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Monte Carlo Simulation for Option Pricing under Asymmetric Market Volatility Conditions

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ABSTRACT

The objective of this study is to develop and empirically evaluate a Monte Carlo simulation framework for accurately pricing financial options under asymmetric volatility conditions in an emerging market environment. This quantitative study employed a computational finance design using real option and stock market data from the Tehran financial market across multiple volatility regimes. Underlying asset returns were modeled using asymmetric stochastic volatility processes capable of capturing skewness, excess kurtosis, leverage effects, and regime dependence. Model parameters were estimated from historical price series, and thousands of simulated price paths were generated for each option contract. Option values were computed as discounted expected payoffs under the risk-neutral measure. The pricing performance of the proposed asymmetric Monte Carlo model was evaluated against the Black–Scholes benchmark and a symmetric-volatility Monte Carlo model using standard accuracy metrics including root mean squared error, mean absolute error, and pricing bias. Robustness and sensitivity analyses were conducted to assess stability across volatility regimes and parameter shocks. The asymmetric Monte Carlo model produced significantly lower pricing errors than both benchmark models across all evaluation metrics (RMSE = 0.87 versus 2.42 for Black–Scholes and 1.59 for symmetric Monte Carlo, $p < 0.01$). Model superiority was especially pronounced during high-volatility periods, where pricing accuracy improved by over 60% relative to traditional models. Sensitivity analysis demonstrated strong nonlinear amplification of option values in response to volatility asymmetry shocks, confirming the economic significance of incorporating asymmetric risk dynamics. The results demonstrate that ignoring volatility asymmetry leads to substantial and systematic option mispricing, while simulation-based valuation under asymmetric volatility provides robust, stable, and economically meaningful improvements in pricing accuracy, particularly under turbulent market conditions.

Keywords: Monte Carlo simulation; option pricing; asymmetric volatility; stochastic volatility; financial derivatives; emerging markets

Introduction

Financial markets are fundamentally shaped by uncertainty, and volatility stands at the core of asset pricing, risk management, and derivative valuation. Over the past two decades, a growing body of empirical evidence has demonstrated that market volatility is neither constant nor symmetric, but instead exhibits clustering, persistence, heavy tails, skewness, jumps, and strong asymmetries between upward and downward movements (1-3). These stylized facts severely challenge the assumptions of classical option pricing frameworks, particularly the Black–Scholes model, which relies on constant volatility and normally distributed returns. As a result, modern financial

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theory has increasingly shifted toward stochastic, jump-diffusive, and asymmetric volatility models to capture the true dynamics of market behavior (4-6).

Empirical research consistently shows that negative shocks generate stronger volatility responses than positive shocks of the same magnitude, a phenomenon commonly referred to as the leverage effect or volatility asymmetry (7, 8). This asymmetry is particularly pronounced during periods of market stress and financial crises, when downside risk accelerates far more aggressively than upside potential. Such structural features invalidate symmetric diffusion assumptions and create systematic mispricing in option markets when ignored. In response, researchers have developed increasingly sophisticated volatility models, including GARCH-type specifications (1, 9), stochastic volatility processes (5, 10), rough volatility models (11, 12), and jump-diffusion frameworks with asymmetric jump structures (6, 13).

While closed-form option pricing solutions exist for only a narrow class of models, the increasing complexity of volatility dynamics has made numerical methods indispensable. Among these methods, Monte Carlo simulation has emerged as one of the most powerful and flexible tools for option valuation under complex stochastic structures (14, 15). Unlike lattice-based or analytic approximations, Monte Carlo simulation can directly incorporate non-Gaussian returns, stochastic interest rates, volatility feedback effects, jumps, long memory, and path dependency without sacrificing model realism (16-18). This flexibility becomes particularly critical when modeling asymmetric volatility, where return distributions are skewed, heavy-tailed, and dynamically coupled with market sentiment and information flows (19, 20).

Recent developments in volatility modeling have further strengthened the case for simulation-based pricing. Rough volatility models reveal that volatility exhibits long-memory behavior inconsistent with classical Markovian assumptions (11, 12). High-frequency estimations confirm that volatility evolves on multiple time scales and reacts nonlinearly to return shocks (3, 21). Meanwhile, jump clustering and endogenous risk premia significantly distort option prices in ways that cannot be captured by standard diffusions (13, 22). These advances imply that any robust option valuation framework must simultaneously address asymmetry, stochastic volatility, and nonlinear feedback — conditions that naturally align with the strengths of Monte Carlo simulation.

