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Advancing Sustainable Investment Strategies through Green Finance and ESG Integration: A Data-Driven Approach to Portfolio Optimization, Risk Management and Long-Term Value Creation

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Abstract
The rapid expansion of sustainable finance has positioned green finance instruments and Environmental, Social, and Governance (ESG) integration as central pillars of modern investment decision-making. However, despite growing investor demand and regulatory momentum, significant challenges persist in effectively translating ESG information and green finance signals into robust portfolio construction, risk management, and long-term value creation. ESG data heterogeneity, rating disagreement among providers, sectoral materiality differences, and uncertainties associated with climate transition risks continue to limit the practical and financial effectiveness of sustainable investment strategies. Addressing these gaps, this study proposes a comprehensive data-driven framework capable to systematically integrate green finance indicators and ESG metrics in portfolio optimization and risk management processes. The proposed framework brings together multi-source ESG data harmonization, sector-specific materiality weighting and green finance exposure metrics like green revenue intensity, green bond allocation and climate transition proxies to create a consistent and investable sustainability signal set. These sustainability variables are simultaneously integrated with the traditional financial factors in a multi-objective portfolio optimization model that aims to maximize risk-adjusted returns while minimizing downside risk while improving sustainability performance. The optimization process explicitly takes into account practical investment constraints such as transaction costs, turnover limits, liquidity

considerations and ESG-based exclusion and tilt requirements. Risk management is taken care of through dynamic estimation of volatility, measures of tail-risk such as Conditional Value-at-Risk (CVaR), and climate aware stress testing in adverse market and transition scenarios. The empirical analysis uses the rolling window backtesting and out-of-sample validation among the diversified equity portfolio in order to analyze the consistency of their performance, drawdown behavior, and portfolio resiliency under different market regimes. Sustainability outcomes are measured with composite ESG scores, carbon intensity and green exposure measures to align with long-term goals for environmental and social outcomes. The results demonstrate that portfolios constructed using the proposed integrated ESG–green finance framework exhibit improved downside protection, reduced tail risk, and enhanced resilience during periods of market stress compared to conventional and ESG-only investment strategies. Importantly, these benefits are achieved without systematically sacrificing long-term return potential, supporting the argument that disciplined ESG integration can coexist with fiduciary performance objectives. This study contributes to the sustainable finance literature by providing a transparent, replicable, and data-driven methodology that bridges the gap between sustainability goals and financial performance, offering practical insights for asset managers, institutional investors, and policymakers seeking to advance resilient, value-creating sustainable investment strategies.

Keywords: Green Finance; ESG Integration; Sustainable Investment; Portfolio Optimization; Risk Management; Data-Driven Investing; Multi-Objective Optimization; Climate Risk; Conditional Value-At-Risk; Sustainable Portfolio Construction; Long-Term Value Creation.

Introduction:

The world-wide investment arena is experiencing a transformation of structure since the concept of sustainability is redefining the principles of capital allocation; risk assessment and development of long term value. Green finance, however, refers to the act of diverting monetary resources into practices that provide quantifiable advantages to the environment including investing in renewable energy usage and energy efficiency gains and low carbon technologies and climate resilient infrastructure [1]. Tools such as green bonds, sustainability linked bonds and climate centric investment funds have been booming in a very short period of time with the help of regulatory initiatives, taxonomies and disclosure standards. Simultaneously, ESG integration has no more been a screening tool that is exclusionary, they are more complex integration tools which directly integrate ESG indicators to financial analysis, portfolio construction and risk management. This development is a progressively growing empirical and regulatory acknowledgement that factors relating to ESG are financially material, and can potentially affect corporate performance, cost of capital, volatility and long-term shareholder value. Despite this progress, there is still difficulty in implementing the concepts of green finance and ESG integration in investment strategies in a practical manner [2]. ESG data are defined by heterogeneity between

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providers, methodological opacification, sectoral imbalances and often inconsistencies in scoring and coverage. Divergent ESG ratings for the same firm can often cause uncertainty for investors which leaves ESG-based signals less confident and may make it challenging to construct a portfolio. Moreover, the green finance indicators (for example, green revenue shares, taxonomy alignment, or issuance of labelled bonds) cannot always be fully integrated into the traditional investment models, which restricts their impact in the opportunities of risk-aware and performance-oriented portfolios. These issues have been giving rise to mixed and even contradictory findings in the empirical literature regarding financial performance of and risk characteristics for sustainable investment strategies [3]. From a portfolio management perspective an important shortcoming of current approaches is the fact that they are based on traditional approaches to mean-variance optimization which mainly taken into account the average return and volatility whereas cannot appropriately reflect downside risk, tails and long-term structural risks. Climate transition risk, regulatory shocks, physical climate hazards and controversies around ESG risks can generate asymmetric losses and non-linear impacts which are incorrectly modeled by variance-based risk measures. As sustainable investing matures, there is an increasingly high demand for better accountability and oversight to environmental, social and governance (ESG) and green finance information from investors that are also explicitly demanding information and disclosure on downside risk, portfolio resilience and performance stability across market regimes [4]. Advances in the availability of data, computational finance and sustainability analytics present new opportunities to overcome these limitations. Expanded ESG disclosures, climate risk metrics and green taxonomy data enable the ability to identify sustainability-related risks and opportunities in an increasingly systematic manner. Studies often have a tilt to ESG scoring or focus on exclusionary screening with no specific inclusion of green finance exposure or modelling downside risk exposure in adverse market and climate related scenarios. This piecemeal approach impedes the ability of investors to fully benefit from the complementarities between performance of ESG, allocation of green capital and long-term financial resilience. Consequently, there is a clear need for comprehensive, data-based frameworks to be jointly designed that tilt ESG metrics, green finance indicators and smart risk management techniques into the portfolio construction process. Against this background, in this study, a unified data-driven investment framework combining green finance indicators and ESG metrics into a multi-objective portfolio optimization and risk management setting is proposed [5]. The framework unifies the ESG data from many sources and sector materiality weighting and green exposure along with the traditional financial factors. By explicitly modelling downside and tail risks, the proposed approach aims to boost the resilience of portfolios and play its part in achieving long-term value creation and sustainability goals. In order to clearly situate this study within existing studies and illustrate its added-value, a summary of key differences between traditional investment approaches, ESG-only strategies, and the proposed integrated ESG-green finance framework are summarized in Table 1.

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Table 1: Comparison of Investment Approaches in Sustainable Portfolio Construction

Dimension	Traditional Investment	ESG-Integrated Investment	Proposed ESG–Green Finance Framework
Primary Objective	Risk–return optimization	ESG-adjusted performance	Joint optimization of returns, risk resilience, and sustainability
ESG Consideration	Not considered	ESG scores or screening	Harmonized ESG metrics with sector materiality weighting
Green Finance Exposure	Absent	Limited or implicit	Explicit integration of green revenue, green bonds, and taxonomy alignment
Risk Measurement	Variance, volatility	Variance with ESG tilt	Volatility, downside risk (CVaR), and stress testing
Climate Risk Treatment	Ignored	Partially implicit	Explicit modeling of transition and tail risks
Investment Horizon	Short- to medium-term	Medium-term	Long-term value creation and resilience
Practical Constraints	Limited	Often simplified	Transaction costs, turnover, liquidity, ESG constraints

The contributions of this study are three fold. First, it is establishing a transparent and replicable data-driven strategy for introducing green finance and ESG information in portfolio optimization. Second, it goes beyond conventional risk management by incorporating downside and tail risk measures relevant to climate- and sustainability-related shocks [6]. Third, it is delivering empirical evidence about the performance of integrated ESG-green finance portfolios versus traditional and ESG-only strategies from the returns, risk and sustainability perspectives. By helping to fill both methodological and practical gaps, this study gives valuable insights for asset managers, institutional investors and policymakers looking to promote sustainable investment strategies that are financially sound, resilient and in line with long-term environmental and social objectives.

