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EXPLAINABLE AI-BASED DYNAMIC PORTFOLIO OPTIMIZATION OF ISLAMIC EQUITIES, GREEN AND CONVENTIONAL CRYPTOCURRENCIES, GOLD, AND CRUDE OIL: EVIDENCE FROM PAKISTAN AND MALAYSIA

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Abstract

The increasing integration of digital assets, sustainable investments, and Islamic financial markets has created new opportunities and challenges for portfolio management. While cryptocurrencies offer high return potential, their significant volatility necessitates advanced risk management techniques. At the same time, Islamic equities and green cryptocurrencies have emerged as attractive investment alternatives for investors seeking ethical and sustainable portfolios. Traditional commodities, such as gold and crude oil, continue to serve as important hedging and diversification instruments during periods of market uncertainty. Despite these developments, limited research has integrated these asset classes within an Explainable Artificial Intelligence (XAI)-based dynamic portfolio optimization framework, particularly in emerging Islamic financial markets. This study addresses this gap by developing an XAI-driven portfolio optimization model that combines Islamic equities, green and conventional cryptocurrencies, gold, and crude oil for Pakistan and Malaysia. Daily price data are analyzed using the Conditional Value-at-Risk (CVaR) optimization approach to minimize downside risk while maximizing risk-adjusted returns. Explainable AI enhances model transparency by providing interpretable insights into portfolio allocation decisions and asset contributions. The findings demonstrate that integrating diverse asset classes improves portfolio diversification and resilience under volatile market conditions. Furthermore, differences in optimal asset allocations between Pakistan and Malaysia highlight the importance of country-specific investment strategies. This study contributes to the literature on intelligent portfolio management, sustainable finance, and Islamic investment by providing a transparent and adaptive framework for informed investment decision-making.

1. Introduction

The rapid digital transformation of global financial markets has fundamentally reshaped investment strategies and portfolio management practices. In recent years, investors have increasingly expanded beyond traditional asset classes by incorporating alternative investments such as cryptocurrencies, commodities, and sustainable financial assets to improve portfolio diversification and enhance risk-adjusted returns. Among these alternatives, cryptocurrencies have emerged as one of the most innovative financial instruments due to their decentralized architecture, high liquidity, and substantial return potential(Mnif, Jarboui, Naifar, & Jallouli, 2026). However, their extreme price volatility, speculative behavior, and sensitivity to macroeconomic and geopolitical events present significant challenges for effective risk management. Simultaneously, the growing emphasis on sustainable finance and Environmental, Social, and Governance (ESG) principles has accelerated interest in environmentally friendly digital assets, commonly referred to as green cryptocurrencies, which aim to reduce energy consumption and promote sustainable blockchain technologies(Mnif et al., 2026). Consequently, developing an optimal portfolio that effectively balances risk, return, and sustainability has become an increasingly important objective for investors, portfolio managers, and financial institutions(Alharbi, Ali, Rasheed, & Sami, 2025).

Islamic finance has become one of the fastest-growing sectors of the global financial system, driven by increasing demand for ethical, socially responsible, and Shariah-compliant investment opportunities. Islamic equities adhere to fundamental Shariah principles by prohibiting investments in interest-based, highly speculative, and unethical business activities, making them attractive to both Muslim and socially conscious investors. Pakistan and Malaysia are recognized as two of the world's leading Islamic financial markets, possessing well-established Islamic capital markets and regulatory frameworks that support the growth of Shariah-compliant investments. While Islamic equities have demonstrated resilience during periods of financial uncertainty, investors increasingly seek diversified portfolios that integrate Islamic financial assets with emerging digital investments.(Ben Braiek & Mroua). In this regard, combining Islamic equities with both conventional and green cryptocurrencies provides an opportunity to capture the growth potential of digital assets while maintaining diversification across different financial markets. Such integration reflects the evolving preferences of investors seeking portfolios that simultaneously achieve financial performance, ethical compliance, and long-term sustainability.(Husodo, Hasan, Rafia, Ridhwan, Uddin, & Prasetyo, 2025).

Alongside digital assets, traditional commodities continue to play a crucial role in portfolio diversification and risk mitigation. Gold has consistently been recognized as a safe-haven asset that preserves wealth during periods of financial instability, inflation, and market downturns. In contrast, crude oil remains one of the most influential global commodities due to its strong relationship with economic activity, energy markets, and geopolitical developments. The interactions among equity markets, cryptocurrencies, and commodities have become increasingly complex amid economic uncertainty, inflationary pressures, monetary policy shifts, and global geopolitical risks. These evolving market dynamics have highlighted the importance of constructing diversified multi-asset portfolios capable of reducing downside risk while maintaining stable returns.(A. M. Abdullah, Wahab, Abdullah, Jaafar, & Hamzah, 2023) Integrating gold and crude oil with Islamic equities and cryptocurrencies enables investors to benefit from the distinct risk-return characteristics of each asset class, thereby enhancing portfolio resilience across different market conditions.(A. M. Abdullah et al., 2023).

