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VOLATILITY DYNAMICS AND CONTEMPORANEOUS LINKAGES AMONG CRUDE OIL, GOLD, AND USD RETURNS: AN ARCH–GARCH ANALYSIS

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ABSTRACT

This study investigates the distributional properties, dependence structure, and volatility dynamics of crude oil, gold, and USD returns, with a particular focus on contemporaneous linkages between crude oil returns and movements in gold and the exchange rate. This study based on daily closing prices over the study period [January 2021 to July 2026]. The study compares the performance of a simple OLS regression model and an ARCH–GARCH framework in explaining crude oil return dynamics. The findings contribute to the literature on commodity–currency–safe-haven interactions and offer practical insights for investors and policy makers concerned with managing exposure to energy price risk in the presence of gold and exchange rate movements. Understanding how returns and volatility in these markets behave, and whether they are interconnected in the short run, is essential for investors, policy makers, and risk managers operating in an increasingly integrated global financial system. Overall, the findings suggest that crude oil volatility is substantial and time-varying, but contemporaneous gold and USD returns play only a modest role in explaining crude oil return dynamics.

1. INTRODUCTION

Volatility in financial markets has long been recognized as a critical dimension of risk, shaping asset pricing, portfolio allocation, and hedging strategies. Among global financial assets, crude oil, gold, and major currencies such as the US dollar (USD) occupy a central position due to their roles as key inputs, stores of value, and pricing benchmarks in international trade and investment. Crude oil is a fundamental commodity driving production costs and macroeconomic activity; gold is widely regarded as a safe-haven and inflation-hedging asset; and the USD functions as the dominant invoicing and reserve currency.

A key feature of financial returns, particularly for commodities such as crude oil, is the presence of volatility clustering, where periods of high volatility tend to be followed by high volatility and calm periods by relative stability. Traditional linear models like ordinary least squares (OLS) regression are ill-equipped to capture such time-varying volatility dynamics, even if they can describe average relationships in the mean of returns. In contrast, models based on Autoregressive Conditional Heteroskedasticity (ARCH) and its generalized extensions (GARCH) provide a flexible framework to jointly characterize return behavior and conditional variance. These models allow researchers to assess not only whether gold and USD returns explain crude oil returns contemporaneously, but also whether shocks to these markets and to crude oil itself propagate through volatility over time.

Against this backdrop, the present study investigates the distributional properties, dependence structure, and volatility dynamics of crude oil, gold, and USD returns, with a particular focus on contemporaneous linkages between crude oil returns and movements in gold and the exchange rate.

2. Literature review

The reviewed literature collectively highlights the pivotal roles of crude oil prices, gold prices, and exchange rates in shaping stock market performance across developed and emerging economies. Early work by Jones and Kaul (1996) and Sadorsky (1999) establishes that rising oil prices and oil price volatility tend to depress stock returns by increasing production costs, heightening uncertainty, and constraining economic growth, thereby forming the foundation of the oil price–stock market nexus. Extending this line of inquiry to emerging markets, Hammoudeh and Li (2008) show that oil price shocks significantly influence stock markets, especially in oil-importing countries, underscoring the vulnerability of these economies to external energy price movements.

Parallel strands of research examine gold and exchange rates as key financial variables interacting with equity markets. Baur and Lucey (2010) and Reboredo (2013) document gold's role as a safe-haven and hedge, demonstrating that investors shift from equities to gold during periods of financial stress and heightened volatility, and that gold provides diversification benefits against stock market risk. Studies on exchange rates, such as those by Kollias, Papadamou, and Siriopoulos (2012) and Singh (2014), reveal that US dollar movements and rupee–USD fluctuations significantly influence investor confidence, capital flows, and stock indices, with currency depreciation affecting foreign investment and long-term market performance.

More recent contributions integrate these macro-financial variables in the context of the Indian stock market. Kumar (2015), Bhunia and Das (2016), and Sharma and Mahendru (2019) collectively show that crude oil prices, gold prices, and exchange rates jointly and dynamically affect Indian equity markets, with both short-run and long-run impacts on stock returns and volatility. Overall, the literature converges on the view that oil, gold, and exchange rate dynamics are closely intertwined with stock market behaviour, influencing risk, returns, and volatility, particularly in emerging and energy-dependent economies.