Green Finance and the Evolution of Sustainable Investing:

Green finance is fundamental transformation of nature of financial systems, to facilitate environmentally sustainable and support to the sustainable economic activities with maintaining the requisites financial efficiency and fiduciary discipline. In this regard, it includes a large variety of instruments, mechanisms and investment practices that clearly target capital towards climate mitigation, climate adaptation, renewable energy, energy efficiency, low carbon technologies and environmentally resilient infrastructure. Prominent examples include green bonds, sustainability-linked bonds, green loans, climate-related aligned equity investments and climate-related taxonomy-aligned project financing. Unlike traditional methods of investing which have generally recognised the environmental impact as an externality, green finance incorporates environmental goals into the financial decision-making process, which

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essentially "binds" capital expenditure to quantifiable sustainability outcomes [7]. The development of green finance has been under much influence of regulatory intervention and policy-driven such standardization. Early green finance initiatives were chiefly voluntary and market driven, and the results include inconsistent definitions and poor verification mechanisms and an increased concern over greenwashing. As sustainable finance gained systemic importance, regulators and standard-setting organisations developed formal frameworks so as to establish a common understanding of what constitutes environmentally sustainable economic activity. In the European context, the EU Taxonomy has become one of the corner stones of sustainable finance regulation through the provision of science-based classification of environmentally sustainable activities. By providing a definition of technical screening criteria and minimum safeguards the taxonomy provides investors the tools to do more accurate and consistent environmental assessments of corporate revenues, capital expenditures and operating expenditures [8]. Complementing the taxonomy, the implementation of the Sustainable Finance Disclosure Regulation (SFDR), in March 2021, has had a significant impact on the disclosure practices of sustainability in European financial markets. SFDR and sustainability disclosure SFDR requires financial market participants to disclose on integration of sustainability risks principally adverse impacts into investment processes through classification of financial products based on sustainability characteristics. This regulatory structure has introduced an element of transparency and comparability to the standards for investors, while at the same time, increasing analytical and compliance requirements as well [9]. As a result, sustainable investment strategies are increasingly requiring robust data management, methodological discitiety and the explicit inclusion of sustainability considerations in the design and design of investment portfolios. Beyond Europe, worldwide convergence in the field of sustainable finance standards has been accelerated with the establishment of the International Sustainability Standards Board (ISSB) under the IFRS Foundation. The purpose of the IFRS S1 and IFRS S2 standards of the International Sustainability Build (ISSB) is to provide global, investor-centric, and consistent sustainability and climate-related disclosures. Table 2 shows the Key Regulatory and Standard-Setting Frameworks Shaping Green Finance.

Table 2: Key Regulatory and Standard-Setting Frameworks Shaping Green Finance

Framework / Initiative	Scope	Primary Objective	Relevance for Investors
EU Taxonomy	European Union	Classification of environmentally sustainable activities	Enables measurement of green revenue, CapEx, and portfolio alignment
SFDR	European Union	Mandatory sustainability disclosures for financial products	Improves transparency and comparability of sustainable investment products
ISSB (IFRS S1	Global	Standardized sustainability	Enhances global consistency

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& S2)		and climate-related disclosures	and decision-usefulness of ESG data
TCFD	Global	Climate risk disclosure framework	Supports assessment of transition and physical climate risks

The structural transition of green finance from early forms of voluntary initiatives, to a mature and regulation-enable sustainable investment ecosystem is conceptually illustrated in Figure 1, and underlines the interaction of green financial instruments, ESG and integration, regulatory frameworks and regulatory decision-making at portfolio levels.

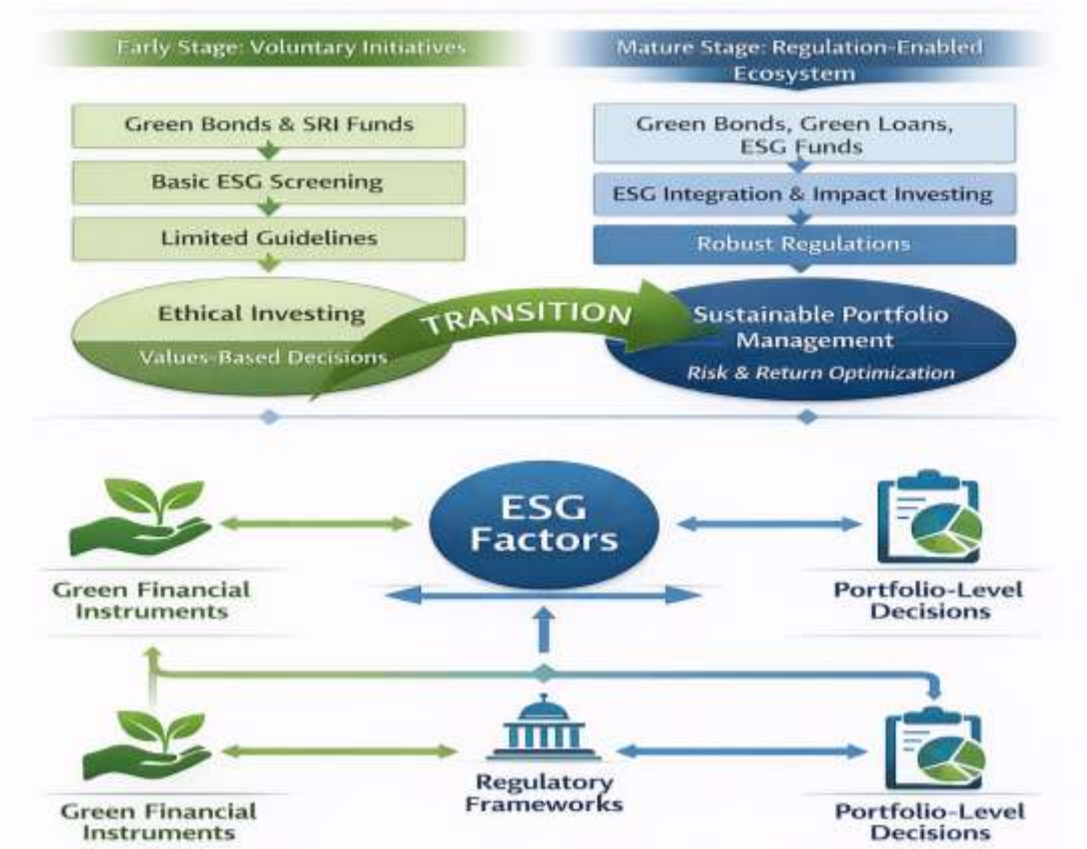

Figure 1: Evolution of Green Finance within Sustainable Investing

The evolution of green finance is part of a broader paradigm shift in sustainable investing from normative and exclusion based approaches towards analytically rigorous, data driven approaches based on regulatory alignment and financial materiality. Whilst increased disclosure and standardisation has done much to add to

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the transparency and confidence of investors, this has also created a greater complexity in the implementation of sustainable investment.

Portfolio Optimization with ESG Constraints and Multi-Objective Formulations: Traditional mean-variance portfolio theory provides a basic framework to balance between expected returns and portfolio volatility, however is limited in the application to the non-financial goals, asymmetric risk profile and long-horizon sustainability considerations. Variance-based risk measures assume, implicitly, that returns are normally distributed and risk preferences are symmetrical, both of which can mean that they underestimate downside exposure and tail risk features that are particularly relevant during situations where ESG-related controversies, regulatory shocks or climate transition risks are effected [10]. As a result, the application of traditional optimization methods to a sustainable investing approach is often unable to adequately reflect the complex trade-offs between financial performance, risk resilience, and sustainability goals. To address these limitations, constrained multi-objective portfolio optimization frameworks for sustainable finance have been used in the sustainable finance literature. Within the ambit of those approaches, investors pursue traditional financial goals such as maximising expected return or minimising risk, but at the same time impose ESG-related constraints. Common constraints are exclusionary screens for controversial sectors or companies with egregious ESG violations, minimum ESG score thresholds against a benchmark and ESG tilts to explicitly favour firms with superior sustainability performance [11]. For example, the use of stringent exclusionary screening method may lead to a smaller investable universe size, and increase the risk of concentration, whereas the ESG tilting method may lead to a better diversification of the invested portfolio while not showing significant improvements in sustainability. These trade-offs highlight the importance of careful thought in the optimization design in relation to investor preferences, regulatory requirements and investment horizons. In this context, the construction of the ESG signals gets as important as deciding which optimization engine to use. ESG ratings suffer from high degree of disagreement across providers and sectoral bias and as well as methodological opacities which can cause noise and instability in the optimized portfolios [12]. As a result, the latest research are focused on harmonization of ESG data, importance of materiality weighting in different sectors, and aggregation of ESG data providers in order to strengthen the robustness of the signal. If ESG signals are poorly constructed, or are inconsistently weighted, even sophisticated optimization models can produce fragile or misleading results. On the other hand, well-designed ESG signals may be helpful in pinpointing the stability of any portfolio, and improve the effectiveness of sustainability constraints in multi-objective optimization settings. An overview of admirably optimization goals, ESG restrictions and risk measures frequently practiced in sustainable portfolio construction are summarized in Table 3. This comparison demonstrates the effect that the method's choice has on both financial and sustainability results and the multidimensionality of ESG-integrated portfolio optimization.

