

Beyond The Green Label : Macro, Structural and ESG Drivers of Global Green Bond Yields

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ABSTRACT

Evidence on green bond pricing remains mixed, particularly in emerging markets where macro-financial risks often dominate sustainability considerations. Prior research seldom integrates sovereign risk, inflation dynamics, and market depth when assessing whether ESG performance lowers financing costs, leaving cross-country yield variation insufficiently explained. This study examines the global determinants of green bond yields and evaluates whether sustainability performance translates into lower borrowing costs, with Indonesia as an emerging market case. The analysis is grounded in Signaling Theory and the semi-strong Efficient Market Hypothesis, which posit that ESG information affects prices only after fundamental macroeconomic risks are accounted for. Using a dataset of 1,362 green bonds issued between 2014 and 2023, the study applies a two-layer framework combining Extreme Gradient Boosting and Shapley Additive Explanations to model non-linear yield behavior and quantify the marginal contribution of each determinant. Robustness tests assess stability across pre-crisis, crisis, and post-crisis periods. The findings indicate that structural and macroeconomic factors particularly issuer domicile are the primary drivers of yield formation. ESG attributes remain relevant but exert heterogeneous effects across pillars. The social dimension shows the strongest yield-reducing impact, while environmental and governance scores largely serve as baseline compliance indicators. Indonesia exhibits a high-yield, high-ESG pattern driven by inflation pressures, sovereign risk premia, and limited market depth. ESG-related cost advantages emerge only after core macro-financial risks are controlled, underscoring the importance of macroeconomic stability and institutional credibility for sustainability performance to reduce financing costs in emerging markets.

Keywords: green bonds; ESG performance; yield determinants; emerging markets; sustainable finance

INTRODUCTION

The global market for sustainable finance has grown rapidly over the past decade, positioning green bonds as a core instrument for mobilizing capital toward low-carbon and climate-aligned investments. In 2024, global issuance of sustainable bonds exceeded USD 1 trillion, reflecting continued investor demand for instruments that align environmental objectives with long-term financial returns (Amundi, 2025). Green bonds have become central to climate financing ecosystems, offering issuers a mechanism to raise funds for projects that deliver measurable environmental benefits (Pietsch & Salakhova, 2022). Their credibility is further reinforced by voluntary disclosure and reporting standards such as the ICMA Green Bond Principles (ICMA, 2025) and certification schemes under the Climate Bonds Initiative, which enhance transparency and align market practices with the goals of the Paris Agreement (Climate Bonds Initiative, 2025). Despite this expansion, the question of how green bonds are priced and whether they consistently deliver lower yields for issuers with strong sustainability credentials remains unsettled. A large body of research explores the existence of a “greenium,” or negative yield premium, suggesting that investors may accept lower returns in exchange for environmental value. However, evidence

across developed markets is notably inconsistent. While several studies document modest yield discounts for green bonds, other research finds that these premiums diminish or disappear once conventional risk and liquidity characteristics are incorporated into pricing models (Climate Bonds Initiative, 2025); (OECD, 2025). These inconsistencies highlight a broader uncertainty regarding the conditions under which sustainability attributes influence borrowing costs, and whether such effects persist across market cycles, regions, and regulatory environments.

The divergence in empirical findings is even more pronounced in emerging markets, where macroeconomic volatility, inflationary pressure, sovereign-risk premia, and structural liquidity constraints often exert stronger influence over yields than issuer-specific sustainability attributes (IMF, 2023); (Tomczak, 2024). In such contexts, investors may prioritize macro-financial stability over non-financial disclosures, resulting in weaker or more conditional pricing effects of ESG performance. This dynamic is particularly relevant in Asia, where green bond markets have expanded rapidly but remain characterized by wide variation in institutional maturity, regulatory frameworks, and sovereign credibility. Existing empirical research in Asia and Indonesia remains methodologically constrained. Most studies rely on linear regression approaches such as OLS, which assume stable marginal effects and often fail to account for the non-linear relationships and variable interactions that characterize bond markets, especially in emerging economies (Wahyuningsih et al., 2025). As a result, these models may overlook threshold effects, interaction patterns, or market segmentation that shape yield determination. Linear assumptions also reduce the ability to compare yield drivers across regions or over time, limiting the interpretation of heterogeneous pricing behavior (Abhilash et al., 2024). Evidence from the ASEAN region further illustrates instability: prior to COVID-19, several studies documented a positive greenium, whereas during the pandemic this premium reversed, underscoring the sensitivity of sustainable debt pricing to macroeconomic stress and liquidity disruptions (Oktavio & Riyanti, 2021); (Darmia & Kim, 2024). Indonesia offers a compelling case for examining these issues. The country has developed comprehensive sustainable finance regulations, including POJK No. 60/2017 and the Indonesia Green Taxonomy, which aim to standardize reporting and strengthen alignment with global norms (Otoritas Jasa Keuangan, 2017, 2022).