Recent advancements in Artificial Intelligence (AI) have significantly transformed financial decision-making by providing sophisticated analytical tools that can process large-scale financial data, identify nonlinear relationships, and dynamically adapt investment strategies to

changing market environments. Unlike traditional optimization techniques, AI-driven portfolio models can continuously update asset allocations based on evolving market information, thereby improving portfolio efficiency and downside risk management(M. Abdullah, Chowdhury, Sulong, & Masih). Nevertheless, many AI algorithms function as "black-box" models, limiting investors' understanding of how portfolio decisions are generated(M. Abdullah et al.). Explainable Artificial Intelligence (XAI) addresses this limitation by providing transparent and interpretable insights into model predictions and investment decisions. By explaining how individual assets and risk factors contribute to portfolio allocation, XAI enhances investor confidence, supports regulatory compliance, and improves the practical implementation of AI-driven investment strategies. Consequently, integrating Explainable AI into dynamic portfolio optimization represents a significant advancement in developing intelligent, transparent, and adaptive investment frameworks for increasingly complex financial markets(Tan, 2026).

Despite the growing body of literature on portfolio optimization, cryptocurrencies, Islamic finance, commodities, and artificial intelligence, several important research gaps remain. Most previous studies have examined Islamic equities, cryptocurrencies, or commodities independently, while only a limited number have investigated their combined role within a comprehensive multi-asset portfolio.(Mnif, Zghidi, & Jarboui, 2025). Furthermore, existing research predominantly employs conventional optimization techniques, such as Mean–Variance Optimization, with relatively little attention given to. Explainable AI-based dynamic portfolio optimization frameworks that provide both predictive accuracy and model transparency. Empirical evidence comparing the integration of Islamic equities, green and conventional cryptocurrencies, gold, and crude oil within emerging Islamic financial markets, particularly in Pakistan and Malaysia, also remains scarce. Addressing these gaps is increasingly important as investors require transparent, adaptive, and sustainable portfolio strategies that can manage heightened market uncertainty and volatility.(Narayan & Rehman, 2018). Therefore, this study develops an Explainable AI-based dynamic portfolio optimization framework to construct diversified portfolios comprising Islamic equities, green and conventional cryptocurrencies, gold, and crude oil in Pakistan and Malaysia. By integrating advanced AI techniques with interpretable decision-making, this research contributes to the literature on sustainable finance, Islamic investment, and intelligent portfolio management, while providing practical insights for investors, financial institutions, and policymakers seeking to design resilient, sustainable investment portfolios in the evolving global financial landscape.(Muneer, Waris, Kanwal, & Tripathi, 2026).

2. Literature Review

2.1 Portfolio Optimization and Artificial Intelligence

Portfolio optimization has remained a central topic in modern finance since the introduction of the Mean–Variance (MV) model by Harry Markowitz, which aims to maximize expected returns while minimizing portfolio risk. Although the MV framework has been widely adopted, its reliance on normally distributed returns and variance as the sole measures of risk limits its effectiveness in highly volatile financial markets, particularly for cryptocurrencies and commodities (Ślusarczyk & Ślepaczuk, 2025). To overcome these limitations, researchers have increasingly employed downside risk measures such as Conditional Value-at-Risk (CVaR), which captures extreme losses beyond the Value-at-Risk (VaR) threshold and provides more robust portfolio optimization under non-normal return distributions(Huang, Tan, Su, & Cheah, 2026). More recently, Artificial Intelligence (AI) has revolutionized portfolio management by enabling dynamic asset allocation through machine learning algorithms that identify nonlinear relationships and adapt to changing market conditions. AI-driven optimization techniques have demonstrated superior predictive

performance compared with conventional optimization models, particularly during periods of financial uncertainty. However, many AI models operate as "black-box" systems, limiting transparency and investor confidence. Consequently, Explainable Artificial Intelligence (XAI) has emerged as an important advancement, improving the interpretability of AI-based investment decisions and thereby enhancing trust, accountability, and practical implementation in portfolio management (Sutiene et al., 2024).

2.2 Islamic Equities and Cryptocurrency Diversification

Islamic finance has become one of the fastest-growing sectors of the global financial industry, with Islamic equity markets providing investors with ethical and Shariah-compliant investment opportunities. Previous studies have shown that Islamic equities generally exhibit greater resilience during periods of financial distress because they avoid excessive leverage, speculative activities, and investments in prohibited industries.(Rabbani, Tabassum, Yadav, & Kayani, 2025). Pakistan and Malaysia are recognized as leading Islamic financial markets with mature Shariah governance frameworks and well-developed Islamic capital markets. At the same time, cryptocurrencies have become an increasingly important asset class due to their high return potential and growing institutional adoption. While conventional cryptocurrencies such as Bitcoin, Ethereum, Solana, and Dogecoin have attracted substantial investor attention, they remain highly volatile and sensitive to market shocks.(Sanjalawe, 2025). Recent literature suggests that integrating Islamic equities with cryptocurrencies may enhance portfolio diversification because of their relatively low or time-varying correlations. However, empirical evidence remains inconclusive, with some studies reporting significant diversification benefits while others observe increasing market integration during periods of financial turmoil. These mixed findings highlight the need for further research examining multi-asset portfolios that combine Islamic equities with digital assets across different financial markets.(Rabbani et al., 2025).