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Table 3: ESG Constraints and Objectives in Sustainable Portfolio Optimization

Component	**Conventional Portfolio**	**ESG-Constrained Portfolio**	**Multi-Objective ESG Portfolio**
Objective Function	Maximize return / minimize variance	Risk–return with ESG tilt	Joint optimization of return, risk, and sustainability
ESG Treatment	Not included	Screening or minimum ESG score	ESG score targets and materiality-weighted integration
Risk Measure	Variance / volatility	Variance with ESG constraints	Volatility, downside risk, tail risk (e.g., CVaR)
Constraints	Budget, short-selling	ESG exclusions, tracking error	ESG, turnover, liquidity, transaction costs
Portfolio Outcome	Financially efficient	Sustainability-adjusted	Balanced performance, resilience, and ESG impact

As Table 3 shows the multi-objective ESG portfolio optimization frameworks exhibit higher flexibility in terms of competing objectives in balancing each other but exhibit higher modeling complexity. The choice of objectives and constraints has a direct impact on portfolio composition, and diversification and sensitivity to ESG data inputs, making the importance of transparent and well-justified methodological choices. The interplay between financial goals, ESG constraints and risk management elements in a sustainable portfolio construction process are conceptually mapped in Figure 2, demonstrating how the ESG signal construction and optimization design contribute towards portfolio outcomes in tandem.

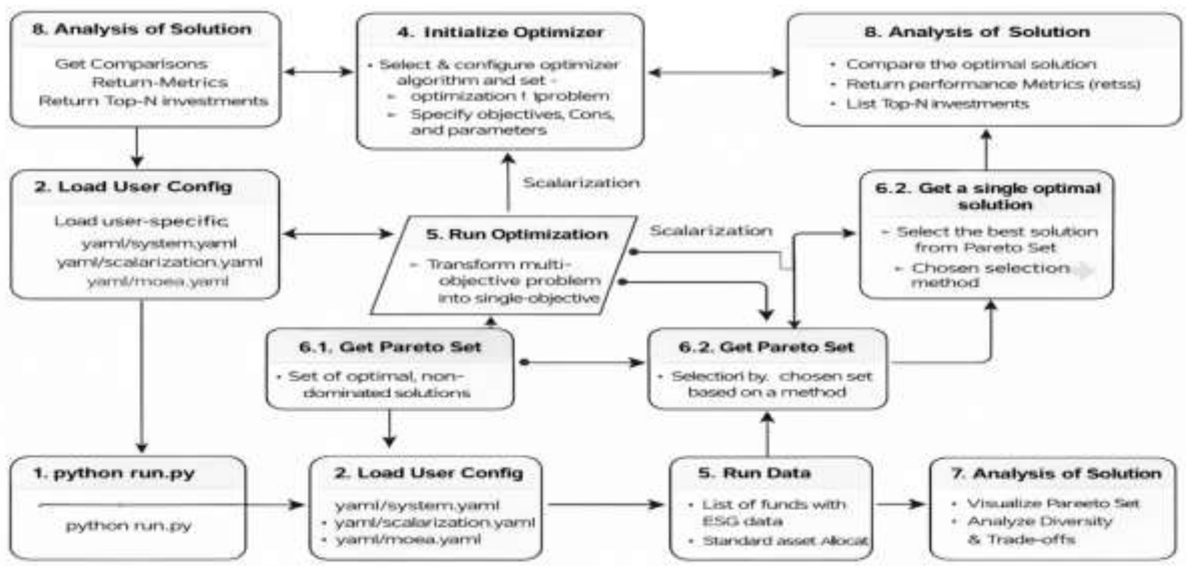

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Figure 2: Multi-Objective ESG Portfolio Optimization Framework

As a whole, the expanding use of ESG constrained and multi-objective optimisation frameworks represent a wider trends of sustainable investing, to move to more sophisticated data-driven decision making. By explicitly modeling financial performance, risk resiliency and sustainability goals in a unified manner, these approaches enable investors to have greater control of trade-offs inherent in the integration of ESGs.

Methodology:

This research is structured by a rigorous methodological framework built on data to examine - in a systematic way - the use of green finance indicators and Environmental, Social, and Governance (ESG) indicators in the combined study to optimise portfolios, risk management, and value creation across the long term. The methodological design is explicitly inspired on recurring problems in the sustainable finance literature such as the heterogeneity and poor comparability of ESG data, serious rating disagreement among ESG providers, and the failure of traditional portfolio optimization models to adequately accommodate asymmetric risks, tail risks and sustainability-related uncertainties [13]. These limitations are relevant in particular in the context of climate transition risk, regulatory shocks and controversies over ESG-related issues, which may lead to non-linear and prolonged impacts on portfolio performance. In order to overcome these problems, the proposed framework discusses various methodological components together in one investment decision making process. First, ESG signals are harmonised based on normalization and sector-specific materiality weighting in order to reduce the amount of noise and maximise stability over time and data sources. Second, green finance indicators (i.e. taxonomy-aligned revenues, green capital expenditures, exposure to labelled green financial instruments) are explicitly included to ensure that sustainability alignment is based on actual economic activity and not simply score-based assessments. Such inputs on sustainability are fed into a multi-objective portfolio optimization model based on a combined optimization of expected financial returns, downside risk exposure and sustainability performance, under realistic investment constraints, such as tracking error, turnover, liquidity and investability requirements [14]. Risk management in the framework goes beyond the traditional variance based measures in that it considers the advanced downside risk as well as tail risk measures, most notably Conditional Value-at Risk (CVaR) which reflect extreme loss scenarios which are of their part of special importance for sustainability-related risks.

Research Framework and Study Design:

The research process begins with collecting and pre-processing of data such as constructing a consistent set of financial returns and also harmonizing the information of ESG and green finance. This is succeeded by ESG signal construction and integration of green finance indicators where a set of variables that address sustainability would be transformed into investable signals, which can be optimized. The following step involves the Best Managed Portfolio Optimization which involves

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the multi objective formulation which is simultaneously concerned with Expected Returns, Downside Risk, ESG Performance and Green Finance Exposure in consideration of the Realistic Investment Constraints. And lastly, the results of the portfolios are evaluated based on the full performance and risk analysis with the assistance of out-of-sample back-testing and robustness analysis [15]. Critically, the study design has taken into account the implementability and realism problems, by incorporating the constraints that are shared by institutional investors. These are monitoring error limits so as to manage the deviation of the benchmark portfolios, turnover limits, so as to limit the transaction cost, and liquidity limits, so as to trade. Inclusion of these elements in the framework of this research will result in the research coming up with the resultant portfolios that are not just optimal on the theoretical viewpoint, but are practical also. Table 4 gives a summary of the main steps of the research framework and their methodological functions.

Table 4: Research Framework Components and Methodological Roles

Framework Stage	**Description**	**Methodological Purpose**
Data Collection and Preprocessing	Financial returns, ESG scores, and green finance indicators are collected and cleaned	Ensures data consistency and reliability
ESG Signal Construction	ESG data are normalized and materiality-weighted	Reduces noise and rating disagreement
Green Finance Integration	Taxonomy-aligned revenues and green exposure measures are constructed	Captures tangible sustainability alignment
Portfolio Optimization	Multi-objective optimization with financial and sustainability objectives	Models trade-offs between return, risk, and sustainability
Performance and Risk Evaluation	Backtesting and downside risk analysis	Assesses robustness and real-world relevance

The step-wise flow of data inputs, sustainability signal construction, portfolio optimization and performance evaluation are conceptually explained in Figure 3 and emphasizes the integrated and iterative nature of the proposed research framework.