Despite these advances, Indonesian green bonds consistently trade at higher yields than those issued by regional peers such as China, even when issuers exhibit strong ESG performance. This persistent high-yield, high-ESG configuration raises an important question regarding the effectiveness of sustainability disclosures within a macro-financial environment characterized by inflation volatility, sovereign-risk premia, and relatively shallow capital markets (Fatmawatie et al., 2024). While prior research highlights the role of macroeconomic conditions in shaping bond yields, the hierarchy of influence between country-level structural factors and issuer-level ESG performance has yet to be systematically examined using non-linear analytical techniques.

Against this backdrop, the present study pursues two core research objectives. First, it evaluates the relative contribution of macroeconomic, structural, ESG-related, and bond-specific determinants in shaping green bond yields across a global dataset. Second, it assesses how these relationships differ across market settings, with a particular focus on Indonesia as a representative emerging economy. These objectives are guided by the following research questions:

RQ1: How is the relative contribution (proportional importance) of each variable in forming green bond yields, both in aggregate and at specific issuer levels?

RQ2: Are these effects consistent across countries and over time, and how do they compare specifically for Indonesia relative to other markets through an Indonesia sub-sample and interaction tests?

These research questions address critical gaps in existing literature, particularly the need for analytical frameworks that can evaluate non-linear effects, cross-country heterogeneity, and the interaction between structural risks and sustainability performance.

STUDI LITERATUR

Theoretical Framework

To evaluate the determinants of green bond yields and the underlying pricing mechanisms in the global market, this study is grounded in three key theoretical frameworks: Signaling Theory,

Stakeholder Theory, and the Efficient Market Hypothesis (EMH). These frameworks provide the lens through which issuer credibility, non-financial disclosure, and market pricing dynamics are interpreted.

Signaling theory explains how issuers reduce information asymmetry by sending signals that are difficult to imitate by less knowledgeable parties. In the context of green bonds, issuers communicate their commitment to environmental sustainability through ESG reporting transparency and external certification (Spence, 1973). High-quality ESG disclosure functions as a credible signal that reduces perceived risk and potentially lowers the cost of capital (Flammer, 2021). Complementing this, Stakeholder Theory posits that companies are networks of value relationships. By issuing green bonds and improving ESG performance, firms address the interests of diverse stakeholders, thereby building legitimacy and long-term resilience (Freeman et al., 2021). Finally, the Efficient Market Hypothesis (EMH) suggests that bond prices should reflect all available information, including sustainability attributes. While the semi-strong form of EMH implies that green labels should be rapidly priced in, empirical evidence often reveals inefficiencies and heterogeneity across emerging and developed markets (Fama, 1970) (Wu, 2022).

Sustainable Finance and Green Bond Market Dynamics

The rapid expansion of green finance has made it a central pillar of the low-carbon transition, particularly in emerging markets where environmental vulnerability is pronounced. Green bonds operate as a critical channel for reallocating capital toward activities that generate measurable environmental benefits (Abbas et al., 2024).

The market has seen a structural shift in investor preferences, with global issuance surpassing USD 1 trillion in 2024 (Amundi, 2025). However, the pricing of these instruments remains a subject of intense debate. While some studies document a "greenium" or yield discount driven by investor demand, others find that this premium is often negligible once fundamental risks are accounted for (Pietsch & Salakhova, 2022). This mixed evidence highlights the need to examine yield formation not just through a binary green-label perspective but through a multivariate analysis of bond characteristics and macroeconomic conditions.