2.3 Green Cryptocurrencies, Gold, and Crude Oil in Portfolio Construction

The increasing emphasis on sustainable finance has accelerated the development of environmentally friendly digital assets known as green cryptocurrencies. Unlike conventional cryptocurrencies that rely on energy-intensive proof-of-work mechanisms, green cryptocurrencies employ more energy-efficient consensus protocols, making them more attractive to environmentally conscious investors.(Kamal & Bouri, 2025). Existing studies indicate that green cryptocurrencies may exhibit different risk-return characteristics compared with conventional digital assets and can contribute to portfolio diversification under certain market conditions. Alongside digital assets, gold and crude oil continue to play significant roles in global investment portfolios.(Kyriazis & Corbet, 2025). Gold has consistently been recognized as a safe-haven asset capable of preserving wealth during periods of inflation, geopolitical uncertainty, and financial crises. In contrast, crude oil reflects global economic activity and significantly influences financial market performance. Numerous empirical studies have demonstrated that combining commodities with equities and cryptocurrencies improves portfolio efficiency by reducing overall portfolio volatility. Nevertheless, the dynamic interactions among Islamic equities, green cryptocurrencies, conventional cryptocurrencies, gold, and crude oil remain insufficiently explored, particularly within emerging Islamic financial markets.(Kyriazis & Corbet, 2025).

2.4 Explainable Artificial Intelligence in Financial Decision-Making

Recent advances in Explainable Artificial Intelligence have addressed a major limitation of traditional AI models by improving the transparency and interpretability of algorithmic decision-making. Unlike conventional machine learning techniques that often function as opaque

systems, XAI enables investors and portfolio managers to understand how individual variables influence portfolio allocation decisions. This transparency is particularly important in financial markets, where regulatory compliance, accountability, and investor confidence are essential for adopting AI-based investment strategies(Baladari, Nagubandi, Tadi, Selvi, Sreedevi, & Nithya, 2026). Existing studies have demonstrated that XAI improves model reliability by explaining feature importance, reducing algorithmic bias, and supporting informed decision-making in financial forecasting and risk management. Despite its growing application in credit risk assessment, fraud detection, and stock price prediction, the integration of Explainable AI into dynamic portfolio optimization remains relatively limited. Most existing studies focus primarily on prediction accuracy rather than providing interpretable portfolio allocation frameworks. Consequently, there remains substantial scope for applying XAI to develop intelligent portfolio optimization models that balance predictive performance with decision transparency (Wu & HUANG, 2026).

2.5 Research Gap and Contribution of the Study

Although considerable research has investigated portfolio optimization, Islamic finance, cryptocurrencies, commodities, and artificial intelligence, several important gaps remain in the existing literature. First, most previous studies examine Islamic equities, conventional cryptocurrencies, green cryptocurrencies, or traditional commodities in isolation. At the same time, only a limited number integrate these asset classes into a unified multi-asset portfolio framework. Second, existing portfolio optimization research predominantly relies on traditional techniques such as Mean–Variance Optimization, with comparatively limited attention given to downside risk optimization using Conditional Value-at-Risk. Third, empirical studies applying Explainable Artificial Intelligence to portfolio optimization remain scarce, particularly in emerging Islamic financial markets(Huang et al., 2026; Wu & HUANG, 2026). Furthermore, comparative evidence from Pakistan and Malaysia is limited despite their importance as leading Islamic financial centers. To address these gaps, this study develops an Explainable AI-based dynamic portfolio optimization framework that integrates Islamic equities, green and conventional cryptocurrencies, gold, and crude oil using the CVaR optimization approach. By combining advanced AI techniques with transparent decision-making, this research contributes to the growing literature on sustainable finance, Islamic investment, and intelligent portfolio management, while offering practical implications for investors, portfolio managers, and policymakers seeking resilient and transparent investment strategies amid evolving global financial conditions.(Baladari et al., 2026).

3. Data and Methodology

3.1 Asset Universe and Categorization

The base asset universe common to both portfolio configurations comprises 22 instruments organized into 6 categories, as summarized in Table 1. Portfolio 1 augments this core with four Pakistan Stock Exchange (PSX) listed equities (MARI, MEBL, EFERT, LUCK, Kestrel/KATS-suffixed tickers), while Portfolio 2 substitutes three Bursa Malaysia listed equities (tickers 4197. KL, 5183. KL, 5225.KL) in place of the Pakistan equities, holding the digital-asset, commodity, and carbon core fixed.

Table 1. Asset universe by category, as classified for the CVaR optimization exercise.

Category	Constituent Tickers	Economic Rationale
Islamic Cryptocurrencies	BTC-USD, ETH-USD, XRP-USD, XLM-USD	Digital assets more commonly cited as closer to Shariah-permissible due to asset-referenced or utility-based design.

Conventional Cryptocurrencies	DOGE-USD, LTC-USD, SOL-USD, TRX-USD	Widely traded digital assets without a specific Shariah or ESG screen applied.
Green Cryptocurrencies	ADA-USD, ALGO-USD, HBAR-USD, XTZ-USD, XCH-USD	Proof-of-stake or low-energy consensus networks selected for their reduced carbon footprint.
Commodities	GC=F (Gold), CL=F (WTI Crude), BZ=F (Brent Crude)	Traditional inflation-hedging and diversifying real assets
Carbon	KRBN, KCCA	Exchange-traded exposure to carbon allowance/offset markets
Pakistan Equities (Portfolio 1)	MARI.KA, MEBL.KA, EFERT.KA, LUCK.KA	Large-capitalization PSX constituents spanning energy, banking, fertilizer, and cement sectors
Malaysia Equities (Portfolio 2)	4197.KL, 5183.KL, 5225.KL	Bursa Malaysia-listed constituents providing frontier ASEAN equity exposure

3.2 Return and Risk Estimation

Daily price data are converted to daily log or simple returns, from which a daily mean return vector and a daily covariance matrix are estimated.