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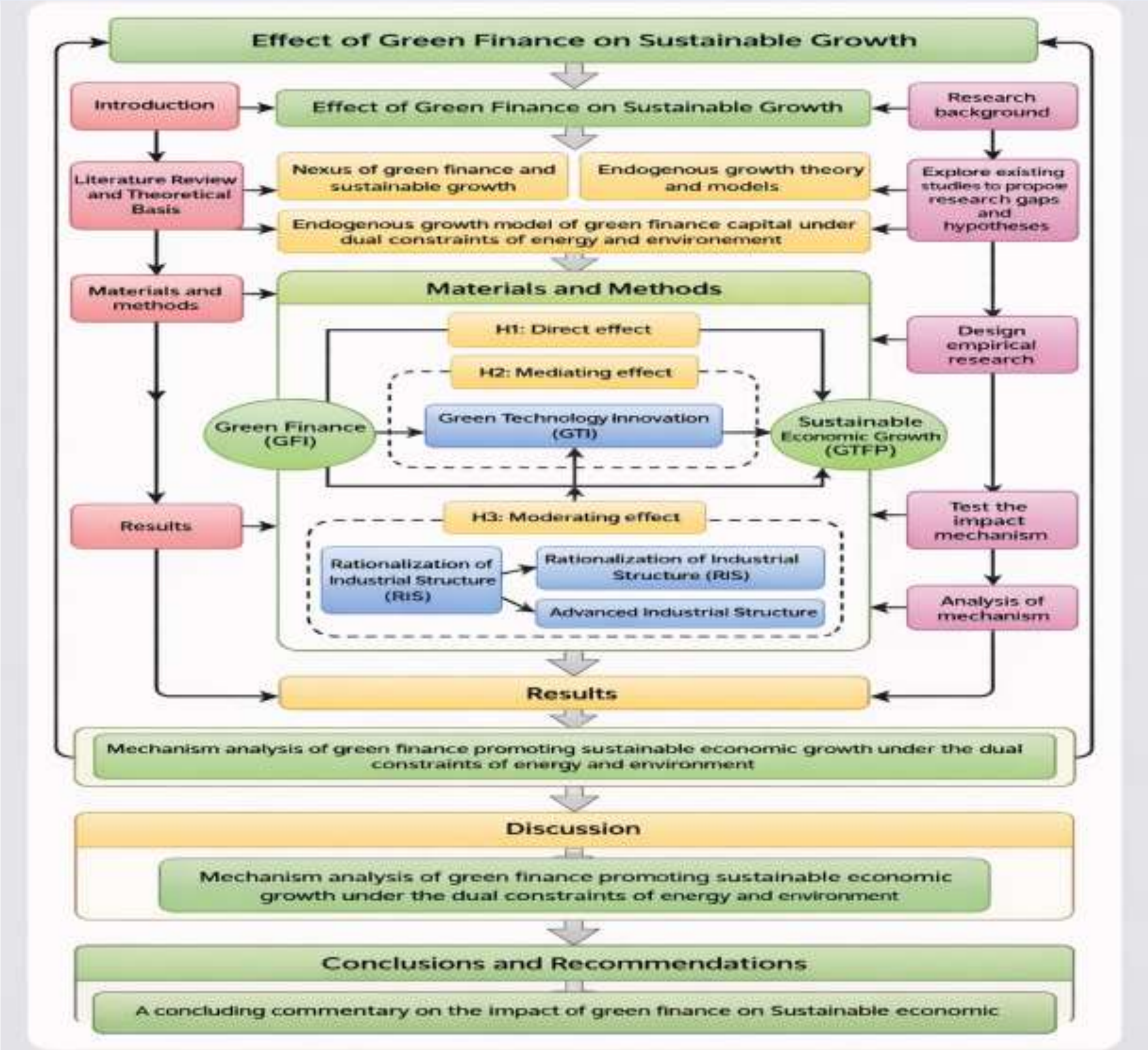

Figure 3: Research Framework and Study Design

The proposed research framework and study design provide a coherent and systematic basis for both analysis of sustainable investment strategies in a data-driven way. By modeling financial return, ESG performance and green finance exposure into a coherent optimization and evaluation framework at once, the study enables the rigorous proof of performance on sustainability trades-off under realistic market and regulatory conditions.

Data Sources and Sample Construction:

The empirical analysis is based on a diversified universe of publicly listed companies, which is built to ensure both broad sectoral representation and adequate variation in both financial performance and sustainability characteristics. The selection of the

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sample is aimed at reflecting the investment opportunity as unique as the institutional investors usually face with the data remaining of the quality, consistency and comparability of assets. Firms are sampled from the major developed and emerging equity markets, so the framework can capture heterogeneous practices of sustainability, a regulatory environment, and market dynamics. Financial market data are data pertaining to asset prices, returns, market capitalization, liquidity measures, and are used to calculate expected returns, risk metrics, and constraints on investability [16]. Returns are calculated at a monthly frequency to trade off noise reduction and being able to capture medium-term investment dynamics relevant for portfolio rebalancing. Market capitalization and trading volume information is used to enforce liquidity screens and prevent excessive concentration in illiquid stocks. ESG data are obtained from multiple ESG rating providers in order to reduce the reliance on the rating from a sole provider and to address well-documented concerns about ESG rating disagreement. The raw ESG dataset comprises overall ESG scores as well as pillar level indicators across the three dimensions of environmental, social and governance. To ensure temporal consistency, ESG scores are made consistent with the financial reporting periods and forward filled only where there are limited disclosure gaps and methodologically justified. Green finance indicators are built based on firm-level disclosures on environmentally sustainable economic activities [17]. These include the percentage of revenues generated from green or taxonomy aligned activities, green capital spending and exposure to labelled green financial instruments such as green bonds or sustainability linked bonds. By getting down to specific activity-based indicators, the dataset reflects real environmental matchmaking instead of focusing solely on perception-based ESG ratings. To ensure data integrity, several screening criteria are used in the construction of samples. Firms with missing or incomplete return histories, with insufficient ESG disclosures or with extreme illiquidity are filtered out from the final sample. Additionally, outliers of financial and sustainability variables are winsorized to decrease the effect of extreme observations [18]. The resulting dataset is a balanced panel that can be used for portfolio optimisation, risk modelling and out-of-sample backtesting. A summary of the data categories, sources, and variable roles used in the empirical analysis is provided in Table 5**.**

Table 5: Overview of Data Sources and Variables

Data Category	**Variables**	**Purpose in Analysis**
Financial Market Data	Prices, returns, market capitalization, trading volume	Portfolio returns, risk estimation, liquidity constraints
ESG Data	Aggregate ESG score, E/S/G pillar scores	Sustainability signal construction and ESG constraints
Green Finance Data	Green revenue share, green CapEx, green bond exposure	Measurement of environmental alignment
Benchmark Data	Market index returns and ESG benchmarks	Performance and tracking-error evaluation

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Control Variables	Sector classification, firm size	Materiality weighting and diversification control

As demonstrated in Table 5, the dataset uses financial, ESG and green financial variables in a unified structure to allow a consistent modeling of the interactions between sustainability and performance over the entire portfolio construction process. The process of multi-source data integration and sample construction used in the current study is schematically framed in Figure 4, indicating how financial, ESG and green finance data streams are combined to create a uniform and investable data set for the effective optimization of investment portfolios.

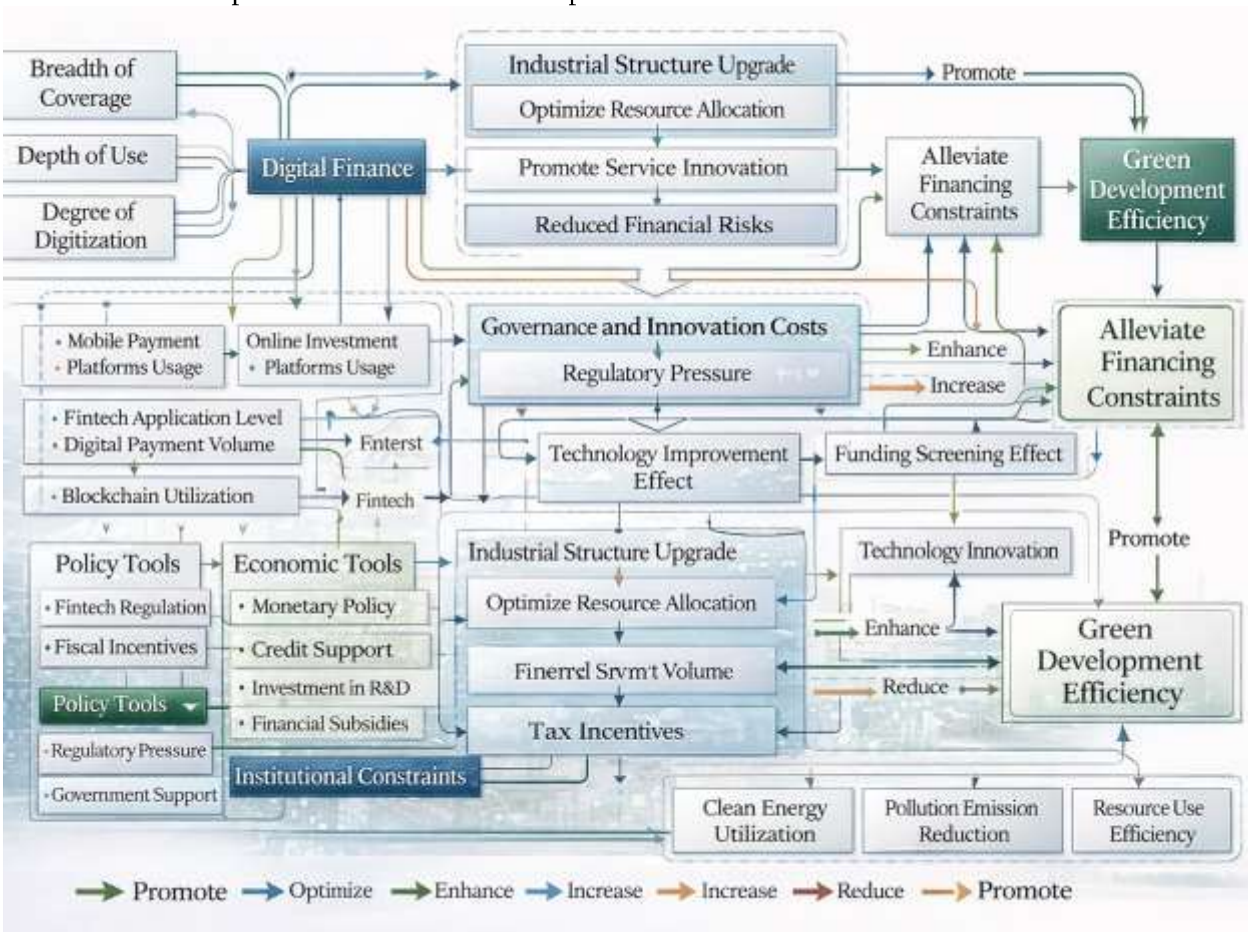

Figure 4: Data Sources and Sample Construction Workflow

The sources of the data and the approach we have taken to creating the sample are designed to facilitate a robust and transparent empirical investigation of the sustainable investment strategies. By combining multi source ESG data with activity-based clean finance data and high quality financial market data, the dataset facilitates stringent modeling of sustainability-related trade-offs in portfolio optimization and risk management.

