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FONT	Times New Roman, 12 pt
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MARGINS	2.5 cm (1 inch) all sides
ABSTRACT	150–250 words (structured)
KEYWORDS	4–6
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An Integrated Predictive-Analytical Modeling Framework for E-Learning Quality Assessment: Evidence from the TBSA Program

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Abstract:

The rapid expansion of e-learning necessitates robust frameworks to evaluate and enhance learner experience. This study proposes an innovative hybrid methodology that integrates machine learning (ML) with fuzzy multi-criteria decision-making (Fuzzy MCDM) to assess perceived e-learning quality. Using data from the TBSA (Training for Business Start-up Advisors) program, we first employ Gradient Boosting with SHAP (SHapley Additive exPlanations) analysis to objectively determine feature importance from learner responses. These data-driven weights are then integrated into a Fuzzy TOPSIS model to manage inherent uncertainties in educational assessments and produce robust quality dimension rankings.

Our results reveal that Responsiveness/Ease of Use (dimension weight: 0.5714) is the most critical dimension, followed by Tangibility (0.2020), Assurance (0.1592), and Security/Reliability (0.0674). The hybrid framework demonstrates substantial explanatory power (R = 0.5156) while providing interpretable, action- able insights for e-learning optimization. This approach offers educational institutions a scientifically-grounded methodology for prioritizing quality improvements and resource allocation.

Keywords: E-Learning Quality, Machine Learning, SHAP Analysis, Fuzzy TOPSIS, Hybrid Methodology, Learner Satisfaction, Educational Analytics.

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1. Introduction and Background

1.1 The E-Learning Quality Assessment Challenge

The global e-learning market has experienced unprecedented growth, projected to surpass $1 trillion by 2030, fundamentally transforming educational delivery worldwide (Global Market Insights, 2023). This rapid expansion, accelerated by digital transformation and the COVID-19 pandemic, has highlighted critical challenges in maintaining educational quality and learner engagement in virtual environments. Despite technological advancements, institutions struggle with high dropout rates and learner dissatisfaction, raising fundamental questions about how to effectively evaluate and enhance e-learning quality (Singh & Thurman, 2019).

Traditional approaches to e-learning quality assessment have predominantly followed two separate trajectories. On one hand, service quality models like SERVQUAL and E-S-QUAL have been adapted to educational contexts, focusing on dimensions such as reliability, responsiveness, and empathy (Parasuraman et al., 1988; Zeithaml et al., 2002). These models, while comprehensive, often rely on subjective expert judgments for criterion weighting, introducing potential biases and limiting objectivity. On the other hand, educational technology research has emphasized pedagogical elements including content quality, instructional design, and technological infrastructure (Mayer, 2017; Garrison & Kanuka, 2004). However, these approaches frequently employ simplistic statistical methods that fail to capture the complex, non-linear relationships between quality dimensions and learning outcomes.

1.2 The Emergence of Data-Driven Approaches

Recent advances in educational data mining have demonstrated the potential of machine learning (ML) for predicting student outcomes and identifying key success factors (Baker & Inventado, 2014; Romero & Ventura, 2020). Algorithms such as Random Forests, Gradient Boosting, and XGBoost have shown remarkable performance in capturing complex patterns in educational data. However, these models often operate as "black boxes," offering limited interpretability and insight into the relative importance of different quality dimensions (Adadi & Berrada, 2018). This interpretability gap

represents a significant barrier to the practical application of ML in educational decision-making.

The emergence of explainable AI (XAI) methods, particularly SHAP (SHapley Additive exPlanations), has addressed this limitation by providing model-agnostic interpretability (Lundberg & Lee, 2017). SHAP values, rooted in cooperative game theory, offer a mathematically rigorous approach to quantifying feature importance, enabling educators to understand which factors most significantly influence learning outcomes. Despite these advances, ML approaches still struggle with handling the inherent uncertainty and imprecision characteristic of educational data, particularly Likert-scale survey responses.

1.3 Fuzzy MCDM in Educational Assessment

Fuzzy Multi-Criteria Decision-Making (MCDM) methods have gained traction in educational quality assessment due to their ability to handle uncertainty and vagueness in human judgments (Zadeh, 1965; Chen & Hwang, 1992). Techniques such as Fuzzy TOPSIS, Fuzzy AHP, and Fuzzy DEMATEL have been successfully applied to various educational evaluation problems (Büyüközkan et al., 2021). These methods excel at managing the linguistic ambiguity and subjective perceptions inherent in educational contexts, where precise numerical assessments often fail to capture the complexity of human learning experiences.