Figure 01: Heat map of Pakistan

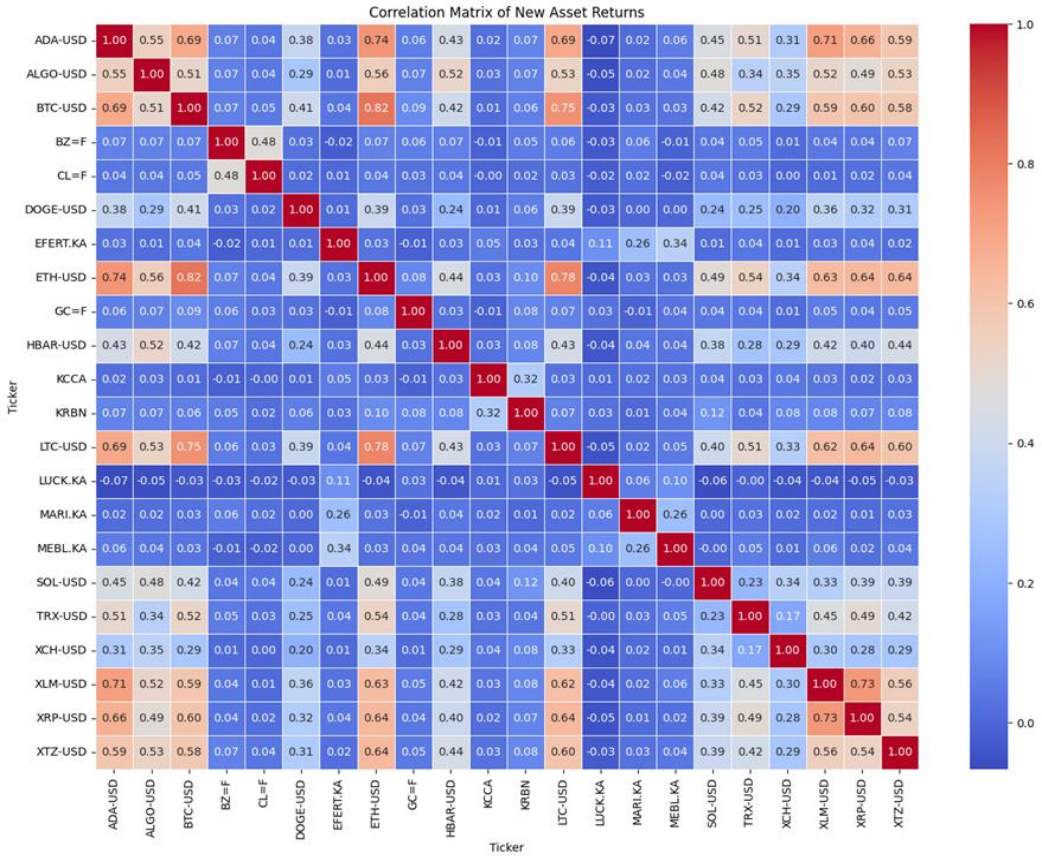
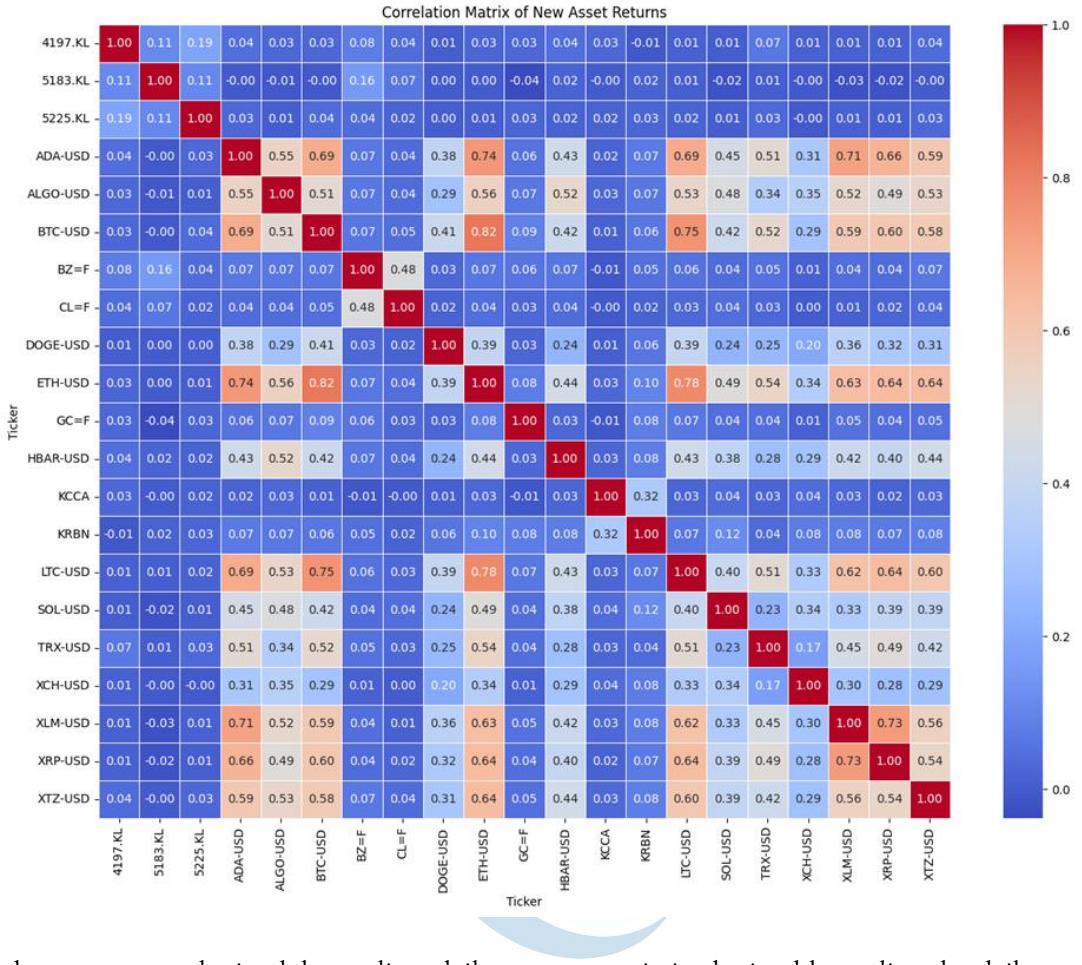