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ESG Signal Construction and Harmonization:
A crucial methodological challenge in ESG-integrated portfolio optimization is the construction of reliable, stable and economically meaningful ESG signals. ESG information has the inherent characteristics of being complex, multidimensional and subject to significant heterogeneity among data providers. Differences in choice of indicators, data sources, weighting methodologies and aggregation rules are often the cause of low correlations across ESG ratings for the same firm. Direct use of raw ESG scores in portfolio optimization can therefore add a lot of noise, amplify estimation noise and result in unstable or unintuitive portfolio allocations [19]. Recognizing these limitations, this study adopts a structured ESG signal construction and harmonization framework that aims to increase comparability, robustness and financial relevance of the ESG signal. The ESG signal construction process starts with gathering ESG data from several rating providers that include, on one hand, aggregate scores of ESG and, on the other hand, disaggregated indicators of pillars for the environment, social, and governance. Using multiple providers helps avoid dependence on any single proprietary methodology and eliminates the risk of systematic bias. In the temporal match to the financial data, ESG observations are matched to respective financial reporting periods and only firms with minimum thresholds of disclosure are retained [20]. Limited missing values are filled in using conservative interpolation techniques; while firms with persistent missing data are dropped in order to maintain signal integrity. With the heterogeneous scales, distributions of ESG scores by providers, the next step is normalization to a common scale. Normalization is used to make ESG indicators consistent across data sources and to avoid providers with broader score ranges from having an overrepresentation on the composite ESG signal [21]. This step is especially important in cases of multi-objective optimization problems, where ESG variables directly impact portfolio weights. By defining the inputs for ESG in a standard way, the methodology minimizes distortions caused by measurement conventions compared to actual performance related to sustainability. Beyond normalization, the framework explicitly includes weightings of sector-specific materialities in recognition of the insight that not all dimensions of ESG are equally relevant across industries. Environmental factors are generally more financially material for energy-intensive and extractive sectors; and social and governance dimensions are often more material for service-oriented and knowledge-based industries. Materiality weighting is applied at ESG pillar level meaning importance of the environmental, social and governance indicators varies by sector. This approach makes ESG signals more relevant from an economic viewpoint in that the signals are better matched to sector-specific risk exposures and longer-term value drivers [22]. After normalization and materiality adjustment, the ESG indicators are then aggregated by pillar and provider to create a composite ESG score for each asset. Aggregation is done through weighted averaging schemes which attempt to trade-off information content with stability. Combining multiple providers decreases idiosyncratic noise and lessens the effect of extreme ratings or methodological outliers. The resultant composite ESG signal is continuous, transparent and interpretable, and can therefore be used as an input to optimization, as

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a constraint variable or as part of the objective function. The key steps involved in ESG signal construction and their methodological roles are summarized in Table 6**.**

Table 6: ESG Signal Construction and Harmonization Methodology

Stage	**Procedure**	**Purpose**
Multi-provider data collection	Aggregate and pillar-level ESG scores from multiple sources	Reduces provider-specific bias
Data alignment and screening	Temporal alignment and disclosure thresholds	Ensures consistency and reliability
Score normalization	Rescaling to a common numerical range	Improves cross-provider comparability
Materiality weighting	Sector-specific weighting of E, S, and G pillars	Enhances financial relevance
Cross-provider aggregation	Weighted averaging across providers	Mitigates rating disagreement
Composite ESG signal	Final ESG score per asset	Input for optimization and constraints

ESG signal construction is not a single transformation but a multi-stage process, where each step contributes to reducing noise and increasing the stability and economic interpretability of ESG inputs used in portfolio optimization. The sequential transformation of raw ESG data into a harmonized, investable ESG signal through normalization, sector materiality weighting, and aggregation across providers is conceptually illustrated in Figure 5**.**

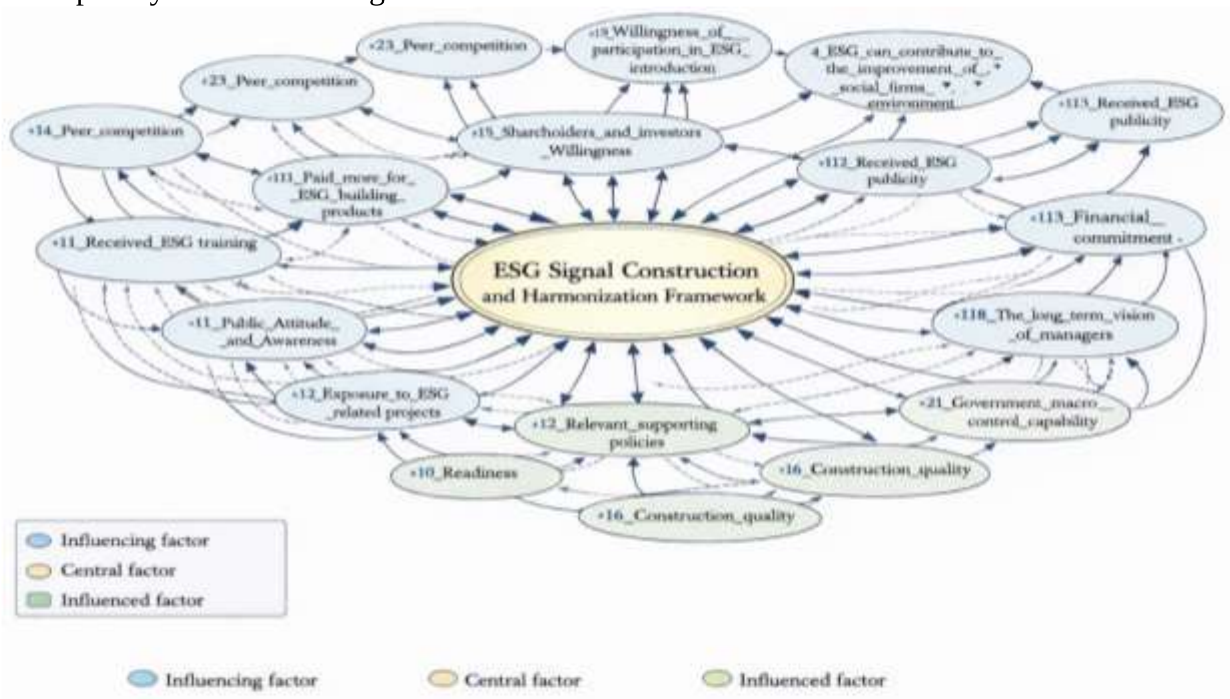

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Figure 5: ESG Signal Construction and Harmonization Framework

The ESG signal construction and harmonization framework is a cornerstone of the proposed methodology, as the quality of ESG inputs fundamentally determines the effectiveness of ESG-integrated portfolio optimization. By explicitly addressing ESG data heterogeneity, rating disagreement, and sectoral differences in materiality, the approach enhances signal robustness and reduces the risk of spurious optimization outcomes driven by measurement noise rather than true sustainability characteristics.