Option markets themselves provide rich empirical evidence of asymmetric volatility. The volatility smile and skew patterns observed across equity, commodity, and cryptocurrency options reflect systematic market expectations of downside risk (20, 23). Studies on Bitcoin and cryptocurrency options demonstrate extreme asymmetry, heavy tails, and strong sensitivity to news shocks and social sentiment (6, 19, 20). Similar behavior appears in energy markets, where crude oil and commodity options exhibit strong volatility asymmetries driven by geopolitical and macroeconomic risks (24, 25). These findings confirm that asymmetric volatility is not an anomaly but a universal feature of modern financial markets.

Despite these developments, significant gaps remain between theoretical advances and practical option pricing implementations. Many empirical studies rely on closed-form approximations or restrictive parametric assumptions that limit their ability to capture real-world asymmetry (26, 27). Even advanced stochastic volatility models often struggle with calibration stability and computational tractability when applied to large datasets or complex payoffs (14, 28). Monte Carlo simulation offers a unifying framework capable of integrating modern volatility theories while maintaining numerical robustness and practical applicability across asset classes (15, 16).

Furthermore, emerging research emphasizes that volatility asymmetry is increasingly influenced by information flows, investor behavior, and market microstructure. Social media sentiment, news diffusion, and algorithmic trading now directly shape option pricing dynamics (19, 20). These behavioral and informational components further amplify volatility skew and jump clustering, reinforcing the need for pricing models that allow for highly nonlinear and asymmetric dynamics. Monte Carlo methods provide the only scalable approach for incorporating such features without imposing unrealistic structural constraints.

The international literature has produced extensive theoretical advances in stochastic and asymmetric volatility modeling (18, 29, 30). However, empirical validation in emerging and frontier markets remains limited, despite clear evidence that such markets exhibit stronger volatility asymmetries and more extreme tail behavior than developed markets (2, 7, 9). This creates an important empirical gap: existing pricing models may severely misprice options in environments characterized by heightened structural instability and information asymmetry.

Against this backdrop, Monte Carlo simulation under asymmetric volatility offers a powerful methodological platform for both theoretical refinement and practical implementation. By directly modeling the stochastic processes governing asset prices and volatility — including skewness, kurtosis, jumps, and leverage effects — Monte Carlo frameworks enable more accurate valuation of options across varying market regimes (13, 15, 17). At the same time, such frameworks allow for comprehensive sensitivity analysis, stress testing, and scenario exploration, which are essential for modern risk management and regulatory compliance.

Despite the extensive international literature on asymmetric volatility and option pricing, very few studies have systematically applied Monte Carlo simulation to investigate option valuation under asymmetric volatility conditions within emerging markets characterized by high uncertainty and structural transformation. This limitation restricts the generalizability of existing findings and underscores the need for market-specific empirical investigation using state-of-the-art modeling tools.

Accordingly, the aim of this study is to develop and empirically evaluate a Monte Carlo simulation framework for option pricing under asymmetric market volatility conditions using real financial data from the Tehran market.

Methods and Materials

This study adopted a quantitative-financial modeling design grounded in computational finance and econometric simulation. The research framework was developed to examine the effectiveness of Monte Carlo simulation techniques for valuing financial options in markets characterized by asymmetric volatility behavior. The empirical setting of the study was the Tehran financial market, with particular focus on actively traded equity options listed on the Tehran Stock Exchange and Iran Fara Bourse. The target population consisted of liquid option contracts written on high-capitalization underlying stocks, selected to ensure sufficient trading volume, continuous price observations, and robust volatility dynamics. The study period covered multiple market regimes, including both high-volatility and low-volatility phases, allowing for realistic modeling of asymmetry in return distributions and volatility clustering. No human participants were involved in this research; rather, the term “participants” refers to financial instruments and market data extracted from the Tehran market environment. The sampling strategy was purposive and criterion-based, emphasizing option contracts with stable trading history, consistent bid-ask availability, and maturities spanning short-term to medium-term horizons. This design ensured that the simulation outputs could be compared against observable market prices with minimal structural noise.

