate for the carbon trading market. National regulations emphasize the importance of REDD+ due to the potential benefits of forest conservation and carbon credits for all industrial efforts in Indonesia. Although Indonesia is a developing country, the UN concept of "Common But Differentiated Responsibilities" (CBDR) implies the need for a tailored approach to carbon trading and comprehensive national regulations to protect forests (Krishnandito, 2024) .

The effectiveness of carbon trading around the world is measured by each country's achievement of its NDC targets to reach net-zero emissions and fulfill its international obligations. An example that can be used as a reference here is the introduction of the EU Emission Trading System (EU ETS) as the world's largest carbon market (European Commission, 2020). Not only that, with its European Green Deal, the EU has also made Europe the first continent in the world to be carbon neutral by 2050, a decade earlier than the global net zero emissions target of 2060 (Pramono, 2024). Similarly, in the United States, the Regional Greenhouse Gas Initiative (RGGI) is a collaborative effort between states in the northeastern and mid-Atlantic regions of the United States that has seen a significant reduction in carbon dioxide emissions from the power sector, which fell by about 47% from 2008 to 2018 (EDF, 2018) . These examples demonstrate the potential of carbon trading schemes to help countries achieve the goals of the Paris Agreement and encourage a transition to cleaner energy sources. Therefore, Indonesia launched IDX Carbon as a carbon trading platform. By starting its journey through IDX Carbon, Indonesia is inspired by these examples, striving to create a carbon market that suits its environmental and economic conditions (Krishnandito, 2024) . The launch of IDX Carbon is evidence of Indonesia's use of market mechanisms to reduce emissions, a process that is in line with its commitment to achieve net-zero emissions by 2060 as stated in its Nationally Determined Contribution (NDC) under the United Nations Framework Convention on Climate Change (UNFCCC) (Wulandari & Salsabiila, 2025) . IDX Carbon will help Indonesia achieve significant reductions in its carbon footprint by adopting the achievements and experiences of established carbon markets, as well as building systems that support its climate goals and promote the SDGs (Krishnandito, 2024) . However, the transparency of carbon emission recording through IDX Carbon is questionable. As IDX Carbon's carbon credit recording system still uses a manual registry system (SRUK) (Peraturan Presiden, 2025). In fact, the carbon trading recording system in Indonesia still faces various challenges, such as a lack of transparency in carbon footprint recording, the risk of data manipulation, and difficulties in verifying actual emissions.

Blockchain offers innovative solutions with a decentralized and immutable recording system, which can increase trust in reported carbon emission data. Therefore, this research is important to develop and propose blockchain-based policies to improve the effectiveness of the carbon footprint tracking system in carbon trading in Indonesia.

RESEARCH METHOD

The research method used is qualitative with a normative approach involving a statutory approach, a conceptual approach, and a comparative approach. The statutory approach is carried out by evaluating legislation or regulations related to carbon trading through carbon exchanges. The conceptual approach was used to develop an ideal concept of carbon trading through carbon exchanges. The comparative approach was conducted by comparing carbon trading regulations through carbon exchanges between Indonesia, Singapore, and the European Union. The data used was secondary data, including primary legal materials in the form of legislation related to carbon trading and carbon exchanges, as well as secondary legal materials such as journals and related literature.