Green Finance Indicator Integration:

While ESG metrics offer a wide and multidimensional analysis of corporate sustainability performance, they certainly do not necessarily reflect the degree to which firms actively invest capital in environmentally sustainable economic activities. ESG scores often integrate outcome-based indicators, policies and disclosure practices, which may reflect governance quality or reporting sophistication rather than concrete environmental investment decisions. To overcome this limitation, the current study explicitly incorporates green finance indicators into the portfolio construction framework, thereby adding ESG-based assessments with activity-based measures to directly show firms' contribution to the environmental transition. Green finance indicators are concerned with the direction, scale and intensity of capital flows towards environmentally sustainable actions, such as climate change mitigation, climate adaptation, energy efficiency and low carbon technologies [23]. By construction, these indicators focus more on concrete economic alignment rather than on reputation- or perception-based performance of sustainability. This distinction is especially important in the context of portfolio optimization where investors are increasingly seeking evidence that the integration of sustainability equates to real world environmental impact and transition financing, not just better ESG scores. In this study, green finance indicators are developed based on firm-level disclosure on environmentally sustainable activities and financing instruments. The most important are the percentage of revenues that come from green or taxonomy-aligned activities, the percentage of capital expenditures spent on green or low-carbon projects, and the exposure to labelled green financial instruments (green bonds and sustainability-linked bonds). Together these measures reflect both operational alignment today (e.g. green revenues) and a transition commitment in the future (e.g. green capital expenditures) and how firms interact with green capital markets [24]. To ensure comparability among firms of different sizes and across different sectors with different production structures, green finance indicators are standardized and expressed as relative measures, such as as percentages of total revenues, capital expenditures or outstanding debt. This normalization helps avoid the situation where large firms have a dominant effect on portfolio-level measures of green exposure simply because of their scale. Furthermore, sectoral context is explicitly accounted for, as it is recognised that there are different opportunities for green investment in different industries. For example, green capital expenditures may be especially informative in utilities, energy and industrial sectors, whereas green revenue shares may be more relevant in manufacturing and technology-intensive sectors. Within the

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framework of portfolio optimization, green finance indicators are incorporated using the dual channel method. First, minimum green exposure constraints are placed to ensure that optimised portfolios have a certain degree of environmental observance as compared to a benchmark portfolio [25]. These constraints ensure that sustainability goals are realised ex ante and not sacrificed in an attempt to achieve short-term financial gains. Second, green finance indicators are included into the multi-objective optimization problem as auxiliary objectives, which makes it possible for the model to endogenously balance expected returns, risk, ESG performance, and green investment intensity. This flexible integration allows the framework to cater to different investor preferences, regulatory requirements and sustainability mandates. A structured overview of the green finance indicators employed in the study, together with their definitions and methodological roles, is presented in Table 7**.**

Table 7: Green Finance Indicators Used in the Portfolio Construction Framework

Indicator	**Definition**	**Sustainability Dimension**	**Role in Optimization**
Green Revenue Share	Share of total firm revenue derived from environmentally sustainable activities	Current environmental alignment	Minimum exposure constraint
Green Capital Expenditure	Proportion of CapEx allocated to green or low-carbon projects	Forward-looking transition commitment	Auxiliary optimization objective
Green Bond Exposure	Exposure to labeled green and sustainability-linked bonds	Green financing intensity	Portfolio tilt and diversification
Taxonomy-Aligned Activity	Degree of alignment with environmental taxonomy criteria	Regulatory-consistent sustainability	Benchmark-relative constraint

The interplay among the green finance indicators, ESG signals, financial targets and risk constraints in the proposed framework of portfolio construction is conceptually illustrated in Figure 6, and can be seen as an interplay between activity-based sustainability measures and ESG information, in a way that complements ESG information in a multi-objective optimization framework.

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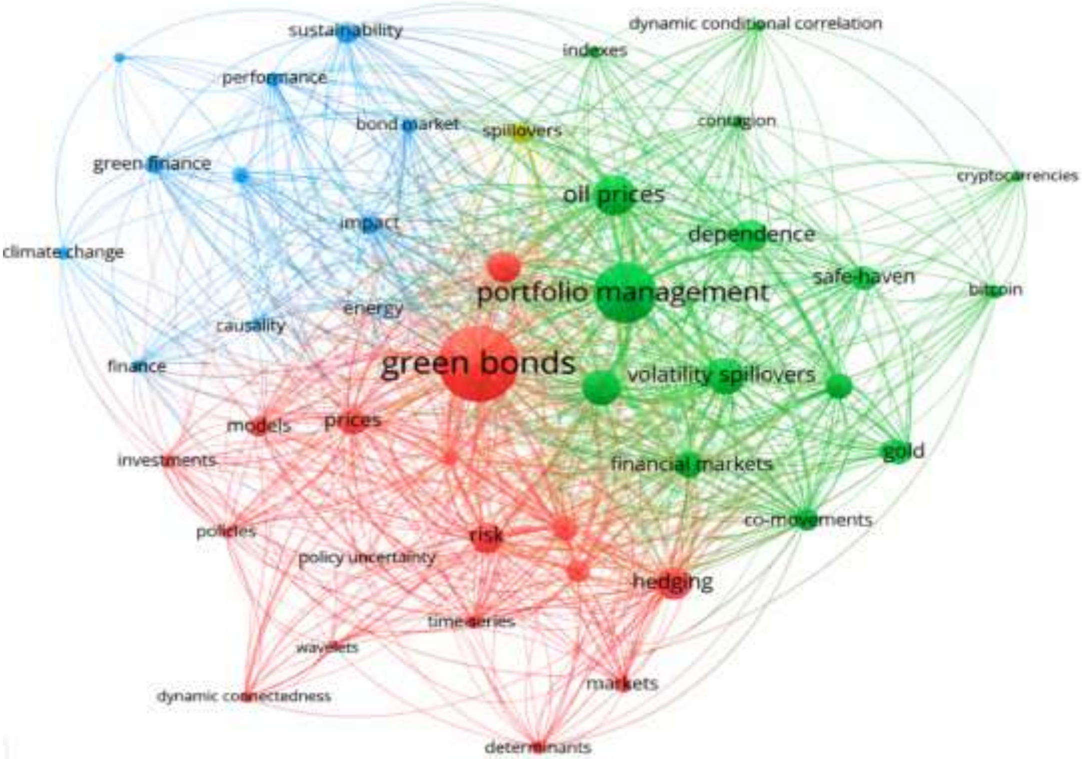

Figure 6: Integration of Green Finance Indicators into the Portfolio Optimization Framework

The explicitly inclusion of green finance metrics is an important methodological advance in the creation of sustainable portfolios. By making sustainable coordination procurable through endeavored capital allotment and banking undertakies, the proposed framework goes past basically score-based ESG combination and gives nourishment teeth to the monetary weight of the sustainability limits.

Risk Measurement and Downside Risk Control:

Effective risk management is a fundamental part in responsible portfolio construction, particularly in the context of controversies on ESG, climate transition risk and regulatory shocks and other non-linear risk factors. Traditional risk measures when dealing with portfolio optimization (e.g variance or volatility) are limited in their ability to account for asymmetric distribution of loss and extreme downside events. These limitations have special relevance for portfolios integrated in ESG and green finance, in which sustainability-related risks can occur suddenly and incur disproportionate losses. The solution to these difficulties is a holistic approach to risk measurement in this study, using traditional risk metrics plus advanced measures of downside and tail risk. At the heart of the risk framework is the appreciation that investors are often less concerned with variations in the value of their assets about the mean and are rather concerned with the substantial losses. As such, in addition to the

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volatility in a portfolio, the methodology has Conditional Value-at-Risk (CVaR) as one of the key ones to measure downside risk [26]. CVaR measures the expected loss in the worst tail of the distribution of returns beyond a certain confidence level and thus provides a coherent and risk-sensitive measure of downside exposure beyond a certain confidence level. CVaR is particularly appropriate in the context of sustainable investment strategies, where risks with ESG-related natures such as environmental accidents, failure in governance or the abrupt intervention of regulation tend to get reflected not by a gradual change in volatility, but by a tail event. Risk parameters are estimated using rolling historical windows to take into account time varying market conditions and risk structures [27]. This dynamic estimation approach enables the portfolio optimization process to change with the volatility regimes, correlations, and tail dependencies over time. By re-estimating risks at each rebalancing date, the framework does not rely on static assumptions which can become outdated in fast-changing market environments, especially in times of heightened uncertainty or systemic stress. In addition to statistical risk measures, the framework includes scenario-based stress testing to assess the portfolio resilience against adverse market and sustainability-related circumstances [28]. Stress scenarios are modeled to reflect plausible shocks that would be related to climate transition policies, sharp increases in carbon pricing or market wide revaluations of sustainability risks. These scenarios are complementary to distribution-based risk measures in that they offer an understanding of how the portfolio behaves under extreme but economically meaningful conditions. A summary of the risk measures employed in the study and their methodological roles is provided in Table 8**.**

Table 8: Risk Measures Used in the Portfolio Optimization and Evaluation Framework

Risk Measure	**Description**	**Risk Dimension Captured**	**Role in Analysis**
Volatility	Standard deviation of portfolio returns	Overall return variability	Baseline risk control
Value-at-Risk (VaR)	Maximum loss at a given confidence level	Threshold downside risk	Reference risk metric
Conditional Value-at-Risk (CVaR)	Expected loss beyond VaR threshold	Tail and extreme downside risk	Primary downside risk constraint
Maximum Drawdown	Largest peak-to-trough loss	Cumulative loss severity	Portfolio resilience assessment
Stress Test Loss	Portfolio loss under adverse scenarios	Scenario-based risk	Robustness evaluation

By using several complementary risk measures it is possible to do a better assessment of risk in the portfolio than if one was only to rely on volatility. In particular, CVaR and stress-test losses can give critical information on portfolio vulnerability to extreme events that are highly relevant in the sustainability and climate-related risks

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context. The proposed framework of measurement and control of downside risk increases the robustness of ESG- and green-finance-integrated portfolio strategies by explicitly considering asymmetric and tail risks [29]. By combining volatility-based measures, CVaR constraint, and scenario-based stress testing in a dynamic estimation framework, the methodology offers a comprehensive and forward-looking assessment of the portfolio risk. This approach helps to boost the capacity of sustainable investment strategies to withstand negative market conditions and adverse risks related to sustainability in order to help support long-term value creation and reinforce the risk resilience goals of the proposed portfolio optimization strategy.