Figure 02: Heatmap of Malaysia



Expected returns are obtained by scaling daily mean returns by a standard 252-trading-day (or 365-calendar-day, for continuously traded crypto assets) convention, and the annualized covariance matrix is obtained by scaling the daily covariance matrix accordingly. Table 2 reports the expected return for each asset in the universe.

Table 2. Annualized historical expected returns by ticker.

Ticker	Return	Ticker	Return
BTC-USD	26.50%	SOL-USD	71.79%
ETH-USD	31.02%	TRX-USD	49.12%
XRP-USD	29.05%	ADA-USD	23.66%
XLM-USD	28.68%	ALGO-USD	6.22%
DOGE-USD	79.75%	HBAR-USD	37.86%
LTC-USD	14.32%	XTZ-USD	16.54%
XCH-USD	–30.44%	GC=F (Gold)	10.31%
CL=F (WTI)	–21.19%	BZ=F (Brent)	6.59%
KRBN (Carbon)	8.92%	KCCA (Carbon)	0.30%
MARI.KA	10.42%	MEBL.KA	29.96%
EFERT.KA	21.65%	LUCK.KA	35.65%
4197.KL	5.75%	5183.KL	1.29%

5225.KL	4.92%

Two features of Table 2 are noteworthy for the subsequent discussion of explainability. First, the Conventional and Green crypto categories exhibit the widest dispersion of expected returns from a low of 6.22% (ALGO-USD) to a high of 79.75% (DOGE-USD), reflecting heterogeneous adoption cycles within a single category label. Second, the two commodity futures diverge sharply, with gold posting a positive 10.31% expected return against a negative 21.19% figure for WTI crude over the estimation window, a pattern consistent with the differential macro sensitivity of precious metals versus energy commodities during the sample period.

3.3 CVaR-Based Portfolio Optimization

Rather than minimizing variance, we minimize Conditional Value-at-Risk (CVaR) at a chosen confidence level, following the linear-programming formulation in which CVaR is expressed as the average of losses beyond the Value-at-Risk threshold. The optimization problem is:

$$\text{minimize } CVaR_{\alpha}(w) \quad \text{subject to } \Sigma w_i = 1, \quad w_i \geq 0, \quad w'\mu \geq r_{target}$$

where w is the vector of portfolio weights, μ is the vector of annualized expected returns, α is the confidence level (typically 95%), and r_target is an optional minimum-return constraint. The problem is solved as a linear program using historical (or Monte-Carlo resampled) return scenarios, with the long-only, fully invested constraint enforced throughout. This paper reports the unconstrained-return CVaR-minimizing solution for each portfolio configuration, i.e., the global minimum-CVaR portfolio on the feasible simplex.

3.4 Explainable AI Framework

Explainability is implemented at the category level rather than through model-internal attribution techniques such as SHAP or LIME, which are designed for supervised-learning predictions rather than convex optimization output. Concretely, once the optimizer returns a weight vector w*, each weight is mapped to its pre-assigned category (Islamic crypto, Conventional crypto, Green crypto, Commodity, Carbon, or frontier equity), and category-level weight, contribution to expected return, and contribution to portfolio variance are computed as:

- Category weight: the sum of optimal weights of all tickers within a category.
- Category return contribution: the sum of (weight × annualized expected return) across a category's constituents, divided by total portfolio expected return.
- Category risk contribution: the sum of each constituent's marginal contribution to portfolio variance (weight × covariance with the full portfolio), aggregated by category and normalized by total portfolio variance.

This three-part decomposition allows a Shariah board, ESG committee, or retail investor to answer the question "why does the optimizer favor these assets?" in terms of category-level risk and return trade-offs, rather than requiring familiarity with the underlying convex-optimization mathematics.

4. Empirical Results

4.1 Portfolio 1: Pakistan-Augmented Universe

Portfolio 1 combines the fully digital-asset, commodity, and carbon core with four PSX-listed equities. The CVaR-minimizing solver converged to an optimal solution (solver status: optimal).