RESULT AND DISCUSSION

a. Carbon Credit Systems: an Overview

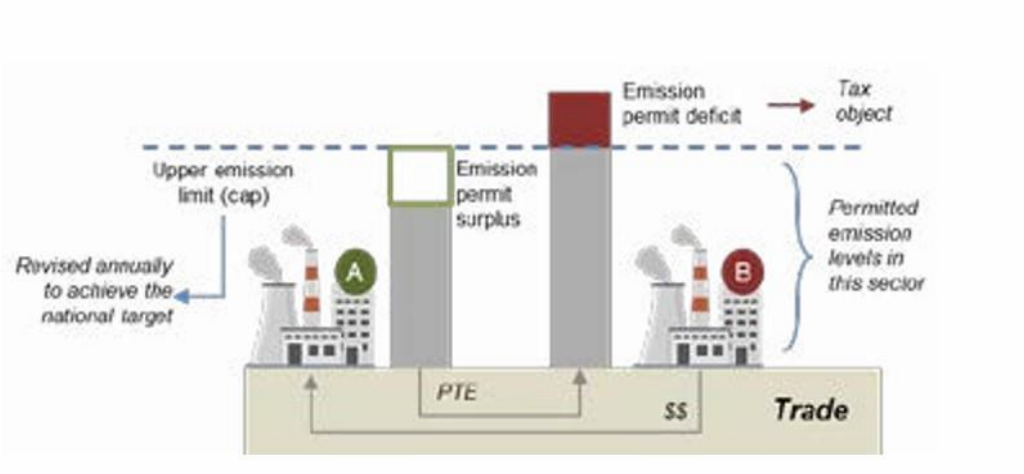

Figure 1. Cap and Trade in Carbon Trading

Carbon trading is a global effort to reduce global carbon emissions through the calculation of carbon emission credits that are traded based on emission allowance limits. Carbon trading involves the buying and selling of emission quotas, which are permits to release emissions into the environment (Ummi A'zizah Zahroh, Yudho Taruno Muryanto, 2024) . Carbon trading is the implementation of points 2 and 8 of Prabowo-Gibran's Asta Cita. Point 2 of Asta Cita encourages a green economy, and point 8 of Asta Cita strengthens the harmonious alignment of life with the environment. This is in line with SDG 9 "industry, innovation, infrastructure" and also SDG 13 "Climate Action".

Carbon credits are a financial tool that represents the reduction of one metric ton of carbon dioxide or its equivalent in other greenhouse gases. These credits are generated through various projects aimed at reducing or eliminating emissions, such as reforestation, renewable energy projects, and improvements in energy efficiency. The two primary types of carbon credits are certified emission reductions (CERs) and voluntary carbon credits.

CERs are issued under the clean development mechanism (CDM), which was established by the Kyoto Protocol. These credits are mainly utilized in compliance carbon markets, where countries and businesses must meet specific emission reduction targets. CERs undergo strict certification processes to verify that the emission reductions are genuine, additional, and permanent.

Voluntary carbon credits, in contrast, are not governed by regulatory frameworks and are traded in voluntary carbon markets. Companies or individuals often purchase these credits to offset their carbon emissions as part of their sustainability or corporate social responsibility initiatives. These voluntary credits can originate from various projects, such as renewable energy, forestry, and waste management, with the most common sources being. On a global scale, carbon credit systems are mainly divided into two types of trading systems: cap-and-trade and carbon offsetting. The European Union Emission Trading System (EU ETS) stands

as the largest carbon market, where companies receive a cap on emissions and can trade credits to achieve their targets. Similarly, the California Cap-and- Trade System enables businesses to acquire carbon credits to comply with state- mandated emissions limits. The certification and verification process plays a vital role in upholding the credibility of carbon credits. Independent third-party auditors assess whether carbon offset projects have genuinely led to emission reductions, confirming that these reductions are "additional" (meaning they would not have occurred without the project). This thorough process guarantees that carbon credits reflect genuine, measurable, and verifiable reductions in emissions, which in turn boosts the integrity and transparency of carbon markets (Yadav et al., 2025).

However, the carbon market also has several challenges. A study by Yadav et al., (2025) points out the following weaknesses in the carbon market:

a. Vulnerability to double counting and invalid credits. Therefore, it is very important to ensure transparency and a robust verification process. Blockchain technology can help by providing tamper-proof tracking and immutable records of credit issuance and transfers.
b. Lack of transparency in tracking cross-border carbon credits. When there is no clarity on how carbon credits move and are transferred, this opens the door to fraud, double counting, and inefficiency. Different countries and jurisdictions often have their own standards for issuing, verifying, and reporting credits, which complicates cross-border trading and undermines trust in the system. This inconsistency makes it difficult to ensure that credits truly reflect emissions reductions and are not counted multiple times. Blockchain technology has the potential to solve this problem by offering a decentralized and transparent ledger, ensuring that carbon credits are tracked, verified, and exchanged securely across national borders without discrepancy.
c. Inefficient transaction processes in the carbon credit market often result in high administrative costs and long processing times. Traditional systems rely on numerous intermediaries (Yadav et al., 2025).

b. Integration of Blockchain Technology with Carbon Market

Blockchain technology is a decentralized and distributed ledger system that tracks transactions across multiple computers, ensuring data integrity and transparency. Unlike traditional centralized databases, blockchain operates on a peer-to-peer network, meaning that no single entity has control over the entire system, which promotes decentralization. The main principle of blockchain is immutability: once a transaction is recorded, it cannot be changed or deleted, ensuring that the record remains permanent and reliable. In addition, blockchain offers strong security through encryption.