3. RESEARCH METHODOLOGY

Research Design

This study adopts a quantitative, empirical research design based on daily closing prices for three financial series—crude oil, gold, and the USD exchange rate—are collected from [name the data source(s), e.g., international financial databases, central bank publications, or commodity exchanges] over the study period [January 2021 to July 2026]. Crude oil prices are proxied by [e.g., Brent/WTI spot price or futures price], gold prices by the international spot price of gold denominated in USD per ounce, and the USD series by the bilateral exchange rate of the US dollar against INR.The analysis proceeds in three stages: (i) descriptive and distributional analysis, (ii) stationarity and dependence diagnostics, and (iii) mean–variance modelling using linear regression and ARCH–GARCH specifications.

Model specification

Distributional Analysis

To characterize the risk–return profiles of the three assets, the study computes descriptive statistics for each return series, including mean, median, standard deviation, minimum, maximum, skewness, kurtosis, and selected quantiles. These measures highlight average performance, volatility, tail behavior, and deviations from symmetry.

Normality is assessed using graphical tools (histograms and kernel density plots) and formal tests such as the Jarque–Bera statistic. This analysis allows identification of non-normal features—such as fat tails and skewness—particularly relevant for modelling volatility and risk.

Stationarity and Dependence Diagnostics

Given the time-series nature of the data, stationarity properties are examined for both price levels and return series. Augmented Dickey–Fuller (ADF) unit root tests are applied. where (X_{t}) denotes the price or return series under consideration, (\Delta) is the first-difference operator, and (p) is the lag order chosen based on information criteria and residual diagnostics. Rejection of the unit root null hypothesis indicates stationarity. _

Serial dependence in returns is evaluated using autocorrelation functions (ACF), partial autocorrelation functions (PACF), and Ljung–Box Q-statistics at various lags. These diagnostics test for the presence of linear dependence in the first and higher moments and help confirm whether the return series are covariance-stationary and suitable for econometric modelling.

Mean Equation: Ordinary Least Squares Regression

To examine contemporaneous linear relationships between crude oil returns and the other markets, an ordinary least squares (OLS) regression model is first estimated:

Volatility Modelling: ARCH–GARCH Specification

To capture time-varying volatility and volatility clustering in crude oil returns, the study employs an Autoregressive Conditional Heteroskedasticity–Generalized ARCH (ARCH–GARCH) framework.

Model Evaluation and Robustness

Model performance is evaluated using information criteria such as the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC), as well as log-likelihood values, to compare the OLS and ARCH–GARCH specifications. Standardized residuals and squared standardized residuals are examined through ACFs and Ljung–Box tests to ensure that serial correlation and remaining ARCH effects have been adequately addressed.

Where appropriate, alternative specifications (e.g., different conditional distributions or higher-order GARCH models) may be estimated as robustness checks. The overall methodological framework thus enables a comprehensive assessment of whether and to what extent gold and USD returns influence crude oil return dynamics, both in terms of average contemporaneous relationships and time-varying volatility behavior.

4. Data analysis & Interpretation

Figure (1) Graph showing the closing prices of crude oil, gold price and USD.

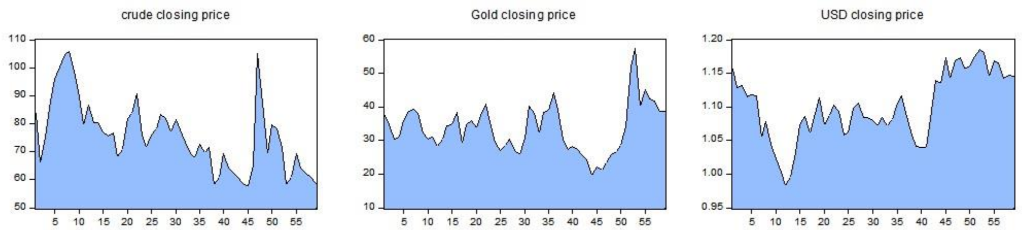
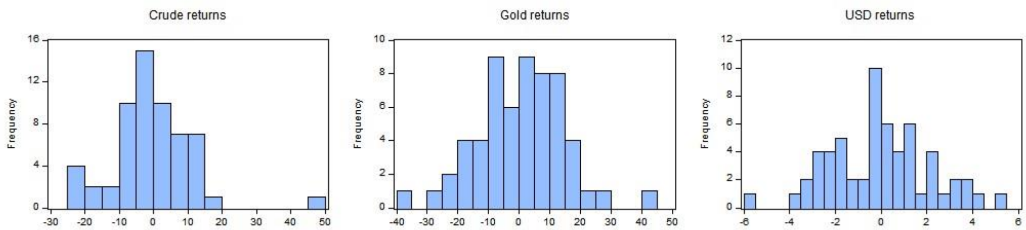


Figure (2) Graph showing the return series of crude oil, gold price and USD.