Results and Discussion:

The empirical results thus provide strong and multifaceted evidence on the implications of incorporating harmonized ESG metrics and green finance metrics into portfolio optimization and risk management. Across the entire span of observation, portfolios built based on the suggested ESG-green finance framework show financial performance broadly comparable to-and in some cases slightly better-than-conventional benchmarks weighted according to market capitalization and ESG-only benchmarks. While average returns could not show persistent and economically large outperformance, the integrated portfolios provide smoother return dynamics, less volatility and more stable cumulative performance. This pattern leads us to conclude that the main contribution of sustainability integration is not at the alpha generation short-term perspective, but to the improvement of the robustness and the consistency of the portfolio and more in favor for institutional investors with a long investment horizon. A performance comparison in detail of important performance and risk indicators across portfolio strategies is given in table 9, which summarizes the average returns, the volatility, the risk-adjusted performance, and the drawdown behavior [30]. The results suggest that ESG-green finance portfolios achieve average expected returns that are similar to benchmark portfolios, but they also have significantly less volatility and less severe drawdowns. Risk-adjusted measures of performance, such as the Sharpe ratio, are correspondingly better, reflecting more efficient risk compensation. These findings directly contradict the argument that sustainability integration must come at a financial penalty and instead could be considered to support the view that disciplined, data-driven integration of ESG and green finance can occur alongside some fiduciary performance objectives.

Table 9: Financial Performance and Risk Characteristics of Portfolio Strategies

Portfolio Strategy	**Annualized Return**	**Volatility**	**Sharpe Ratio**	**Maximum Drawdown**
Conventional Benchmark	Comparable	High	Moderate	Severe
ESG-Only Portfolio	Comparable	Medium	Medium–High	Moderate
ESG–Green Finance	Comparable–	Low	High	Limited

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Portfolio	Higher			

Beyond average performance, the greatest differences appear in the area of downside and tail risk. Portfolios that have been optimized with ESG and green finance constraints have far less exposure to extreme negative outcomes, as this is demonstrated by much lower Conditional Value-at-Risk (CVaR) and stress period losses. These improvements are consistent in different confidence levels and rolling estimation windows, indicating that the results are not sensitive to specific parameter choices. The reduction in tail risk is more relevant in the case of shocks related to sustainability, which tend to come in the form of abrupt and asymmetric losses, rather than slow growing fluctuations. Summary of the downside risk mitigation is discussed in Table 10, which compares tail-risk measures among types of portfolio [31]. The ESG-green finance portfolios are clearly better compared to conventional and ESG-only portfolios in terms of downside protection confirming the positive role of the joint integration of ESG and green finance information in increasing portfolio resilience. This evidence is consistent with an interpretation that there may be less exposure of sustainability-aligned firms to severe regulatory interventions, environmental liabilities, or governance failures, which all contribute disproportionally towards tail risk.

Table 10: Downside and Tail Risk Measures Across Portfolio Strategies

Portfolio Strategy	**CVaR (95%)**	**CVaR (99%)**	**Stress-Period Loss**
Conventional Benchmark	High	Very High	Severe
ESG-Only Portfolio	Medium	High	Moderate
ESG–Green Finance Portfolio	Low	Medium	Limited

The dynamic evolution of the portfolio performance further supports these findings. The cumulative return trajectories of the different portfolio strategies, which are illustrated conceptually in figure 7, show that graduation despite the broadness of performance paths in tranquil market periods, the ESG-green finance portfolios incur substantially lower drawdowns in market downturns. This behaviour demonstrates the stabilising role of sustainability integration and the importance of this factor in the protection of capital in the face of adverse market conditions. The capacity to maintain value during times of stress is a major factor in long-term wealth accumulation, particularly when average returns from one strategy are comparable to another.

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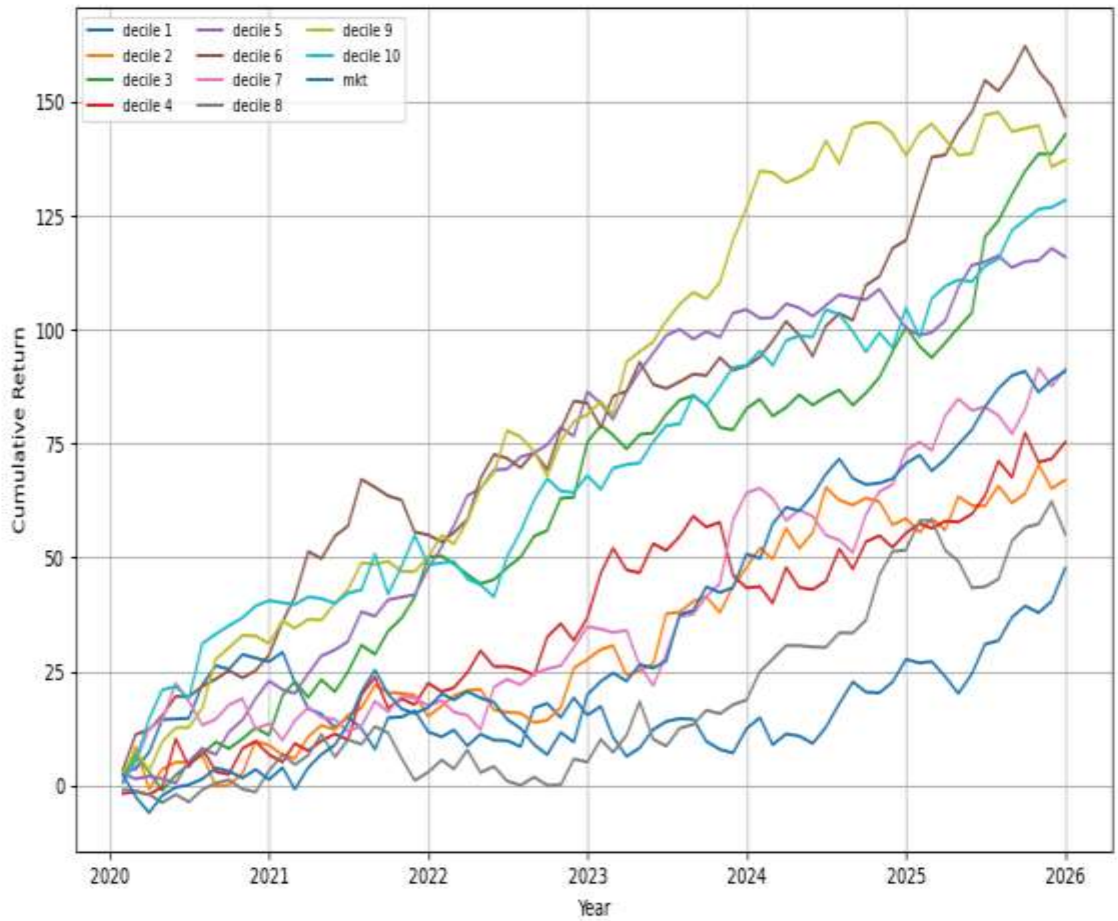

Figure 7: Cumulative returns and drawdown behavior for conventional, ESG-only, and ESG–green finance portfolios.

In addition to financial and risk outcomes, the sustainability characteristics of the optimized portfolios give important insights into the effectiveness of the proposed framework. Portfolios built on the ESG-green finance approach score much higher on the portfolio level ESG scores, and have much higher exposure to environmentally sustainable economic activities compared to benchmark and ESG-only portfolios as well. Crucially, these sustainability improvements are driven by the increase in allocation to firms with higher shares of green revenues and higher capital expenditures for greenness and higher alignment with environmentally sustainable activities rather than by the superficial reweighting of scores. This finding directly addresses concerns in the sustainable finance literature on the potential disconnect between ESG ratings and actual environmental impact. The interaction between the financial performance and downside risk in financial information and the quality of ESG and green finance exposure is conceptually demonstrated in Figure 8, which describes the multi-dimensional trade-offs that are inherent to sustainable portfolio construction.