This system helps eliminate fraud, prevent double counting, and ensure credit validity by offering real-time and transparent access to carbon credit information. In addition, blockchain's ability to automate processes through smart contracts simplifies verification and certification, leading to lower administrative costs and reduced delays. By transforming how carbon credits are monitored and converted, blockchain has the potential to improve the efficiency and integrity of the carbon market (Yadav et al., 2025).

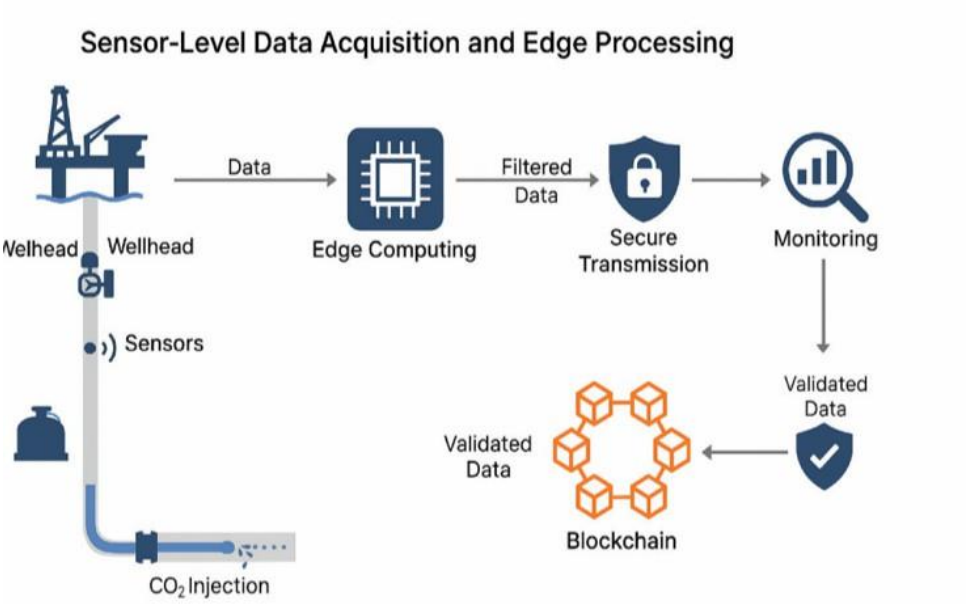

Figure 2. Blockchain in tracking carbon footprint

From the above information, the author believes that real-time carbon credit tracking through blockchain technology ensures that the issuance, transfer, and termination of credits can be carried out quickly and transparently. The decentralized nature of blockchain allows all participants in the carbon market, governments, businesses, and organizations, to access a shared ledger that is constantly updated. This direct sharing of data eliminates delays and the need for intermediaries, speeding up transactions and building trust. By offering visibility into the entire credit lifecycle, blockchain helps prevent fraudulent activities such as double counting or misreporting. In addition, blockchain facilitates instant verification of carbon credits, ensuring that emission reductions are genuine and measurable. The ability to monitor credits in real time also supports improved tracking of progress toward climate goals, enhancing decision-making and market efficiency.

In addition, blockchain's decentralized ledger technology can address these issues by offering a unified, immutable platform for monitoring carbon credits, regardless of where transactions occur.

c. Comparison of Carbon Trading Tools in Indonesia, Singapore, and the European Green Deal

The use of blockchain technology in carbon footprint tracking shows different levels of development between Indonesia, Singapore, and the European Union, reflecting variations in institutional capacity, regulatory frameworks, and climate policy orientations in each region. These differences are evident in aspects such as blockchain usage, legal frameworks, carbon trading instruments, and long-term policy objectives.