Bond-Specific Determinants of Yield

The variation in green bond yields is primarily driven by the structural characteristics of the instrument itself. Two critical factors in this domain are maturity structure and liquidity. According to the Term Structure Theory, investors typically demand a higher yield for longer-dated bonds to compensate for duration risk and interest rate uncertainty. In the green bond market, this relationship generally holds, where longer tenors are associated with higher yields (Wahyuningsih et al., 2025). However, demand from long-term institutional investors such as pension funds can sometimes flatten the yield curve for green assets.

Liquidity, proxied by *Issue Size*, acts as another pivotal determinant. Theory suggests that larger issuances enjoy greater liquidity in the secondary market, thereby reducing the liquidity premium demanded by investors. Empirical evidence from Latin America supports this, showing a negative relationship between issue size and yields (Abhilash et al., 2024). In contrast, evidence from Asian markets has been mixed, with some studies suggesting that liquidity effects are less pronounced due to market fragmentation (Oktavio & Riyanti, 2021).

The Role of ESG Performance: Social vs Environmental Signals

Beyond financial characteristics, sustainability performance serves as a key differentiator in the green bond market. While early literature focused heavily on environmental scores, recent trends suggest a more nuanced signaling mechanism. Investors increasingly view environmental compliance as a standard expectation or "hygiene factor" rather than a differentiating signal. Consequently, the social dimension of ESG is gaining prominence. Strong social performance acts as a proxy for robust management quality and stakeholder engagement, which can effectively lower perceived risk (Roggi et al., 2024). This implies that a higher composite ESG score, and specifically strong social metrics, should theoretically be associated with lower bond yields, as they reduce

information asymmetry and enhance issuer credibility (C. , Zhang et al., 2023); (Jin & Turvey, 2024).

Macro-Structural Determinants: Inflation and Domicile Risk

In the context of global and emerging markets, yield formation cannot be separated from the macroeconomic environment. Inflation serves as a primary driver of nominal yields through the Fisher Effect, where investors require higher returns to offset the erosion of purchasing power. Empirical findings from Indonesia confirm that inflation and benchmark interest rates are dominant drivers of green bond yields, often overshadowing issuer-level sustainability efforts (Wahyuningsih et al., 2025).

Furthermore, the issuer's Domicile acts as a comprehensive proxy for sovereign risk, regulatory quality, and institutional depth. Research indicates that sovereign creditworthiness sets the baseline pricing floor for all issuers within a jurisdiction. For instance, green bonds issued in markets with higher sovereign risk premiums, such as Nigeria or Egypt, consistently trade at higher yields compared to those from core European markets, regardless of the project's green credentials (Tomczak, 2024). This highlights a structural hierarchy where macroeconomic stability and sovereign risk are priced in before sustainability attributes (Panizza et al., 2025).

Methodological Gap and Analytical Approach

Most existing research on green bond yields relies on linear regression models (OLS), which assume stable and linear relationships among predictors. However, financial markets are inherently complex, characterized by non-linear thresholds and interaction effects between variables (Gu et al., 2020). For example, the impact of inflation on yields may intensify non-linearly after crossing a certain threshold, or the value of ESG scores may differ across market regimes. To address these limitations, this study employs a machine learning approach using Extreme Gradient Boosting (XGBoost) combined with Shapley Additive Explanations (SHAP). This methodology allows for the capture of complex, non-linear dependencies and provides a transparent decomposition of how each factor contributes to yield formation, offering a more robust alternative to traditional linear modeling (Chen & Guestrin, 2016); (Lundberg & Lee, 2017)

METHOD

This study aims at examining the determinants of green bond yields in the global market with a specific spotlight on Indonesia. To analyze the influence of bond characteristics and macroeconomic factors, we have created a dataset extracted from three authoritative sources to ensure consistency and comparability across markets. Bond level information such as yields, tenor, issue size, and domicile were obtained from Refinitiv Eikon. ESG Scores were sourced from the LSEG ESG database to capture issuer sustainability performance. Meanwhile, macroeconomic indicators, particularly inflation rates, were collected from the World Bank. Our sample encompasses 1,362 green bonds issued between 2014 and 2023, covering various regions including Asia Pacific, Europe, and the Americas. In the final dataset, we split the observation period into pre pandemic, pandemic, and post pandemic regimes to test stability.