However, traditional fuzzy MCDM approaches typically depend on expert-derived weights, which can introduce subjectivity and limit reproducibility (Tzeng & Huang, 2011). The integration of data-driven weights from ML models represents a promising direction for enhancing the objectivity and robustness of fuzzy decision-making in education.

1.4 Research Gap and Contribution

This research addresses a critical gap in the literature by developing a novel hybrid framework that integrates machine learning with fuzzy MCDM for e-learning quality assessment. While previous studies have either applied ML for prediction or used MCDM for evaluation, few have successfully integrated both approaches to leverage their complementary strengths. Our methodology uniquely combines:

- **The predictive power and objectivity of ML** with SHAP-based interpretability

- **The uncertainty-handling capabilities of fuzzy logic** through Fuzzy TOPSIS
- **Data-driven weight derivation** that eliminates subjective expert bias

This integrated approach enables us to address the fundamental research question**: How can educational institutions objectively identify which quality dimensions most significantly impact learner satisfaction and behavioral intentions in e-learning environments, while accounting for the inherent uncertainty in educational assessments.**

The proposed framework represents a significant methodological advancement in educational analytics, providing both high predictive accuracy and transparent, actionable insights for educational decision-makers. By bridging the gap between data-driven prediction and interpretable evaluation, our approach offers a comprehensive solution to the challenges of e-learning quality assessment in the digital age.

2. Methodology

2.1 Data Collection and Variable Specification

The study utilizes data from the TBSA e-learning program, comprising responses from approximately 150 learners. The comprehensive questionnaire captured:

- **Sociodemographic variables:** Age, gender, education level, professional experience, prior e-learning exposure
- **Perceived quality dimensions**: 10 constructs measured through validated Likert-scale items
- **Outcome variables**: Satisfaction (SAT) and Behavioral Intentions (INT)

The conceptual model organizes these variables into three interconnected constructs:

- **Independent Variables:** Ten quality dimensions (FCLT, SEC, UTLT, CNT, PED, TANG, FIAB, SERVB, ASS, EMP)
- **Mediating Variable:** Learner Satisfaction (SAT)
- **Dependent Variable**: Behavioral Intentions (INT)

2.2 Hybrid Analytical Framework

Our methodology follows a sequential three-phase approach:

Phase 1: Machine Learning with SHAP Interpretation

We employed ensemble methods, particularly Gradient Boosting, for their superior performance in capturing complex, non-linear relationships in educational data. The model was trained to predict learner satisfaction using the ten quality dimensions as features:

$$\hat{y}_i = F_n(x_i) = \sum_{m=1}^{M} \gamma_m h_m(x_i)$$

where n is the total number of trees and h_m is the mth decision tree and γ_m its associated weight.

The weights of the criteria w_j are extracted from the SHAP values. The SHAP value for a variable j and an observation i is defined by:

$$\boldsymbol{\phi_j} = \sum_{\boldsymbol{S \subseteq N \setminus \{j\}}} \frac{|\boldsymbol{S}|!\,(\boldsymbol{n} - |\boldsymbol{S}| - \boldsymbol{1})!}{\boldsymbol{n}!} [\boldsymbol{f}(\boldsymbol{S} \cup \{\boldsymbol{j}\}) - \boldsymbol{f}(\boldsymbol{S})]$$

where: N is the set of variables and $f(S)$ is the model trained on the subset S.

The objective weight of a criterion is obtained by normalization:

$$\boldsymbol{w_j} = \frac{|\boldsymbol{\phi_j}|}{\sum_{\boldsymbol{k=1}}^{\boldsymbol{m}} |\boldsymbol{\phi_k}|}$$

Phase 2: Fuzzy TOPSIS Integration

To handle the inherent uncertainty and imprecision in learner responses, we integrated the ML-derived weights into a Fuzzy TOPSIS model. Each response was represented as a triangular fuzzy number:

Consider a fuzzy decision matrix $\tilde{X}$= ($\tilde{x}_{ij}$), where a triangular fuzzy number represents each data point $\tilde{x}_{ij}$:

$$\tilde{x}_{ij} = (l_{ij}, m_{ij}, u_{ij})$$

Then the normalization of fuzzy values is defined by:

$$\tilde{r}_{ij} = \frac{\tilde{x}_{ij}}{\sqrt{\sum_{i=1}^{n} (u_{ij})^2}}$$

And the matrix weighting is defined by:

$$\tilde{v}_{ij} = w_j \,.\, \tilde{r}_{ij}$$

After normalization and weighting, we define the ideal solutions $\boldsymbol{A}^{+}$, and anti-ideal solutions $\boldsymbol{A}^{-}$. The distances are calculated as:

$$A^{+} = \left\{\max_{i} u_{ij}, \mathrm{j} = 1,2,\dots,\mathrm{m}\right\} \quad \text{and} \quad A^{-} = \left\{\min_{i} l_{ij}, \mathrm{j} = 1,2,\dots,\mathrm{m}\right\} \quad (7)$$

The distance of each learners from the ideal and anti-ideal is given by:

$$D_i^{+} = \sum_{j=1}^{m} d\left(\tilde{v}_{ij}, A_j^{+}\right)$$

$$D_i^{-} = \sum_{j=1}^{m} d\left(\tilde{v}_{ij}, A_j^{-}\right)$$

Where d (.) is a distance between fuzzy numbers.

Finally, the proximity score is given by:

$$C_i = \frac{D_i^{-}}{D_i^{+} + D_i^{-}}, 0 \le C_i \le 1$$

Phase 3: Hybrid Scoring and Robustness Validation

The final step is to combine the results from the two approaches, machine learning and Fuzzy TOPSIS, to generate a final ranking of features. The predictive score provided by Gradient Boosting is compared and integrated with the proximity score obtained by TOPSIS, in order to ensure double validation of the results. This strategy reinforces the stability of the ranking and reduces the risk of erroneous conclusions linked to dependence on a single method. The final ranking combines the predictive score of the ML model and that of Fuzzy TOPSIS according to:

$$H_i = \lambda \,.\, \widehat{\hat{y}_i} + (1 - \lambda) \,.\, C_i, 0 \le \lambda \le 1$$

3. Results and Analysis

This section presents comprehensive findings from our hybrid ML-Fuzzy MCDM analysis, organized to provide both statistical rigor and practical interpretability. All analyses were con- ducted using Python 3.9 with Scikit-learn 1.0.2, SHAP 0.41.0, and custom fuzzy logic implementations.

3.1 Descriptive Statistics and Preliminary Analysis

Table 2 presents the comprehensive descriptive statistics for all variables after standardization (mean = 0, SD = 1). This standardization facilitates comparison across different measurement scales and enhances model convergence. The standardized means near zero and standard deviations of 1.0 confirm successful normalization. Negative skewness values for most variables indicate distributions skewed toward higher satisfaction ratings, common in educational con- texts where participants tend to rate positively. Kurtosis values show varied distribution shapes, with CNT and PED displaying leptokurtic distributions indicating peaked distributions, while others show platykurtic tendencies.

Table 2: Descriptive Statistics of E-Learning Quality Variables (N = 103)

Variable	Mean	SD	Min	Median	Max	Skewness	Kurtosis
FCLT	0.000	1.000	-3.273	0.068	1.164	-0.562	-0.098
SEC	0.000	1.000	-1.673	0.232	1.568	0.218	-1.197
UTLT	0.000	1.000	-3.067	0.094	0.963	-0.793	-0.036
CNT	-0.000	1.000	-2.907	0.086	1.808	-0.371	0.755
PED	-0.000	1.000	-3.577	-0.123	1.593	-0.467	1.129
TANG	-0.000	1.000	-2.531	-0.125	1.459	-0.140	-0.472
FIAB	0.000	1.000	-3.595	-0.134	1.285	-0.487	0.583
SERVB	-0.000	1.000	-2.985	-0.034	1.222	-0.430	-0.112
ASS	0.000	1.000	-2.453	-0.157	1.360	-0.125	-0.791
EMP	-0.000	1.000	-2.386	0.062	1.470	-0.113	-0.824
SAT	0.000	1.000	-2.987	0.240	1.056	-0.463	-0.712

Shapiro-Wilk normality tests revealed that all variables except EMP significantly deviate from normal distribution (p : 0.05), justifying our use of non-parametric and robust analytical methods (see Appendix A, Table 6). This non-normality particularly supports our choice of tree-based ML methods (Gradient Boosting) which do not assume normality.