In Indonesia, blockchain has not yet been used for carbon footprint tracking. Blockchain has not become the backbone of the monitoring, reporting, and verification (MRV) system, but is still limited to pilot projects and digital environmental policy discussions. The

national emissions recording system still uses a manual registry system that is fragmented across sectors and institutions (Peraturan Presiden, 2025). This situation means that emissions data traceability is not yet fully transparent and real-time, so the benefits of blockchain as an immutable ledger cannot be optimized. This situation contrasts with Singapore, which has strategically positioned digital technology, through “Climate Impact X” Singapore has already built its firm carbon tracing registry and its carbon trading system, including blockchain, as infrastructure that support the credibility of the carbon market (Li, 2025).

Singapore demonstrates a much more advanced and integrated approach. Blockchain is not only understood as a technology, but as part of the carbon platform architecture that supports cross-border carbon credit trading. Through initiatives such as Climate Impact X and bilateral cooperation under Article 6.2, Singapore is developing a system that enables transparency, traceability, and interoperability of emissions data between jurisdictions. According to Li Ruoxuan (2025), Singapore's strength lies in its ability to build a governance platform, where the state acts as a carbon market facilitator without having to control the production of carbon credits itself. In this context, blockchain serves as a trust infrastructure that strengthens the legitimacy of carbon transactions (Li, 2025).

Meanwhile, the European Union, through the European Green Deal framework, is implementing blockchain on a more systemic and normative scale. This technology is aimed at supporting established emissions trading systems, such as the EU Emissions Trading System (EU ETS), with the goal of improving MRV accuracy, data integrity, and cross-border compliance among member states. Unlike Singapore, which is market oriented and flexible, the European Union places blockchain within a strict and standardized regulatory framework, in line with a rule-based governance approach. The ultimate goal is not only market efficiency, but also the collective and binding achievement of the 2050 net-zero emissions target and becoming the leading continent in world green transition (Motani, 2024).

The role of the private sector also shows a significant contrast. In Indonesia, private sector involvement is still limited and highly dependent on government direction. In contrast, the Singaporean government actively mobilizes global financial and corporate actors to build a technology-based carbon trading ecosystem (Li, 2025), while the European Union integrates the private sector into a compliance framework mandated by regulation (European Comission, 2020). Thus, this comparison shows that the successful adoption of blockchain in carbon footprint tracking is largely determined by the alignment between technology, institutional design, and climate policy orientation.

Table 1. Comparison of Carbon Trading Tools in Indonesia, Singapore, and the European Green Deal

ASPECT	Indonesia	Singapore	European Green Deal
Blockchain Usage	Not explicitly mentioned in carbon regulations; limited to pilot projects and voluntary initiatives	Selective and experimental use (carbon exchanges, fintech-led pilot projects)	Strongly encouraged (Digital Product Passport, ETS registries, blockchain-based MRV)
Legal Framework	NEK, Presidential Regulation No. 110/2025	Carbon Pricing Act, Project Greenprint – innovation-friendly	EU Climate Law + ETS Directive (digitally integrated & binding)

	(tech-neutral, non-digital specific)		
Trading Instruments	Indonesian Carbon Exchange (manual / system registry unit karbon / SRUK)	Climate Impact X (CIX), voluntary carbon markets with digital registries	Cap-and-trade ETS with integrated digital & blockchain-compatible MRV
Private Sector Role	Limited access; mostly pilot projects and state-dominated initiatives	Strong participation from banks, fintech, and carbon exchanges	Highly incentivized participation (allowances, compliance markets, green finance)
Monitoring & MRV	Manual reporting and periodic audits	Digital MRV platforms; blockchain-ready infrastructure (selective use)	Real-time, automated, blockchain- verified MRV systems
Data Transparency	Fragmented & institution-centric	High transparency with centralized digital hubs	High transparency with decentralized & interoperable systems
Policy Orientation	Obligation-based emissions reduction	Market-driven, innovation-oriented	Systemic transformation and regulatory enforcement
End Goal	Compliance with NDC & national targets	Becoming a global carbon trading and green finance hub	Net Zero 2050 with sectoral digital roadmaps