As mentioned in the previous section, the dependent variable of this study is the Green Bond Yield to Maturity (YTM). YTM refers to the return investors expect when holding a green bond to maturity. It captures the market’s assessment of issuer risk, creditworthiness, and sustainability signaling. Utilizing YTM allows for a direct measurement of the cost of capital for green issuers.

Table 1. Summarizes the definitions and sources of the variables used in this study

Variable	Symbol	Measurement	Source
Outcome Variable			
Green Bond Yield	Y	Annual yield-to-maturity based on market price and cash flows	Refinitiv Global Green Bond Database
Bond Specific Characteristic Predictor Variables			



ESG Score	X1	Composite ESG rating (0–100)	LSEG ESG Score
Issue Size	X2	Total issuance value in USD millions	Refinitiv Eikon
Tenor	X3	Years to maturity	Refinitiv Eikon
Macro Characteristic Predictor Variables			
Inflation Rate	X4	Annual CPI inflation (%) of issuer country	World Bank CPI
Domicile/ Region	X5	Country and region categories of issuer	Refinitiv Eikon

To explain the variation in yields, this research includes five key predictor variables derived from the literature review: ESG Score, Issue Size, Tenor, Inflation Rate, and Domicile.

First, this research utilizes the ESG Score as a key predictor of sustainability performance. Theoretically, comprehensive ESG disclosure functions as a credibility signal to investors. Previous literature using Chinese market data reports that higher ESG scores correlate negatively with bond risk premiums, meaning issuers with stronger ESG performance obtain lower yields (C. , Zhang et al., 2023). Other studies support this pattern, suggesting that effective ESG disclosure reduces risk premiums and mitigates greenwashing risks, increasing investor confidence in financed green projects (Jin & Turvey, 2024).

Second, the study includes Issue Size as a proxy for market liquidity. Larger issuances tend to be more liquid and therefore offer lower yields because investors do not require compensation for illiquidity premiums. Empirical evidence in Latin America finds a significant negative effect, although in Asia and Indonesia the relationship appears weaker due to market fragmentation (Oktavio & Riyanti, 2021).

Third, the variable Tenor reflects the time to maturity. Longer maturities generally carry higher exposure to interest rate risk, so investors demand compensation through higher yields. This positive tenor–yield relationship is consistent with term structure theory and has been empirically validated in Indonesian green bond markets (Wahyuningsih et al., 2025).

Fourth, the Inflation Rate captures the macroeconomic environment. Inflation is a consistent driver of green bond yields across emerging and developed markets. When inflation rises, investors require higher nominal returns to offset declining real purchasing power. Evidence from Indonesia shows that inflation significantly increases green bond yields (Wahyuningsih et al., 2025), while European data also identifies inflation as a key determinant of corporate green bond pricing (Grishunin et al., 2023).

Finally, the study incorporates Domicile as a categorical variable to account for sovereign risk and regional differences. Literature shows that regional maturity and risk structures create contrasting yield behaviours between Asian and Latin American markets (Abhilash et al., 2024). Cross-country studies further indicate that sovereign risk is a central driver of yield divergence in green bond markets (Tomczak, 2024). Recent evidence adds that sovereign risk interacts with climate vulnerability, leading emerging markets to exhibit larger green premiums than advanced economies (Panizza et al., 2025).

Figure 3.1 presents the conceptual framework illustrating how these variables operate within the model.

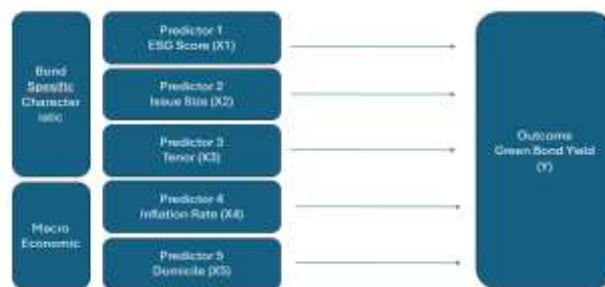


Figure 1. Research Framework

Unlike previous studies that largely rely on linear regression (OLS), this study employs a two-layer analytical approach using Extreme Gradient Boosting (XGBoost) and Shapley Additive Explanations (SHAP). XGBoost is selected because linear regressions often struggle to capture nonlinear thresholds and complex interactions among bond variables. We used the following functional relationship to investigate how the determinants affect yields :

$$GBY_{it} = f(ESG_{it}, IssueSize_{it}, Maturity_{it}, Inflation_{ct}, IssueDomicile_i) + \epsilon_{it}$$

Where GBY_{it} denotes the green bond yield to maturity for bond i at time t , and $f(\cdot)$ is the non-linear function learned by the XGBoost algorithm. To ensure interpretability, SHAP values are applied to decompose the contribution of each predictor. This method allows for a comprehensive analysis of the specific impact of each variable on yield formation.