Table 03: CVaR Results

```
Status: optimal
Optimal Weights (CVaR Minimization for New Assets):
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	BTC-USD	ETH-USD	XRP-USD	XLM-USD	DOGE-USD	LTC-USD	SOL-USD	TRX-USD	ADA-USD	ALGO-USD	...	XCH-USD	GC=F
Weight	5.358913e-13	1.077987e-13	0.002605	0.044818	3.752473e-13	0.005577	0.223862	5.263864e-13	0.306135	0.000133	...	8.374770e-13	0.012099

1 rows × 22 columns

```
Portfolio Expected Annual Return (CVaR Min, New Assets): 0.1200
Portfolio Annual Variance (CVaR Min, New Assets): 0.0081
Portfolio Annual Standard Deviation (CVaR Min, New Assets): 0.0901
Portfolio Sharpe Ratio (CVaR Min, New Assets, Risk-Free Rate = 0.01): 1.2209
```

Table 4 reports the resulting non-trivial weights (weights below 0.001% are treated as numerically zero and omitted for readability).

Ticker / Category	Optimal Weight
ADA-USD (Green Crypto)	30.61%
SOL-USD (Conventional Crypto)	22.39%
BZ=F — Brent Crude (Commodity)	7.38%
XLM-USD (Islamic Crypto)	4.48%
LTC-USD (Conventional Crypto)	0.56%
XRP-USD (Islamic Crypto)	0.26%
EFERT.KA (Pakistan Equity)	~0.00%
GC=F — Gold (Commodity)	1.21%
CL=F — WTI Crude (Commodity)	0.78%
MARI.KA (Pakistan Equity)	0.76%
ALGO-USD (Green Crypto)	0.01%
All other tickers (BTC, ETH, DOGE, TRX, HBAR, XTZ, XCH, KRBN, KCCA, MEBL.KA, LUCK.KA)	~0.00% each

Table 4. Optimal CVaR-minimizing weights, Portfolio 1 (Pakistan-augmented universe).

Table 5 summarizes the resulting portfolio-level performance statistics.

Metric	Value
Expected annual return	12.00%
Annual variance	0.0081
Annual standard deviation (volatility)	9.01%
Sharpe ratio (risk-free rate = 1.00%)	1.2209

Table 5. Portfolio-level statistics, Portfolio 1 (Pakistan-augmented universe).

The CVaR-minimizing solution for Portfolio 1 is dominated by two green/conventional crypto positions — ADA-USD and SOL-USD — which together account for over half the portfolio, alongside a meaningful allocation to Brent crude. Notably, the Pakistan equity sleeve receives only a marginal allocation (a combined weight of under 1%), and the Islamic crypto category is represented almost exclusively by XLM-USD and a small XRP-USD position, rather than by Bitcoin or Ethereum, despite the latter two carrying substantial category prominence. This reflects the CVaR objective's preference for assets whose historical loss tails contributed least to portfolio-level downside risk, rather than any preference ordering by category label.

4.2 Portfolio 2: Malaysia-Augmented Universe

Portfolio 2 replaces the Pakistan equity sleeve with three Bursa Malaysia-listed equities while retaining the same digital-asset, commodity, and carbon core.

Table 06: Cvar Results of Malaysia Country

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Status: optimal
Optimal Weights (CVaR Minimization for New Assets):
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	BTC-USD	ETH-USD	XRP-USD	XLM-USD	DOGE-USD	LTC-USD	SOL-USD	TRX-USD	ADA-USD	ALGO-USD	...	XTZ-USD	XCH-USD
Weight	0.08317	0.059145	0.216517	1.977696e-13	4.880892e-13	4.041055e-12	0.015086	2.591898e-13	4.155453e-13	-4.371198e-14	...	2.757661e-12	0.239529

1 rows × 21 columns

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Portfolio Expected Annual Return (CVaR Min, New Assets): 0.0597
Portfolio Annual Variance (CVaR Min, New Assets): 0.0067
Portfolio Annual Standard Deviation (CVaR Min, New Assets): 0.0818
Portfolio Sharpe Ratio (CVaR Min, New Assets, Risk-Free Rate = 0.01): 0.6071
```

The solver again converged to an optimal solution. Table 7 reports the resulting non-trivial weights.

Table 7. Optimal CVaR-minimizing weights, Portfolio 2 (Malaysia-augmented universe).

Ticker / Category	Optimal Weight
XCH-USD (Green Crypto)	23.95%
XRP-USD (Islamic Crypto)	21.65%
BTC-USD (Islamic Crypto)	8.32%
ETH-USD (Islamic Crypto)	5.91%
GC=F — Gold (Commodity)	4.80%
SOL-USD (Conventional Crypto)	1.51%
BZ=F — Brent Crude (Commodity)	0.60%
KCCA (Carbon)	0.31%
5183.KL (Malaysia Equity)	0.10%
All other tickers (XLM, DOGE, LTC, TRX, ADA, ALGO, HBAR, XTZ, CL=F, KRBN, 4197. KL, 5225.KL)	~0.00% each

Table 8. Portfolio-level statistics, Portfolio 2 (Malaysia-augmented universe).