d. Reasons Indonesia Has Not Adopted Blockchain in Tracking Carbon Footprints

1. Technology Barriers

Research by Wulandari & Salsabiila (2025) found that the application of blockchain technology in carbon footprint tracking conceptually offers transparency, data immutability, and automation of the monitoring, reporting, and verification (MRV) process. However, in the context of developing countries such as Indonesia, the adoption of blockchain still faces significant technological barriers, particularly related to system scalability, energy consumption, digital infrastructure interoperability, and the technical readiness of data management institutions. These obstacles are crucial because carbon footprint tracking requires a system capable of processing large volumes of data in real-time, across sectors, and across administrative regions (Wulandari & Salsabiila, 2025).

One of the main obstacles in implementing blockchain is the issue of scalability. Blockchain networks tend to slow down as transaction volumes increase, which can hamper the operational efficiency of governments. In addition, blockchains that use proof-of-work consensus mechanisms require significant energy consumption, which can be a problem for governments seeking environmentally friendly solutions.

The issue of blockchain scalability is the biggest challenge in the adoption of blockchain technology in Indonesia. Most public blockchain architectures have limitations in the number of transactions per second, so network performance tends to slow down as transaction volume increases, which can hamper government operational efficiency. In the context of national carbon footprint tracking, the system must be able to simultaneously record millions of data points on emissions from the energy, industrial, forestry, and transportation sectors.

The next technological obstacle relates to the blockchain consensus mechanism, particularly the use of proof-of-work, which consumes a great deal of energy. This is a paradox, given that the initial goal of carbon trading is to reduce carbon emissions in Indonesia, yet the use of blockchain technology requires a great deal of electrical energy

(Purba, 2024). In the Indonesian context, where the energy mix is still dominated by fossil fuel-based power plants, the issue of blockchain energy consumption poses a significant obstacle to the legitimacy of digital technology-based carbon tracking policies.

In addition, limited interoperability of digital systems also hinders the adoption of blockchain. The emissions tracking system in Indonesia is currently managed by various ministries and agencies with different data standards. Integrating blockchain into this ecosystem requires harmonization of data formats, communication protocols, and uniform reporting methodologies. The low level of interoperability between digital environmental systems in Indonesia has the potential to reduce the accuracy of emissions reporting and increase the risk of data inconsistency when new technologies are implemented without systemic reform.

Furthermore, the adoption of blockchain also faces obstacles in its integration with supporting technologies, such as Internet of Things (IoT) sensors, remote sensing systems, and spatial databases. The effectiveness of emissions tracking is highly dependent on the quality of primary data generated by automated monitoring devices. The reality in Indonesia is that the level of digital

infrastructure and internet network availability between regions is very limited. Some urban areas have adequate digital infrastructure and internet networks. This is in stark contrast to eastern Indonesia and several remote areas where internet access is very limited, resulting in a significant gap between regions in Indonesia. The limitations of digital infrastructure in remote areas mean that emissions data is still largely collected manually, making it impossible to use blockchain in areas without internet networks.

Thus, the technological barriers to adopting blockchain for carbon footprint tracking in Indonesia are multidimensional and interrelated. Without improvements in system scalability, energy efficiency, digital infrastructure interoperability, and human resource technical capacity, blockchain has the potential to be a conceptually promising solution that is difficult to implement effectively. Therefore, blockchain adoption must be placed within the broader framework of national digital transformation, in line with the strengthening of the MRV system and the readiness of blockchain technology for tracking carbon footprints in Indonesia (Wulandari & Salsabiila, 2025).

2. Regulatory and Legal Barriers

A critical review of previous research, the study by Nikmah Mentari, et al. (2024) entitled “Implementation of Carbon Trading Regulations in Indonesia from the Perspective of Green Investment and Economic Constitution”. Several previous studies have not discussed the use of blockchain technology for tracking carbon footprints in Indonesia, nor have they discussed policy recommendations related to blockchain for tracking carbon footprints in Indonesia. Previous similar studies only discussed policy regulations related to conventional carbon markets in Indonesia, but did not specifically integrate blockchain technology (Mentari et al., 2024).