To operate the model effectively, the dataset’s distributional characteristics must first be examined to understand the structure of the green bonds included in the analysis. The numerical profile of the data is presented below.

Table 2 Descriptive Statistics of Numerical Variables

Variable	Mean	Median	Std. Dev.	Min	Max	Skewness	Kurtosis	Obs
Yield to Maturity (%)	4.74	5.14	2.16	0.11	13.98	0.256	1.297	1362
Tenor (years)	6.71	5.00	4.35	1.00	30.00	2.670	10.413	1362
Amount Outstanding (USD)	3.75e+08	2.13e+08	4.40e+08	4.26e+05	4.15e+09	3.178	19.565	1362
ESG Score (0–100)	66.31	68.00	15.30	16.00	92.00	-0.688	0.053	1362
ESG Environment Score	71.13	73.00	18.55	5.00	98.00	-0.686	-0.029	1362
ESG Social Score	67.50	73.00	18.20	8.00	96.00	-0.817	0.091	1362
ESG Governance Score	60.39	65.00	20.99	6.00	96.00	-0.414	-0.702	1362
Inflation Rate (%)	2.99	2.32	2.76	-1.61	11.64	0.774	-0.419	1362

The numerical distribution shows 1,362 green bonds with diverse characteristics. Yield to Maturity averages 4.74 percent with moderate variation and a slight positive skew, indicating a small group of higher-yield bonds from emerging markets. Tenor averages 6.71 years but extends to 30 years, and its high skewness and kurtosis show that only a limited number of bonds have very long maturity. Amount Outstanding also has strong right skewness and high kurtosis, meaning most issuances are relatively small while a few very large deals dominate the upper tail. ESG scores display mild negative skewness, suggesting issuers tend to cluster toward stronger sustainability performance. Inflation exhibits moderate positive skewness, reflecting that only certain countries experience high inflation.

These skewness and kurtosis patterns show that several variables have long right tails and uneven distributions, reinforcing that the dataset captures a mix of small, medium, and large issuances as well as diverse macroeconomic conditions. This distributional shape supports the use of non-linear modelling approaches to account for these heterogeneous characteristics. The geographic composition of issuers is shown below to complement the numerical characteristics.

Table 3. Descriptive Statistics for Categorical Variables (Domicile)

Variable	Category	Bond Count	Percentage
Domicile	China (Mainland)	149	10.9 %
	Germany	147	10.8 %
	Japan	145	10.6 %
	Sweden	106	7.8 %
	France	85	6.2 %
	United States	84	6.2 %
	South Korea	64	4.7 %
	Italy	52	3.8 %
	Norway	51	3.7 %

	Netherlands	39	2.9 %
	Others	440	32.3 %
Total		1362	100%

The issuer distribution reflects strong participation from major economies such as China, Germany, and Japan. Sweden, France, and the United States also contribute meaningfully. The large share categorized as Others ensures broad sovereign representation, which strengthens the comparative assessment across regions, including the position of Indonesia within the global green bond market.

RESULTS AND DISCUSSION

This chapter presents the empirical results of the modelling framework introduced in the previous section. The analysis begins by evaluating the performance of the benchmark linear regression model and comparing it with the tuned XGBoost algorithm. This comparison is essential to determine the most suitable modelling approach for predicting green bond yields, considering the presence of nonlinearities, cross-country heterogeneity, and interaction effects among financial, macroeconomic, and ESG-related variables.

The two models were estimated to use the same dataset to ensure comparability. Linear regression serves as the conventional benchmark widely used in bond yield studies, while XGBoost represents an advanced ensemble-based method that allows flexible nonlinear functional forms. Table 4.4 reports the predictive accuracy of both models using three performance metrics: Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and the coefficient of determination (R^2). These indicators provide a comprehensive evaluation of model fit by capturing overall error magnitude, sensitivity to large deviations, and explanatory power. Before proceeding with SHAP-based interpretability, this chapter first establishes which model offers the strongest predictive performance. The choice of the most accurate model is critical because it influences the validity of the subsequent feature-attribution analysis.