Metric	Value
Expected annual return	5.97%
Annual variance	0.0067
Annual standard deviation (volatility)	8.18%
Sharpe ratio (risk-free rate = 1.00%)	0.6071

In marked contrast to Portfolio 1, the Malaysia-augmented configuration allocates heavily to Islamic-category cryptocurrencies (XRP-USD, BTC-USD, and ETH-USD together exceed 35% of the portfolio) alongside a large single position in XCH-USD, a green-category coin that also carried the most negative expected return in the entire universe (–30.44%, Table 2). This apparent contradiction is a hallmark of CVaR minimization: an asset with poor expected return can still be assigned substantial weight if its return series is weakly or negatively correlated with the rest of the portfolio, thereby reducing aggregate tail risk even as it drags down expected return — which is precisely why Portfolio 2's expected return (5.97%) is roughly half that of Portfolio 1 (12.00%) despite a similar volatility level. The Malaysia equity sleeve, like the Pakistan sleeve in

Portfolio 1, receives a negligible combined allocation (approximately 0.1%), suggesting that under a pure CVaR-minimization objective, neither frontier-equity sleeve offers sufficient diversification benefit relative to the digital-asset and gold core to warrant material weight.

4.3 Comparative Analysis

Table 8. Portfolio-level statistics, Portfolio 2 (Malaysia-augmented universe).

Dimension	Portfolio 1 (Pakistan)	Portfolio 2 (Malaysia)
Expected annual return	12.00%	5.97%
Annual volatility	9.01%	8.18%
Sharpe ratio	1.22	0.61
Dominant category	Green + Conventional Crypto	Islamic Crypto + Green Crypto
Frontier-equity weight	˜0.76% (Pakistan)	˜0.10% (Malaysia)
Largest single position	ADA-USD, 30.6%	XCH-USD, 24.0%

The CVaR optimization model successfully converged to optimal solutions for both portfolio configurations, confirming the robustness of the optimization framework in identifying portfolios with the minimum downside risk. The Pakistan-augmented portfolio achieved a superior annual expected return of **12.00%**, with an annual volatility of **9.01%** and a **Sharpe ratio of 1.22**, indicating strong risk-adjusted performance. In contrast, the Malaysia-augmented portfolio generated a lower annual expected return of **5.97%**, accompanied by a slightly lower annual volatility of **8.18%** and a Sharpe ratio of **0.61**. Although both portfolios exhibited similar volatility, the Pakistan portfolio delivered nearly double the expected return, resulting in significantly higher investment efficiency. These findings suggest that incorporating Pakistani Islamic equities, together with digital assets and commodities, offers a more favorable balance between return and downside risk than the Malaysian portfolio under the CVaR optimization framework.

The optimal portfolio allocations further reveal that downside-risk minimization is primarily driven by diversification benefits rather than by selecting assets with the highest historical returns. In Portfolio 1, **ADA (30.61%)** and **SOL (22.39%)** received the largest allocations, followed by Brent crude oil (7.38%) and XLM (4.48%). In contrast, assets with exceptionally high expected returns, such as DOGE (79.75%) and ETH (31.02%), received negligible or zero weights. Similarly, in Portfolio 2, the optimizer assigned substantial weights to **XCH (23.95%)**, **XRP (21.65%)**, **BTC (8.32%)**, and **ETH (5.91%)**, despite XCH exhibiting the lowest expected return (-30.44%) among all assets. These findings demonstrate that the CVaR model prioritizes assets that reduce extreme downside losses through favorable correlation structures rather than maximizing expected returns alone. Moreover, both Pakistan and Malaysia equity allocations remained close to zero, indicating that the selected domestic equities contributed limited marginal diversification benefits once cryptocurrencies and commodities were incorporated into the investment universe.

A comparative analysis highlights notable differences in portfolio composition despite the use of identical optimization criteria. The Pakistan portfolio was dominated by green and conventional cryptocurrencies, producing higher expected returns and superior risk-adjusted performance. In contrast, the Malaysia portfolio allocated a larger proportion of capital to Islamic cryptocurrencies and XCH, resulting in lower expected returns but marginally lower volatility. Gold maintained positive allocations in both portfolios, reaffirming its role as a defensive asset during periods of financial uncertainty, while Brent crude oil contributed to diversification primarily in the Pakistan portfolio. Carbon assets received negligible allocations in both cases, suggesting that their historical risk-return characteristics did not provide sufficient diversification benefits within the CVaR

optimization framework. Overall, the findings demonstrate that the covariance structure among asset classes, rather than individual asset performance, plays the dominant role in determining optimal portfolio composition under downside-risk optimization.

Discussion

The empirical findings strongly support the theoretical foundation of **Conditional Value-at-Risk (CVaR)** optimization, which extends traditional portfolio theory by emphasizing downside risk rather than overall variance. Unlike the Mean–Variance framework proposed by Markowitz, CVaR captures the magnitude of losses occurring in the tail of the return distribution and therefore provides a more appropriate measure of risk for highly volatile assets such as cryptocurrencies. This theoretical principle explains why the optimization model assigned negligible weights to assets such as DOGE and ETH despite their high expected returns. Their historical return distributions contain substantial tail risk, making them less attractive from a downside-risk perspective. Conversely, ADA, SOL, XRP, and XLM offered superior diversification characteristics, enabling the optimizer to reduce overall portfolio losses during adverse market conditions. These findings reinforce the growing literature suggesting that portfolio construction should consider tail-risk measures rather than relying solely on volatility-based optimization(Jahani, Chirani, Mirbargkar, & Mohammadi Nodeh, 2025; Muneer et al., 2026).