In Indonesia, there is not yet a single law or government regulation that explicitly regulates the application of blockchain technology for carbon footprint tracking in

Indonesia. The latest regulation, Presidential Regulation No. 110 of 2025 concerning the Implementation of Carbon Economic Value Instruments, signed by President Prabowo on October 10, 2025, does not regulate the use of

blockchain for tracking carbon footprints in Indonesia. Articles 59 and 87-89 of this Presidential Regulation only regulate the Carbon Unit Registry System (SRUK) as a manual carbon footprint tracking system. Therefore, based on this latest Presidential Regulation, the carbon footprint recording system in Indonesia still uses manual recording under the name Sistem registry Unit karbon (SRUK). The Carbon Unit Registry System (SRUK) functions to transparently record the ownership and transaction history of Carbon Units (SPE GRK).

The following are the points related to SRUK in Presidential Regulation 110/2025:

Definition and Function (Articles 59, 87): The SRUK is dedicated specifically to recording ownership status, transaction history, and the results of Monitoring, Reporting, Verification (MRV) that are legalized as Greenhouse Gas Emission Reduction Certificates.

Legality of Units (Articles 88, 89): SPE GRK recorded in the SRUK are valid as objects of Carbon Trading, the basis for Performance-Based Payments, or instruments of compensation for emissions.

Although various regulations have been issued, none explicitly regulate the application of blockchain technology for carbon footprint tracking in Indonesia:

- Presidential Regulation No. 110 of 2025 concerning the Implementation of Carbon Economic Value Instruments touches on sectoral aspects, but does not provide space for blockchain technology innovation for carbon footprint tracking. Presidential Regulation 110 regulates manual recording for carbon footprint tracking using the Carbon Registry Unit System (SRUK), and is not yet integrated with blockchain technology. This Presidential Regulation replaces Presidential Regulation 98/2021 and emphasizes the use of the new SRUK in conjunction with the National Registry System (SRN-PPI) (Ailesh, 2026).
- UU No. 4 of 2023 concerning the Strengthening and Development of the Financial Sector, Article 23 concerning the Carbon Exchange, is still very general and does not mention technology-based recording mechanisms. Article 5 concerning Carbon Economic Value (NEK) also does not explain the technical implementation integrated with digital systems such as blockchain
- UU No. 16 of 2016 on the Ratification of the Paris Agreement and UU No. 17 of 2004 on the Kyoto Protocol are international commitments without a concrete domestic roadmap for the application of digital technology.

All of these regulations indicate a legal vacuum regarding the legality and standards for implementing blockchain for tracking carbon footprints. Therefore, it is necessary to reconstruct new regulations that provide a strong legal, technical, and adaptive foundation for the development of blockchain technology in carbon trading.

3. Lack of Public Readiness and Awareness

Technological readiness is also greatly influenced by human resource capacity. The implementation of blockchain for carbon footprint tracking requires multidisciplinary expertise, including cryptography, distributed systems, and carbon emission modeling. However, currently, the technical capacity of government officials and industry players in managing blockchain systems is still limited. Reliance on external technology providers increases the risk of long-term dependence and raises concerns about national data sovereignty.

In Indonesia, public awareness of blockchain technology is still low. It is the government's responsibility to massively socialize blockchain technology to the public. Without sufficient understanding of the benefits and risks of this technology, it is difficult for the government to gain widespread public support. In addition, the skills and human resources needed to manage and develop blockchain technology are also limited, which can hinder effective implementation.

e. Blockchain Policy Recommendation in Tracking Carbon Footprint in Indonesia

A critical review of previous research, the study by Nikmah Mentari, et al. (2024) entitled “Implementation of Carbon Trading Regulations in Indonesia from the Perspective of Green Investment and Economic Constitution”. Several previous studies have not discussed the use of blockchain technology for carbon footprint tracking in Indonesia, nor have they discussed policy recommendations related to blockchain for carbon footprint tracking in Indonesia. Previous similar studies only discussed policy regulations related to conventional carbon markets in Indonesia, but did not specifically integrate blockchain technology (Mentari et al., 2024).