As demonstrated in the literature, model comparisons are commonly used as a preliminary step to ensure that final interpretations are drawn from the best-performing estimator. For instance, recent green finance studies employ similar benchmarking to decide between conventional regression models and machine-learning alternatives when modelling yield behaviour under heterogeneous financial conditions (Yan & Hu, 2024); (Wang et al., 2022). With this motivation, the following section discusses the accuracy comparison shown in Table 4. and establishes the empirical justification for selecting the tuned XGBoost model as the primary engine for analysis.

Table 4. Model Performance Comparison

<i>Metric</i>	<i>Linear Regression</i>	<i>Tuned XGBoost</i>
<i>Mean Absolute Error (MAE)</i>	<i>0.8860</i>	<i>0.6610</i>
<i>Root Mean Square Error (RMSE)</i>	<i>1.3891</i>	<i>1.2084</i>
<i>R² (Coefficient of Determination)</i>	<i>0.6755</i>	<i>0.7545</i>

Table 4 shows that the tuned XGBoost model outperforms linear regression across all metrics. MAE decreases from 0.8860 to 0.6610, RMSE drops from 1.3891 to 1.2084, and R^2 increases from 0.6755 to 0.7545. These improvements indicate that XGBoost captures nonlinear patterns in green bond yields more effectively than the linear benchmark.

The findings are consistent with previous evidence. XGBoost has been shown to sharply reduce bond pricing errors by modelling nonlinear interactions (Yan & Hu, 2024) and to outperform linear and logistic models in credit risk prediction due to its robustness and regularisation features (Wang et al., 2022). Research in fixed-income markets also confirms that tree-based ensembles provide superior fit when yield curves exhibit nonlinearities (J. Zhang, 2024). In ESG-related applications, XGBoost performs well when handling heterogeneous predictors such as ESG pillars, issue size, tenor, and inflation (Aisy et al., 2025).

Given that the tuned XGBoost model demonstrates superior predictive performance, the next step is to examine how each variable contributes to yield formation. To achieve this, SHAP interpretability tools are applied to decompose the model's predictions into direction and magnitude effects for all predictors. Figure 2. presents the global SHAP beeswarm plot summarizing the overall influence of each factor on YTM.

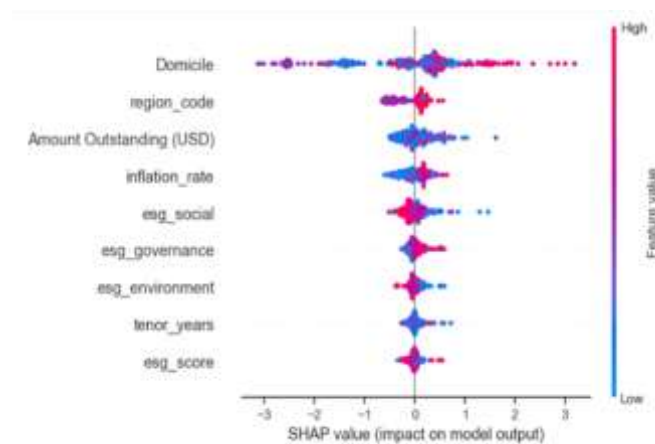


Figure 2. SHAP Beeswarm: Direction and Magnitude of Feature Effects on YTM

The SHAP beeswarm plot in Figure 2 shows that domicile is the dominant driver of yield differences. The wide SHAP range indicates strong cross-country heterogeneity in sovereign risk and monetary credibility. Low-risk jurisdictions such as Japan and Germany appear with negative SHAP values, while higher-risk or more volatile markets cluster on the positive side, consistent with evidence that sovereign fundamentals remain central to green bond pricing (Tomczak, 2024); (Panizza et al., 2025). Region code reinforces this pattern by capturing broader structural gaps between advanced and emerging markets (Abhilash et al., 2024). Bond-specific characteristics play a secondary but visible role. Issue size has SHAP values near zero for most smaller deals, but large issuances shift into negative territory, indicating a modest liquidity discount on yields. This is consistent with liquidity-based theories and findings that only sufficiently large issues enjoy clear pricing benefits, with stronger effects in Latin America than in Asia or Indonesia (Oktavio & Riyanti, 2021). Inflation, in turn, exhibits a non-linear pattern: low to moderate inflation has little impact, but SHAP values increase sharply once inflation exceeds roughly 4 percent, in line with the Fisher Effect and studies showing that inflation becomes a key driver of funding costs when price stability deteriorates (Wahyuningsih et al., 2025); (Grishunin et al., 2023).