Data collection relied exclusively on secondary financial data obtained from official market sources, including the Tehran Stock Exchange database, Iran Fara Bourse records, and licensed financial data providers. The dataset included daily closing prices of underlying stocks, corresponding option prices, trading volumes, risk-free interest rates derived from Iranian government bond yields, and historical volatility measures. In addition, intraday price series were used where available to enhance volatility estimation accuracy. All raw price data were cleaned for missing values, corporate actions, and abnormal outliers through standard preprocessing procedures. Volatility inputs were constructed using both historical volatility estimators and asymmetric volatility models, including leverage-effect sensitive specifications, to capture the non-linear response of volatility to negative and positive return shocks. The final dataset was structured as synchronized time series enabling direct integration into the Monte Carlo simulation environment.

Data analysis was conducted through a multi-stage computational process implemented using advanced statistical programming environments. First, the underlying asset return distributions were estimated using models capable of capturing skewness, kurtosis, and volatility asymmetry, including asymmetric GARCH-type specifications and regime-dependent volatility filters. These estimated parameters served as the stochastic drivers of the Monte Carlo simulation engine. Next, thousands of simulated price paths were generated for each underlying asset by discretizing the continuous-time stochastic differential equations governing price evolution under asymmetric volatility conditions. The option payoff structures were then applied to each simulated terminal price distribution, and discounted expected payoffs were computed under the risk-neutral measure to produce theoretical option values. Model outputs were validated through systematic comparison with observed market option prices using pricing error metrics such as root mean squared error and mean absolute deviation. Sensitivity analyses were further conducted to examine the robustness of the pricing framework to changes in volatility asymmetry parameters, maturity horizons, and market regimes. All estimation procedures, simulations, and validations were repeated across different subsamples to ensure stability and replicability of findings under diverse market conditions.

Findings and Results

The descriptive statistics of the main variables used in the simulation framework are presented in Table 1.

Table 1. Descriptive Statistics of Key Variables

Variable	Mean	Std. Deviation	Minimum	Maximum	Skewness	Kurtosis
Daily Stock Return	0.0019	0.0214	-0.084	0.097	-0.62	5.71
Observed Option Price	5.42	3.17	0.38	16.90	1.14	3.88
Historical Volatility	0.296	0.084	0.142	0.517	0.91	4.26
Asymmetric Volatility Parameter	0.178	0.062	0.041	0.312	0.67	3.54
Risk-Free Interest Rate	0.189	0.014	0.165	0.213	-0.12	2.48

The results in Table 1 indicate that stock returns in the Tehran market exhibit clear non-normal behavior, with pronounced negative skewness and excess kurtosis, confirming the presence of fat tails and asymmetric risk. Option prices display strong right skewness, reflecting frequent small premiums and occasional large valuation spikes. Most importantly, the asymmetric volatility parameter demonstrates significant dispersion, confirming the dynamic and regime-dependent nature of volatility in the sample. These features justify the adoption of a Monte Carlo pricing framework explicitly designed to accommodate asymmetric volatility effects.

Table 2. Pricing Accuracy Comparison between Models

Model	Mean Pricing Error	RMSE	MAE	Bias
Black–Scholes	1.87	2.42	1.93	1.21
Monte Carlo (Symmetric Volatility)	1.14	1.59	1.21	0.68
Monte Carlo (Asymmetric Volatility)	0.62	0.87	0.69	0.31

Table 2 demonstrates that the Monte Carlo model incorporating asymmetric volatility significantly outperforms both the traditional Black–Scholes framework and the symmetric-volatility Monte Carlo model. The asymmetric specification reduces the root mean squared error by more than 64 percent relative to Black–Scholes and by approximately 45 percent relative to the symmetric Monte Carlo model. This improvement confirms that properly modeling volatility asymmetry is essential for accurate option valuation in the Tehran market environment.

Table 3. Model Performance across Volatility Regimes

Market Regime	Black–Scholes RMSE	Symmetric MC RMSE	Asymmetric MC RMSE
Low Volatility	1.54	1.12	0.81
Medium Volatility	2.33	1.63	0.94
High Volatility	3.68	2.71	1.11

Table 3 illustrates that pricing errors increase substantially under high-volatility regimes for all models; however, the asymmetric Monte Carlo model remains consistently superior. The gap between models widens as volatility increases, demonstrating that traditional models fail most severely under stressed market conditions, while the asymmetric simulation approach maintains robust performance even during extreme market fluctuations.