From UU No. 4 of 2023 on the Carbon Market to the latest Presidential Regulation No. 110 of 2025 on the Implementation of Carbon Economic Value Instruments, none of them explicitly regulate the application of blockchain technology for carbon footprint tracking in Indonesia. All of these regulations indicate a legal vacuum regarding the legality and standards for the application of blockchain for carbon footprint tracking. Therefore, it is necessary to reconstruct new regulations that provide a strong, technical, and adaptive legal basis for the development of blockchain technology in carbon trading

Policy recommendations for the adoption of blockchain for carbon footprint tracking in Indonesia need to be designed in a gradual and systematic steps to ensure the compatibility of the technology with national institutional capacity. This gradual approach is important to minimize regulatory, technical, and governance risks, while maintaining the credibility of the national carbon trading system.

The first step is the establishment of a legal basis that explicitly recognizes blockchain as a valid instrument in the carbon verification and recording system, so that manual recording through the carbon registry unit system (SRUK) is no longer necessary, but servers for blockchain technology must be prepared. Existing regulations, including Presidential

Regulation No. 110 of 2025 and UU No. 4 of 2023, need to be amended to accommodate distributed ledger technology as part of the monitoring, reporting, and verification (MRV) mechanism. Without clear legal legitimacy, the use of blockchain risks not being recognized administratively or internationally, thereby hindering market confidence.

The second stage is the development of a national carbon ledger, the development of a government-supported permissioned blockchain network integrated with the SRN-PPI system. This national ledger serves as a single database that records emissions, carbon credits, and transactions in a transparent and tamper-proof manner. The permissioned model is considered more suitable for Indonesia because it allows state control over strategic data while maintaining interoperability with international systems.

The third step involves mandating smart contracts to automate the issuance, transfer, and retirement of carbon credits. This automation is important to prevent double counting, which has been a major weakness of conventional carbon systems. With smart contracts, each carbon credit can only be used once and its entire life cycle is documented in real time, thereby enhancing the environmental integrity of the national carbon market.

The fourth step is the accreditation of verification oracles, the certification of IoT devices and digital auditors as trusted data sources. Blockchain cannot stand alone without credible input data; therefore, emission sensors, digital reporting systems, and independent auditors need to be officially recognized as oracles. This approach ensures that the data entered into the ledger is not only transparent, but also accurate and scientifically accountable.

The final step is a pilot phased rollout, which is a gradual implementation through pilot projects in strategic sectors such as electricity (PLN), cement industry, and forestry. The selection of these sectors reflects their significant contribution to emissions as well as their relatively better data readiness. The pilot- first approach allows for technical and institutional evaluation before the system is expanded nationally, thereby reducing the risk of policy failure and enhancing policy learning.

Overall, these policy stages show that the adoption of blockchain in carbon footprint tracking in Indonesia is not merely a matter of technology, but rather a process of environmental governance transformation that requires the synchronization of regulations, institutions, and digital innovation.

CONCLUSION

This study confirms that the application of blockchain technology in carbon footprint tracking in Indonesia is a strategic necessity to improve the transparency, accuracy, and credibility of the national carbon trading system. Although Indonesia already has various regulations related to Carbon Economic Value and carbon trading, the results of the study show that there are legal and institutional gaps related to the use of digital technology, particularly blockchain, in the monitoring, reporting, and verification (MRV) mechanism. Reliance on manual registry systems such as the Carbon Unit Registry System (SRUK) poses risks of data manipulation, delays in verification, and limited cross-sector and cross-regional transparency.

Through a normative, conceptual, and comparative approach with Singapore and the European Union, this study shows that the success of blockchain adoption is largely determined by the alignment between regulation, institutional design, and technological readiness. Singapore and the European Union have proven that blockchain can function as a trust infrastructure that strengthens the integrity of carbon markets, both in the context of voluntary and compliance markets. Therefore, this study recommends a phased policy approach which are establishing a legal basis, developing a national carbon ledger, implementing smart contracts, accrediting verification oracles, and implementing sectoral pilot projects.

Theoretically, this study contributes to the development of literature on technology-based carbon footprint recording in developing countries. Practically, the findings of this study are expected to serve as a reference for policymakers in designing Indonesia's carbon market digital transformation in line with global climate commitments and Indonesia's net zero emission targets.

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