Among ESG attributes, the social pillar stands out. Higher social scores systematically align with negative SHAP values, indicating that issuers with stronger labour, community, and human-rights practices face lower required yields. This finding sharpens prior evidence of a general negative ESG spread link (Roggi et al., 2024) by showing that the pricing benefit is concentrated in the social dimension. Environmental and governance scores, by contrast, display SHAP distributions tightly clustered around zero, suggesting that these dimensions behave more as hygiene factors than active yield differentiators in the current sample, which is consistent with the view that environmental compliance is now a baseline requirement for labelled green bonds (Stefaniuc & Thörning, 2021). The composite ESG score still shows a mild negative relationship with yields, confirming that stronger overall ESG performance reduces risk premia through enhanced credibility (C., Zhang et al., 2023); (Jin & Turvey, 2024). However, the SHAP structure reveals that this effect is largely driven by the social pillar, in line with signaling theory, which argues that credible non-financial disclosure lowers information asymmetry and strengthens investor confidence (Boulding & Kirmani, 1993); (Flammer, 2021).

Finally, tenors contribute positively but moderately to yields. Most bonds have maturities below ten years, where SHAP values are slightly positive, reflecting a modest term premium for duration and inflation risk, consistent with term-structure evidence in green bond markets (Abhilash

et al., 2024). At very long maturity, SHAP values tend to flatten, suggesting that strong demand for long-dated sustainable assets compresses yields at the far end of the curve, as also observed by (Suloeva et al., 2023). Overall, the beeswarm plot indicates that green bond yields arise from layered interactions between domicile-driven sovereign risk, liquidity and inflation conditions, and differentiated ESG performance, with the social pillar playing the most tangible role on the sustainability side. After reviewing the global effects of all predictors in the SHAP beeswarm plot, the analysis now shifts to the regional context to examine how green bond yields differ across Asia-Pacific markets. The following figure presents the mean Yield to Maturity by domicile within the region and highlights Indonesia's position relative to its peers.

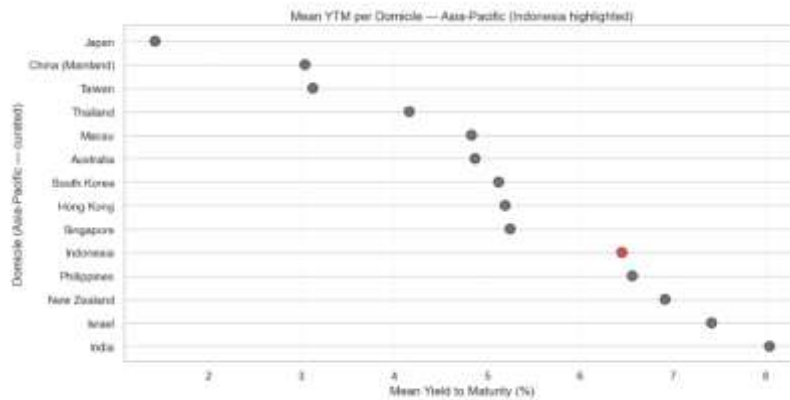


Figure 3. Mean Yield to Maturity per Domicile – Asia-Pacific (Indonesia highlighted)

Figure 3 shows that Indonesia is positioned in the upper range of the Asia Pacific yield distribution, with average yields slightly above 6 percent, a level that exceeds Singapore, Hong Kong, South Korea, and Australia. When Indonesia is compared with major regional peers, a notable contrast appears. Although Indonesia records one of the strongest ESG performances in the region, with average scores higher than China, the United States, and Germany, its green bonds continue to be priced at a premium. This occurs because macro financial conditions, particularly higher inflation and smaller issuance sizes, create upward pressure on yields that outweigh the benefits of strong sustainability performance. As a result, Indonesia reflects a high yield and high ESG profile within the Asia Pacific region, indicating that improvements in macroeconomic stability and sovereign risk are required before strong ESG credentials can translate into lower borrowing costs.