Interpretation: Figures 1 and 2 illustrate the closing price movements and return distributions of crude oil, gold, and the USD exchange rate over the study period. The graphs provide preliminary insights into the behaviour, volatility, and distributional characteristics of the selected financial variables. The graphical analysis suggests that while all three financial variables exhibit time-varying price movements, their levels of volatility differ considerably. The return histograms for all three variables are centred near zero, indicating that positive and negative returns occur around an average close to zero, which is a common characteristic of financial return series. However, the wider dispersion and greater occurrence of extreme returns in crude oil highlight its higher investment risk relative to gold and the USD.Crude oil experiences substantial price swings and highly dispersed returns, gold demonstrates moderate volatility with strong appreciation during periods of uncertainty, and the USD maintains relatively stable price and return behaviour. These findings indicate that the variables possess distinct dynamic characteristics, providing a strong basis for conducting further econometric analyses.

Table 01: Descriptive statistics.

	Crude_returns	Gold_returns	USD_returns
Mean	-0.420351	0.430156	-0.021908
Median	-1.835983	1.300831	-0.036897
Maximum	47.70140	42.05249	5.088209
Minimum	-23.33063	-36.03856	-5.676851
Std. Dev.	11.51082	13.80639	2.161301
Skewness	0.898761	0.057359	0.036405
Kurtosis	6.803003	3.677672	2.840051
Jarque-Bera	43.49755	1.161314	0.075926
Probability	0.000000	0.559531	0.962749

Table 01 depicts the descriptive statistics of Crude oil, gold, and USD returns exhibit clearly different risk–return characteristics. Crude oil shows mildly negative average returns with the strongest volatility and the widest range of values, along with a right-skewed, fat-tailed distribution and clear non-normality. Gold delivers positive average returns, is also highly volatile, and displays moderately heavy tails but no significant departure from normality. The USD, by contrast, has near-zero average returns, much lower volatility, a relatively narrow range, and a distribution that is close to normal. Overall, crude oil is the riskiest and most non-normal asset, gold offers positive but volatile performance, and the USD is comparatively stable with minimal average movement.

Table 02: Augmented Dickey-Fuller test statistic.

closing price series		
crude oil closing price	-2.77316	0.0684
gold closing price	-2.77492	0.0681
USD closing price	-1.90922	0.3259
return series		
crude oil returns	-7.64966	0
gold returns	-7.24771	0
USD returns	-7.05489	0

Table 03: Correlogram analysis.

<table>
<tr><th>Autocorrelation</th><th>Partial Correlation</th><th></th><th>AC</th><th>PAC</th><th>Q-Stat</th><th>Prob</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>.|. |</td><td>.|. |</td><td>1</td><td>-0.056</td><td>-0.056</td><td>0.1952</td><td>0.659</td></tr>
<tr><td>**|. |</td><td>**|. |</td><td>2</td><td>-0.325</td><td>-0.329</td><td>6.8493</td><td>0.033</td></tr>
<tr><td>.|. |</td><td>.|. |</td><td>3</td><td>-0.004</td><td>-0.053</td><td>6.8506</td><td>0.077</td></tr>
<tr><td>.|. |</td><td>.*|. |</td><td>4</td><td>0.051</td><td>-0.069</td><td>7.0179</td><td>0.135</td></tr>
<tr><td>.|. |</td><td>.|. |</td><td>5</td><td>0.060</td><td>0.046</td><td>7.2589</td><td>0.202</td></tr>
<tr><td>**|. |</td><td>**|. |</td><td>6</td><td>-0.255</td><td>-0.284</td><td>11.672</td><td>0.070</td></tr>
<tr><td>.|*. |</td><td>.|*. |</td><td>7</td><td>0.077</td><td>0.089</td><td>12.085</td><td>0.098</td></tr>
</table>