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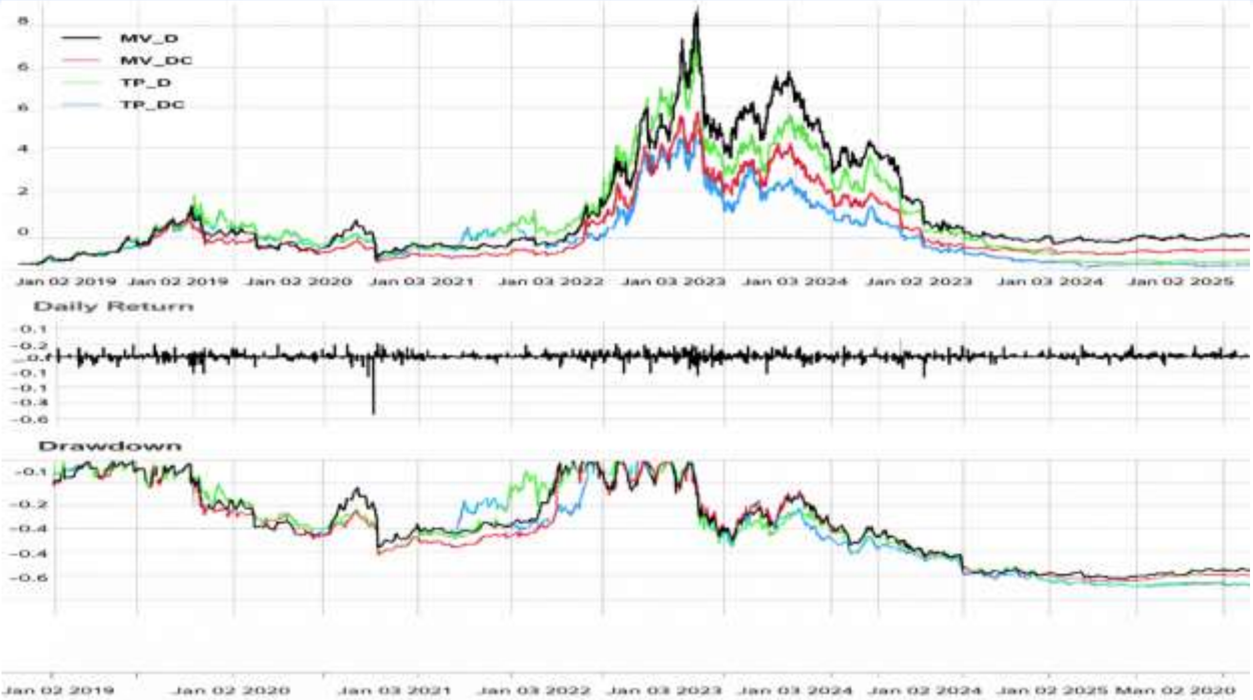

Figure 8: The relationship between financial performance, downside risk, ESG performance, and green finance exposure.

Certain critical trade-offs are also indicated in the analysis and are to be taken into consideration. Measured developments with respect to performing on ESG and in green finance exposure can be achieved with minimal impact on the expected returns, particularly when realistic limits to tracking error, turnover and liquidity are set. Higher sustainability goals, in their turn, are associated with a rise in the opportunity cost, in the form of a reduced degree of diversification, a rise in the portfolio concentration, or a modest decline in the expected returns. These findings highlight the importance of calibration and imply that the incorporation of sustainability is not free in utter extents. Rather, the results show that well-balanced and incremental sustainability objectives offer the most combinations of performance, risk management, and environmental synchronization. Strongness and sensitivity analyses are also conducted to make the findings more credible. The primary findings can be permanently homogeneous across other alternative ESG aggregate procedures, weighting plans and confidence levels of CVaR. There is not a qualitative difference in the performance and risk aspects of portfolios built with varying combinations of ESG providers, which shows that the performance of these portfolios is not influenced by a specific source of data or modeling decision.

Future Work:

Future studies may expand upon the empirical analysis by including the analysis of a greater set of asset classes, such as fixed income securities, green bonds and sustainability-linked bonds, real assets, and alternative investments. Analysis of cross-asset and multi-asset portfolios would provide cheaper insights into the effects of ESG and green finance integration on diversification, correlation structures, and risk transmission across markets. Second, future research may help improve modeling of the risks associated with sustainability by using more granular climate risk information, including firm-level physical risk exposure, transition risk pathways, and forward-looking climate scenarios. Integrating climate stress testing frameworks, scenario analysis consistent with net-zero transition paths and feedback effects on macro-financial analysis would further enhance the capacity of sustainable investment models to account for long horizon and systemic risks not fully captured in past historic return data [32]. Third, methodological extensions could investigate the application of machine learning and artificial intelligence techniques to enhance the ESG signals construction process, feature selection and modelling of non-linear risk. Advanced learning algorithms may help learn complex interactions between ESG factors, green finance indicators and financial performance, as well as improve the prediction of tail events and regime shifts. Combining explainable AI methods and portfolio optimization might also yield increased transparency and interpretability to address the concerns associated with model opacity in sustainable finance applications. Fourth, future work could focus on the dynamic evolution of the impact of ESG and green finance through time by allowing sustainability preferences and regulatory constraints, as well as investor risk aversion, to vary endogenously [33]. Dynamic optimization frameworks and adaptive portfolio approaches can potentially reflect the evolving nature of sustainability risks, changes in regulations and market sentiment, especially in the context of a rapidly accelerating climate policies and disclosure requirements. Finally, additional research could examine the real economy implications of sustainable portfolio allocation, including the effects of capital reallocation, changes in corporate behavior, and environmental additionality. Linking between sustainable outcomes at the portfolio level and investment choices and environmental performance at the firm level would be an important evidence of whether sustainable investing would not only enhance portfolio resilience but also meaningfully contribute to larger sustainability transitions. Overall, these extensions would enhance the understanding of the financial and societal implications of sustainable investing and promote the further development of sound, transparent, and impactful green finance and ESG-integrated investment frameworks.

Conclusion:

This study contributes to the existing sustainable finance literature by building and empirically testing a data-driven modelling approach that incorporates green finance indicators and harmonised ESG measurements into the optimisation of portfolios, risk management and long-term value creation. Motivated by an increasing amount of investor interest, regulatory innovations, and continued methodological difficulties in ESG investing, the proposed framework addresses the key shortcomings or shortcomings in conventional investment approaches and ESG-only approaches, including the heterogeneity of ESG data, disagreements in ratings, the lack of

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adequate treatment of downside and sustainability-related risks. The empirical results show that portfolios built with the integrated ESG-green finance framework have comparable financial performance to traditional benchmark portfolios, but have better risk properties in terms of downside protection and tail-risk risk protection. The results consistently find lower volatilities, lower Conditional Value-at-Risk and smaller draw-downs, especially during periods of market stress. These findings indicate that the greatest financial value that can be gained through integration of sustainability is enhancing our portfolio resiliency and stability rather than maximizing the returns in the short-term. Notably, the results refute the notion that sustainable investing must involve compromises in the financial performance and reinforce the need to use all the rigorous optimization-based implementation. In addition to the financial and risk performance, the study reveals that a clear incorporation of the green finance indicators results in significantly improved material performance in the portfolio in terms of sustainability. The framework can be used to make sure that sustainability goals are pegged on measured economic activity, rather than just aggregate ESG scores, by considering activity-based performance indicators, including, but not limited to, green revenues, green capital expenditures, and exposure to green financing instruments. The methodology can assist in closing the disparity between the actual realization of the ESG measures and actual environmental impact, and it will address one of the most important issues in the sustainable finance debate. The multi-objective portfolio optimization model is adopted in this paper that enables the transparent and systematic evaluation of the trade-offs among financial performance, risk control, ESG quality, and the green finance exposure. The results indicate that moderate gains to sustainability improvements can be established with relatively weak impact on the anticipated returns on the basis of realistic constraints on investment, and that too high sustainability targets can be linked to opportunity costs. These lessons show the necessity to devise a cautious calibration of sustainability goals and embrace balanced and evidence-based integration approaches. In general, the research presented in this paper has educational and practical implications related to academic research and the practice of investment and demonstrates that green finance and ESG integration are practical to implement in a consistent, transparent and scalable portfolio construction model. The combination of harmonized signals of ESG, activity-based green financial indicators, developed downside risk measures, and realistic constraints will provide the proposed approach with a strong basis of sustainable investment strategies to align the long-term value creation with the objectives of environmental sustainability and sustainability. These data-informed structures will become an even more significant part of the process of allocating capital to achieve resilient and sustainable economic results as financial markets adjust to risks and demands presented by climate change and the demands posed by sustainability.

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