Robustness Test

To confirm the consistency of the findings, the model is re-evaluated through a time-series stability check to ensure that its predictive patterns remain reliable across different market periods.

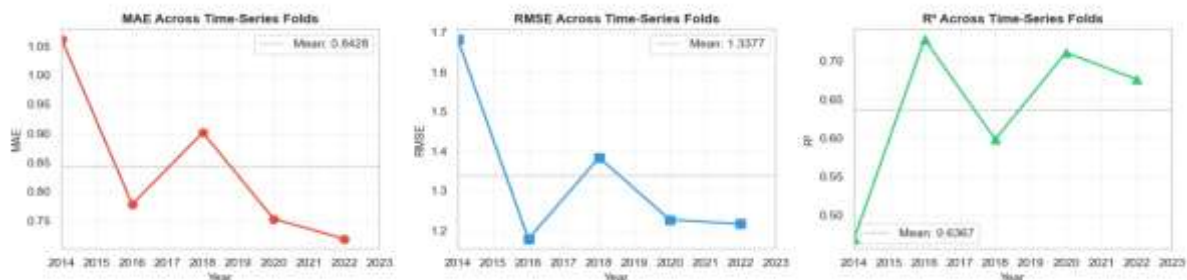


Figure 4. Robustness Test Through Pre-Covid, Covid, Post-Covid

Figure 4. illustrates how the predictive accuracy of the green bond yield model changes across consecutive time windows representing pre-COVID, COVID, and post-COVID periods. In

the earliest window, when the available training data are still limited, the model records higher error levels and weaker explanatory power. As the dataset expands in the subsequent pre-COVID window, prediction errors decrease, and the model captures yield variation more effectively. During the COVID shock, accuracy temporarily deteriorates and the fit declines, reflecting the heightened uncertainty and abrupt shifts in market conditions. In the post-COVID windows, the model's performance improves again, with lower errors and stronger fit, indicating that the predictive structure remains stable once market conditions return to more normal patterns.

Table 5. Model Performance Through Pre Covid, Covid and Post Covid (in average)

Metric	Mean	Standard Deviation (σ)	Interpretation
Mean Absolute Error (MAE)	0.8428	0.1255	Moderate variability across periods
Root Mean Square Error (RMSE)	1.3377	0.1863	Consistent accuracy despite shocks
R ² (Coefficient of Determination)	0.6367	0.0949	Explanatory power remains robust

The aggregated results in Table 4. support the visual evidence from Figure 4., confirms that even when the model is tested strictly on future, out-of-sample data, it retains substantial explanatory power over green bond yields across different macroeconomic regimes.

CONCLUSION

This study shows that green bond yields are shaped first and foremost by structural and macroeconomic conditions, then by sustainability performance. Domicile acts as the main pricing anchors. Investors look at sovereign risk, monetary stability, and market depth before they respond to issuer level ESG information. ESG still matters, but it operates on top of a structural pricing floor rather than replacing it.

The results also indicate a shift in how markets read ESG signals. Environmental performance now functions more as a basic requirement, while the social pillar carries the strongest marginal impact on yields. Strong social performance sends a more credible and costly signal of responsibility, reduces information asymmetry, and helps compress required returns. The greenium, where it exists, appears as a rational discount for lower perceived risk rather than as a sentimental reward for a green label.

The Indonesian spotlight highlights a clear high yield and high ESG configuration. Indonesian issuers display very strong ESG scores yet continue to face elevated yields. This pattern is consistent with a context where persistent inflation risk, sovereign premia, and relatively shallow market depth dominate price formation. In such settings, ESG serves as a risk mitigant that prevents yields from rising even further, but it cannot fully offset macro and structural constraints.

Methodologically, the two layer analytics framework combining XGBoost, SHAP, and regime-based validation proves robust across pre crisis, crisis, and post crisis periods. The model retains meaningful explanatory power even during the COVID shock, which supports the stability of the inferred hierarchy of determinants. Conceptually, the findings refine signaling theory for sustainable finance and support a semi-strong view of market efficiency in the green bond space. Investors integrate green information, but only after they core sovereign, macroeconomic, and liquidity risks.

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