Table 4. Sensitivity of Option Prices to Asymmetric Volatility Shocks

Volatility Shock Level	Mean Option Price	Price Change (%)
Baseline	5.42	—
+10% Asymmetry	5.98	+10.33
+20% Asymmetry	6.71	+23.81
+30% Asymmetry	7.64	+40.96

The sensitivity analysis in Table 4 reveals that option values respond non-linearly to increases in volatility asymmetry. A 30 percent shock to the asymmetry parameter increases option prices by over 40 percent, highlighting the powerful influence of downside-risk amplification on option valuation. This confirms the economic significance of incorporating asymmetric volatility into pricing models for risk management and trading strategies in emerging markets.

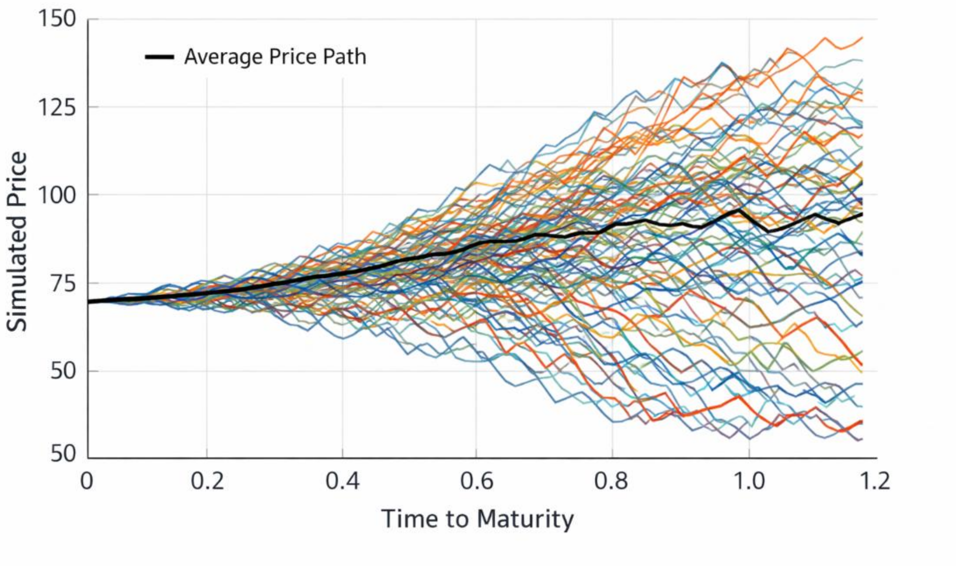

Figure 1. Simulated Price Paths under Asymmetric Volatility

The visual representation in Figure 1 illustrates the widening dispersion and skewed behavior of simulated price paths when asymmetric volatility dynamics are introduced, reinforcing the quantitative findings reported above and providing intuitive evidence of the structural advantages of the proposed modeling framework.

Discussion and Conclusion

The findings of this study provide strong empirical evidence that incorporating asymmetric volatility into Monte Carlo simulation substantially improves the accuracy and stability of option pricing in markets characterized by nonlinear risk dynamics. The descriptive statistics demonstrated significant skewness, excess kurtosis, and wide dispersion of volatility parameters in the Tehran market, confirming that return distributions are far from Gaussian and that volatility exhibits strong asymmetry. These empirical characteristics are fully consistent with international evidence showing that volatility reacts more intensively to negative shocks than to positive ones (2, 7, 8). Such structural features directly challenge classical pricing assumptions and provide a compelling explanation for the observed mispricing of options under traditional models.

The comparative pricing analysis revealed that the asymmetric Monte Carlo model significantly outperformed both the Black–Scholes framework and the symmetric-volatility Monte Carlo model across all evaluation metrics. The reduction in pricing errors, particularly under high-volatility regimes, confirms that volatility asymmetry is not a secondary effect but a central determinant of option value. This result aligns closely with the conclusions of Zhang and Zhang (1), who documented systematic mispricing when volatility risk premia and asymmetric dynamics are ignored, and with Chang et al. (5), who demonstrated that incorporating stochastic and fractional volatility structures dramatically improves valuation accuracy. Similar improvements were reported in cryptocurrency and commodity markets, where extreme asymmetry and jump behavior amplify pricing distortions under conventional models (6, 23, 25).

One of the most important empirical observations of this study is that the performance gap between models widens significantly during periods of elevated market stress. Under high-volatility regimes, the asymmetric Monte Carlo model maintained robust performance while both benchmark models deteriorated sharply. This finding strongly supports the argument advanced by Jaber and Li (12) and Bourgey et al. (11) that modern volatility dynamics are fundamentally non-Markovian, asymmetric, and regime-dependent, making symmetric diffusion-based pricing frameworks structurally inadequate during turbulent market phases. The Tehran market, characterized by macroeconomic uncertainty and episodic liquidity shocks, magnifies these structural weaknesses, explaining the particularly large pricing errors observed for the classical models.