3.2 Correlation Analysis and Bivariate Relationships

Table 3 presents the top correlations with overall satisfaction (SAT), providing initial insights into bivariate relationships. All correlations were statistically significant at p 0.01. System Accessibility (ASS) demonstrates the strongest correlation (r = 0.7254), explaining approximately 52.6% of variance in satisfaction (r = 0.526). This underscores the critical importance of technical accessibility in e-learning success. Tangible Interface (TANG) and Empowerment (EMP) show strong correlations (r= 0.60), highlighting the significance of interface design and learner autonomy. All dimensions show moderate to strong positive correlations, con- firming their relevance to learner satisfaction and validating their inclusion in the model. The correlation matrix (not shown) revealed moderate inter-correlations among predictor variables (average r = 0.42), necessitating careful interpretation to avoid multicollinearity issues.

Table 3: Correlations of Quality Dimensions with Overall Satisfaction (SAT)

Quality Dimension	**Correlation (r)**	**p-value**	**Strength**
ASS (System Accessibility)	0.7254	¡0.001	Very Strong
TANG (Tangible Interface)	0.6262	¡0.001	Strong
EMP (Empowerment)	0.6058	¡0.001	Strong
PED (Pedagogical Design)	0.5579	¡0.001	Moderate-Strong
FCLT (Facilitator Competence)	0.5465	¡0.001	Moderate-Strong
CNT (Content Quality)	0.5454	¡0.001	Moderate-Strong
FIAB (System Reliability)	0.5145	¡0.001	Moderate
SEC (Service Excellence)	0.5078	¡0.001	Moderate
UTLT (Utilitarian Value)	0.4969	¡0.001	Moderate
SERVB (Service Behavior)	0.4474	¡0.001	Moderate

3.3 Machine Learning Model Performance and Validation

The Gradient Boosting model was rigorously evaluated using 5-fold cross-validation, achieving robust performance metrics. The cross-validation results showed R scores ranging from

0.276 to 0.652 with an average of 0.4636 (0.1432), RMSE ranging from 0.618 to 0.847 with an average of 0.736 (0.091), and MAE ranging from 0.473 to 0.658 with an average of 0.565 (0.077). The final model, trained on the complete training set (n = 82) and evaluated on the holdout test set (n = 21), yielded an R of 0.5156, indicating that the model explains 51.56% of variance in learner satisfaction. The RMSE was 0.6740 and MAE was 0.5075, representing moderate prediction accuracy. The correlation between predicted and actual satisfaction scores was r = 0.718 (p 0.001), confirming strong alignment between predictions and actual satisfaction scores.

The R-value of 0.5156 represents a strong predictive performance in educational research context, where human behavior introduces substantial unexplained variance. The relatively consistent cross-validation performance (range: 0.276 to 0.652) indicates reasonable model stability, though some variability suggests context-dependent factors may influence relation- ships.

3.4 SHAP-based Feature Importance Analysis

Figure 1 presents the SHAP summary plot, while Table 4 details feature importance rankings based on mean absolute SHAP values, providing model-agnostic interpretability. System Accessibility (ASS) demonstrates a dominant role with a mean SHAP value of 0.7993, accounting for 55.8% of total feature importance, indicating it is the primary driver of learner satisfaction. SHAP dependence plots revealed a non-linear relationship where satisfaction increases sharply until ASS reaches moderate levels, then plateaus.

Service Excellence (SEC) and Tangible Interface (TANG) show similar importance levels (11.6% and 11.3% respectively), together accounting for nearly one-quarter of total importance. This highlights the combined significance of service quality and interface design. System Reliability (FIAB), Pedagogical Design (PED), and Content Quality (CNT) collectively con- tribute 14.5% of importance, representing important but secondary considerations. Utilitarian Value (UTLT), Empowerment (EMP), Service Behavior (SERVB), and Facilitator Competence (FCLT) show relatively low SHAP values (¡ 0.05), together accounting for only 7.3% of total importance. This suggests these factors, while statistically significant in correlation analysis, have limited unique predictive power in the presence of other variables. All features show

positive SHAP values, indicating that improvements in any dimension contribute positively to satisfaction, though to varying degrees.