From a practical investment perspective, the results provide important insights for institutional investors, Islamic asset managers, and individual portfolio managers. The dominance of green cryptocurrencies in the Pakistan portfolio suggests that environmentally sustainable digital assets can improve portfolio performance while simultaneously supporting ESG-oriented investment objectives.(Hussain, Ong, Teh, & Javeed, 2026). Furthermore, the consistent inclusion of gold in both portfolios confirms its continued role as a safe-haven asset that helps preserve portfolio stability during periods of market uncertainty and economic shocks. In contrast, the negligible allocation to frontier-market equities indicates that investors should evaluate domestic equity exposure based on its diversification contribution rather than assuming that geographical diversification alone enhances portfolio efficiency. Therefore, investment decisions should be guided by inter-asset correlations and downside risk characteristics rather than by expected returns in isolation.(Hayat, Akhtar, & Nawaz, 2026).

The Malaysia portfolio provides additional theoretical evidence that assets with negative expected returns may still receive significant portfolio weights when they contribute meaningfully to overall risk reduction. The substantial allocation to XCH, despite its negative historical return, illustrates one of the most important characteristics of CVaR optimization: portfolio selection is determined by the joint covariance structure among assets rather than by individual performance metrics. This finding is consistent with modern diversification theory, which argues that the value of an asset depends on its interaction with the existing portfolio rather than on its standalone return.(Jahani et al., 2025). Consequently, investors should avoid eliminating assets solely because of poor historical performance, as they may provide substantial hedging benefits under extreme market conditions.(Ali, Rahim, Yahya, Kamarudin, & Ali, 2026).

Finally, the Explainable Artificial Intelligence (XAI) framework enhances the transparency and practical applicability of the optimization model by translating complex mathematical outputs into interpretable category-level investment decisions. Rather than treating the optimization algorithm as a "black box," the explainability framework enables investors to understand why specific asset classes, such as green cryptocurrencies, Islamic cryptocurrencies, commodities, or frontier equities, receive higher or lower portfolio allocations. This transparency improves investor confidence, facilitates regulatory compliance, and supports informed decision-making in sustainable

and Islamic finance.(Sutiene et al., 2024). Consequently, this study contributes not only to the theoretical advancement of AI-driven portfolio optimization but also to the practical implementation of transparent, adaptive, and sustainable investment strategies in emerging financial markets such as Pakistan and Malaysia.

Conclusion

This study developed an Explainable Artificial Intelligence (XAI)-based dynamic portfolio optimization framework by integrating Islamic equities, green and conventional cryptocurrencies, gold, and crude oil for the emerging Islamic financial markets of Pakistan and Malaysia. Using the Conditional Value-at-Risk (CVaR) optimization approach, the findings demonstrate that portfolio allocation is primarily influenced by downside-risk reduction and diversification benefits rather than by expected returns alone. The Pakistan portfolio outperformed the Malaysia portfolio, with a higher expected annual return (12.00%) and a superior Sharpe ratio (1.22), indicating more efficient risk-adjusted performance. The optimization results further reveal that green cryptocurrencies, particularly ADA, together with selected conventional cryptocurrencies and gold, play a significant role in constructing resilient portfolios under volatile market conditions. At the same time, domestic equity allocations remained relatively limited due to their lower marginal diversification benefits.

Furthermore, the incorporation of Explainable Artificial Intelligence enhanced the transparency and interpretability of portfolio decisions by providing a clear explanation of category-level asset allocation and risk contributions. Unlike conventional black-box optimization models, the proposed framework enables investors and portfolio managers to understand the rationale behind portfolio construction, thereby improving decision-making confidence and supporting sustainable investment practices. Overall, this study contributes to the growing literature on intelligent portfolio management by integrating AI, downside risk optimization, Islamic finance, and sustainable digital assets into a unified framework. The findings provide valuable practical guidance for investors, Islamic financial institutions, asset managers, and policymakers seeking transparent, adaptive, and risk-efficient investment strategies in increasingly dynamic global financial markets.

Limitations

Despite its contributions, this study has several limitations. First, the analysis relies on historical daily price data obtained from Yahoo Finance; therefore, the results are subject to historical market conditions and may not fully capture future structural changes or extreme economic events. Second, the study focuses only on two emerging Islamic financial markets, Pakistan and Malaysia, which may limit the generalizability of the findings to other developed or emerging economies. Third, the portfolio optimization is based on a long-only CVaR framework without considering transaction costs, taxes, liquidity constraints, short selling, or rebalancing costs that may influence real-world portfolio performance. Finally, the explainability framework is implemented at the category level and does not incorporate advanced model-specific interpretation techniques, such as SHAP or LIME, to explain individual asset-level contributions.

Recommendations and Future Research

Future studies should extend the proposed framework by incorporating additional Islamic and conventional financial markets, including countries such as Saudi Arabia, Indonesia, the United Arab Emirates, and other GCC economies, to provide broader comparative evidence. Researchers may also integrate other sustainable asset classes, including carbon markets, green bonds, ESG indices, and renewable energy stocks, to examine their impact on portfolio diversification. Furthermore, future research should compare the performance of CVaR optimization with advanced artificial intelligence and machine learning techniques, such as deep reinforcement learning, transformer-based forecasting models, and multi-objective optimization algorithms. Finally, incorporating

transaction costs, dynamic portfolio rebalancing, macroeconomic variables, geopolitical risk, and advanced Explainable AI techniques such as SHAP, LIME, and counterfactual explanations would improve the practical applicability, transparency, and robustness of intelligent portfolio optimization models for sustainable investment decision-making.

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