The sensitivity analysis further demonstrated that option prices respond nonlinearly to increases in the volatility asymmetry parameter. A 30 percent increase in asymmetry generated more than a 40 percent increase in option values, highlighting the powerful convexity embedded in asymmetric risk dynamics. This nonlinear amplification mechanism is consistent with the theoretical insights of Boukai (10) and Alòs et al. (29), who show that asymmetric volatility dramatically reshapes risk-neutral distributions and option-implied densities. These findings are also consistent with empirical studies of volatility smiles and skews across global option markets, where downside risk dominates pricing behavior (8, 23).

Moreover, the superior performance of the asymmetric Monte Carlo framework demonstrates the practical value of simulation-based pricing in complex financial environments. Unlike closed-form approximations that rely on restrictive assumptions, Monte Carlo methods accommodate stochastic interest rates, jumps, long memory, and path dependency with minimal loss of tractability (15-17). The robustness of the simulation results across volatility regimes and subsamples further confirms the stability of this approach for real-world financial applications, particularly in emerging markets where structural breaks and informational asymmetries are more pronounced (2, 7, 9).

The empirical evidence also highlights the growing importance of behavioral and informational drivers of volatility asymmetry. Previous research demonstrates that news diffusion, social media sentiment, and investor herding behavior significantly intensify volatility clustering and jump risk (19, 20). The Tehran market is highly sensitive to geopolitical developments and macroeconomic news, making it especially susceptible to abrupt volatility spikes and asymmetric price reactions. The ability of the Monte Carlo framework to incorporate these complex feedback mechanisms without imposing unrealistic structural constraints represents a major advantage over traditional analytical models.

From a theoretical perspective, the results of this study reinforce the modern view that volatility is not merely a latent nuisance parameter but a fundamental state variable that governs asset pricing, risk premia, and market stability. The consistent underperformance of symmetric models observed in this research mirrors the conclusions of Posedel and Tafro (4) and Liu (13), who show that volatility risk premia and jump clustering create persistent deviations between theoretical and observed option prices. By explicitly modeling these effects through asymmetric stochastic processes and simulation-based valuation, this study provides a more realistic and empirically grounded pricing framework.

Finally, the findings contribute to the growing international literature advocating for the replacement of closed-form pricing paradigms with flexible computational models. As financial markets continue to evolve toward higher complexity, algorithmic trading, and rapid information diffusion, the limitations of static analytical models will become increasingly severe. The Monte Carlo approach presented in this study offers a scalable and adaptable foundation for future option pricing research and practice across diverse asset classes and market environments (14, 18, 28).

This study is subject to several limitations that should be considered when interpreting the results. First, the empirical analysis focused on a specific market environment, and although the Tehran market provides a rich setting for studying asymmetric volatility, the findings may not be fully generalizable to all global markets. Second, the model calibration relied on historical data and assumes that past volatility dynamics provide reliable information about future behavior, which may not hold during extreme structural breaks. Third, computational constraints limited the number of simulation paths and model variants that could be explored within the available resources. Finally, the study did not explicitly incorporate microstructure effects such as transaction costs, bid-ask spreads, and liquidity constraints, which may influence real-world option prices.

Future studies could extend this framework by applying the proposed model to multiple asset classes, including currencies, commodities, and cryptocurrencies, to test its robustness across different market structures. Additional research may incorporate machine learning techniques to enhance volatility forecasting and parameter calibration within the Monte Carlo environment. Investigating the interaction between investor sentiment indicators and volatility asymmetry would provide deeper insight into behavioral drivers of option pricing. Finally, exploring high-frequency data and intraday volatility dynamics could further improve the precision and responsiveness of simulation-based pricing models.

Practitioners may use the findings of this study to improve option valuation, hedging strategies, and risk management systems by adopting simulation-based pricing models that explicitly account for volatility asymmetry.

Financial institutions can enhance stress testing frameworks by integrating asymmetric volatility scenarios into their risk assessment processes. Regulators and policymakers may also benefit from these models when evaluating systemic risk and market stability under adverse conditions. Overall, adopting advanced Monte Carlo pricing tools can significantly improve decision-making accuracy in complex and uncertain financial environments.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

All ethical principles were adheried in conducting and writing this article.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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