. |*. |	. | . |	8	0.133	-0.040	13.337	0.101
.*| . |	.*| . |	9	-0.188	-0.162	15.886	0.069
. | . |	. | . |	10	0.038	0.041	15.994	0.100
. | . |	.*| . |	11	-0.015	-0.112	16.011	0.141
.*| . |	.*| . |	12	-0.076	-0.165	16.452	0.171
. | . |	.*| . |	13	-0.019	-0.076	16.481	0.224
. | . |	.*| . |	14	-0.040	-0.114	16.611	0.278
. |*. |	. | . |	15	0.147	-0.015	18.390	0.243
. | . |	. | . |	16	0.002	-0.012	18.390	0.302
. | . |	. | . |	17	-0.052	-0.032	18.623	0.351
. | . |	.*| . |	18	-0.061	-0.200	18.954	0.395
. | . |	. | . |	19	-0.019	-0.049	18.988	0.458
. |*. |	. | . |	20	0.125	-0.023	20.432	0.431
. |*. |	. |*. |	21	0.090	0.085	21.198	0.447
. | . |	. | . |	22	-0.012	0.031	21.212	0.508
. | . |	. | . |	23	-0.061	-0.045	21.578	0.546
.*| . |	.*| . |	24	-0.099	-0.167	22.577	0.545

From the table 02 and table 03, results of stationarity test using Augmented Dickey–Fuller test shows that crude oil, gold, and USD closing prices are non-stationary in levels, as their test statistics and p-values fail to reject the presence of a unit root at the 5% level. However, the corresponding return series for all three assets are highly significant in the ADF test, indicating stationarity and confirming that the variables are integrated of order one, I(1). Correlogram analysis of the return series further reveals that, apart from a few early lags with moderate negative autocorrelations, most autocorrelation and partial autocorrelation coefficients lie within the 95% confidence bands and the Ljung–Box Q-statistics become insignificant at higher lags. Overall, the results indicate that the return series are weakly dependent, covariance-stationary, and suitable for subsequent time series and econometric modelling.

Table 04: Method: Least Squares.

Dependent Variable: CRUDE_RETURNS				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
GOLD_RETURNS	0.068443	0.122512	0.558665	0.5786
USD_RETURNS	0.385118	0.782607	0.492096	0.6246
C	-0.441355	1.513282	-0.291654	0.7716
R-squared	0.017104	Mean dependent var		-0.420351
Adjusted R-squared	-0.017999	S.D. dependent var		11.51082
S.E. of regression	11.61395	Akaike info criterion		7.791801
Sum squared resid	7553.499	Schwarz criterion		7.897438
Log likelihood	-226.8581	Hannan-Quinn criter.		7.833037
F-statistic	0.487247	Durbin-Watson stat		2.107408
Prob(F-statistic)	0.616895			

From the table 04, the results from OLS regression of crude oil returns on gold and USD returns shows no meaningful contemporaneous relationship. Neither gold nor USD returns have statistically significant coefficients, and the model's explanatory power is essentially zero (very low R^2 and insignificant F-statistic), indicating that these variables do not explain variations in crude oil returns in this linear specification. The residuals appear well behaved with no evidence of first-order autocorrelation (Durbin–Watson ≈ 2.11).

Table 05: ARCH/GARCH MODEL.

Dependent Variable: CRUDE_RETURNS				
Variable	**Coefficient**	**Std. Error**	**z-Statistic**	**Prob.**
GOLD_RETURNS	0.141203	0.084179	1.677417	0.0935
USD_RETURNS	0.178646	0.521774	0.342382	0.7321
C	-1.601202	1.167359	-1.371646	0.1702
	Variance Equation			
C	25.28757	18.80443	1.344766	0.1787
RESID(-1)^2	0.974717	0.341360	2.855394	0.0043
GARCH(-1)	0.099412	0.194709	0.510570	0.6097
R-squared	0.001212	Mean dependent var		-0.420351
Adjusted R-squared	-0.034459	S.D. dependent var		11.51082
S.E. of regression	11.70747	Akaike info criterion		7.622526
Sum squared resid	7675.625	Schwarz criterion		7.833801
Log likelihood	-218.8645	Hannan-Quinn criter.		7.704999
Durbin-Watson stat	2.100561			

From the table 05, the results from the test of ARCH–GARCH results show that gold returns have a weak, marginally significant positive effect on crude oil returns, while USD returns do not have a meaningful impact and the mean equation overall has very low explanatory power. In the variance equation, a highly significant ARCH term confirms strong volatility clustering in crude oil returns, but the insignificant GARCH term suggests limited longer-run volatility persistence beyond the immediate impact of shocks. Compared with the OLS model, the ARCH–GARCH specification improves the log-likelihood and lowers the AIC, indicating a better overall fit once time-varying volatility is taken into account, even though the role of gold and USD returns in explaining mean crude oil returns remains modest.

5. FINDINGS

The empirical results highlight distinct risk–return and distributional characteristics across crude oil, gold, and USD returns. Descriptive statistics (Table 01) show that crude oil generates mildly negative average returns but is associated with the highest volatility, the widest range, and a markedly right-skewed, leptokurtic distribution, indicating pronounced tail risk and clear deviations from normality. Gold, in contrast, delivers positive average returns and is also highly volatile, with moderately heavy tails but no strong evidence of non-normality. The USD return series exhibits near-zero average returns, substantially lower volatility, a relatively narrow dispersion, and an approximately normal distribution, underscoring its comparatively stable behaviour. Overall, these patterns suggest that crude oil is the riskiest and most non-normal asset, gold offers higher but more volatile returns, and the USD behaves as a relatively stable asset with minimal average movement.

The stationarity analysis based on the Augmented Dickey–Fuller test (Tables 02 and 03) indicates that crude oil, gold, and USD closing prices are non-stationary in levels, as the test statistics and associated p-values fail to reject the null of a unit root at the 5% significance level. However, the corresponding return series for all three assets are highly significant in the ADF test, confirming stationarity and establishing that the variables are integrated of order one, I(1). Correlogram analysis of the return series further reveals that, aside from a few early lags with moderate negative autocorrelations, most autocorrelation and partial autocorrelation coefficients lie within the 95% confidence bounds, and Ljung–Box Q-statistics become insignificant at higher lags. These findings indicate that the return series exhibit only weak short-run dependence, are covariance-stationary, and are therefore suitable for subsequent time-series and econometric modelling.

The contemporaneous linkages among the three assets were first examined using an OLS regression of crude oil returns on gold and USD returns (Table 04). The estimated coefficients on both gold and USD returns are statistically insignificant, and the model exhibits negligible explanatory power, as reflected in the very low R^2 and insignificant joint F-statistic. This implies that, within a simple linear framework, neither gold nor USD returns can be regarded as meaningful contemporaneous determinants of crude oil returns. Diagnostic results further show that the residuals are free from serious first-order autocorrelation (Durbin–Watson ≈ 2.11), suggesting that the lack of explanatory power is not due to autocorrelation in the error term but to the limited relevance of these regressors in the mean equation.

To account for time-varying volatility, an ARCH–GARCH specification was subsequently estimated (Table 05). In the mean equation, gold returns display a positive coefficient that is marginally significant at the 10% level, indicating a weak contemporaneous comovement between gold and crude oil returns, while USD returns remain statistically insignificant. Nonetheless, the overall explanatory power of the mean equation remains low, reinforcing the view that these financial variables play only a modest role in driving crude oil returns. In the variance equation, the ARCH(1) term is positive and highly significant, providing strong evidence of volatility clustering, whereby large shocks to crude oil returns are likely to be followed by further large shocks. By contrast, the GARCH(1) term is not significant, suggesting limited persistence of volatility beyond the immediate impact of shocks. The ARCH–GARCH model improves the log-likelihood and yields a lower AIC relative to the OLS specification, indicating that explicitly modelling conditional heteroskedasticity offers a better statistical representation of crude oil return dynamics, even though gold and USD returns remain weak predictors in the mean process.

6. CONCLUSION

The study provides a comprehensive assessment of the distributional properties, stationarity, and conditional dynamics of crude oil, gold, and USD returns. The evidence from descriptive analysis underscores that crude oil is characterised by high volatility, substantial tail risk, and pronounced non-normality, distinguishing it from gold, which offers positive but volatile returns with more moderate departures from normality, and from the USD, which exhibits relatively stable, low-volatility behaviour. These differences in risk–return profiles highlight the heterogeneous roles that these assets may play in portfolio construction, risk management, and hedging strategies.

Incorporating time-varying volatility via the ARCH–GARCH model yields a richer description of crude oil return dynamics. Volatility clustering emerges as a key feature, with significant ARCH effects indicating that shocks have an immediate and substantial impact on conditional variance, although volatility persistence beyond one period is not strongly supported. The marginally significant effect of gold returns in the mean equation suggests only a weak short-run linkage between gold and crude oil, while USD returns do not exert a statistically meaningful influence.

Taken together, the findings suggest that modelling and forecasting crude oil returns require explicit consideration of conditional heteroskedasticity and that reliance on contemporaneous gold and USD returns as key explanatory variables is likely to be inadequate. Future research could extend the analysis by incorporating additional macroeconomic, geopolitical, and market-specific factors, exploring alternative volatility models, and examining different horizons or regimes to better capture the complex drivers of crude oil price dynamics and their interactions with related financial markets.

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