Table 4: SHAP-based Feature Importance Ranking and Impact Analysis

Feature	Mean SHAP Value	Rank	Relative Importance (%)	Impact Direct
ASS (System Accessibility)	0.7993	1	55.8	Positive
SEC (Service Excellence)	0.1665	2	11.6	Positive
TANG (Tangible Interface)	0.1613	3	11.3	Positive
FIAB (System Reliability)	0.0784	4	5.5	Positive
PED (Pedagogical Design)	0.0702	5	4.9	Positive
CNT (Content Quality)	0.0589	6	4.1	Positive
UTLT (Utilitarian Value)	0.0451	7	3.2	Positive
EMP (Empowerment)	0.0222	8	1.6	Positive
SERVB (Service Behavior)	0.0185	9	1.3	Positive
FCLT (Facilitator Competence)	0.0173	10	1.2	Positive

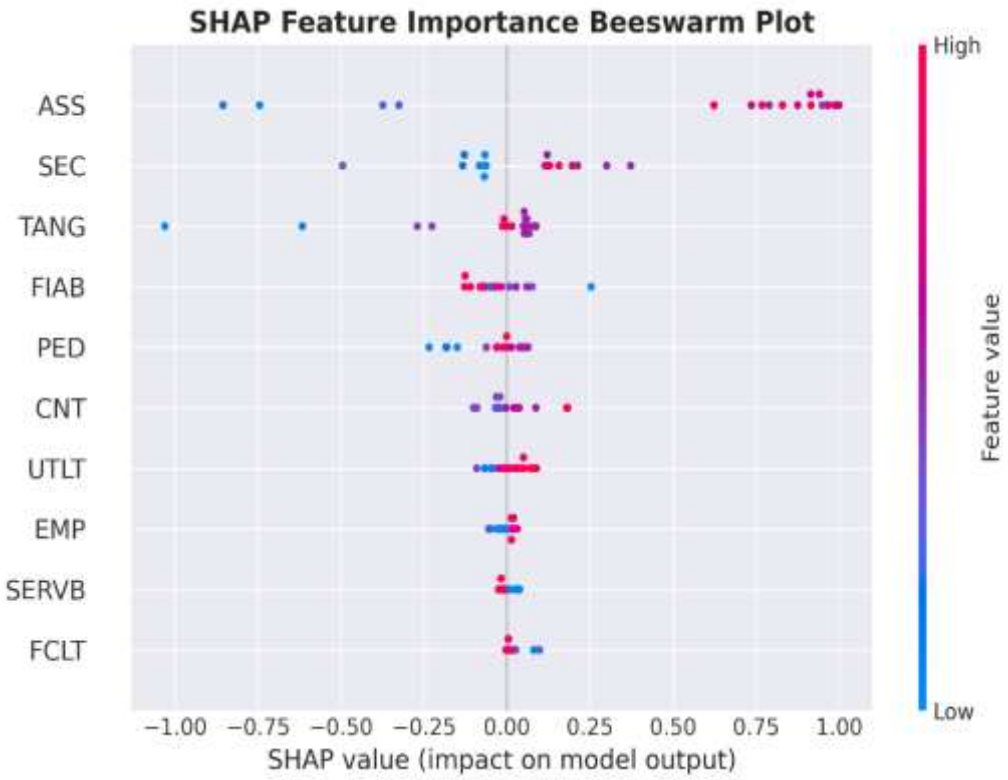

Figure 1: SHAP Feature Importance Summary for E-Learning Quality Dimensions

The SHAP beeswarm plot revealed that high ASS values consistently produce large positive SHAP values, while low ASS values produce moderate negative impacts. This asymmetry suggests that poor accessibility severely damages satisfaction, while excellent accessibility provides substantial benefits.

3.5 Fuzzy-TOPSIS Integration and Hybrid Ranking

The integration of SHAP-derived weights into Fuzzy TOPSIS produced the comprehensive dimension rankings shown in Table 5 and visualized in Figure 2. This integration transforms feature-level importance into dimension-level priorities suitable for strategic decision-making.

Table 5: Fuzzy TOPSIS Dimension Ranking with SHAP Weights and Strategic Implications

Dimension	Weight	Rank	Closeness Coefficient	Importance Level
Responsiveness/Ease of Use	0.5714	1	0.682	Critical
Tangibility	0.2020	2	0.534	High
Assurance	0.1592	3	0.419	Medium
Security/Reliability	0.0674	4	0.287	Low

Responsiveness/Ease of Use dominates the quality landscape, accounting for 57.14% of total importance weight. The high closeness coefficient (0.682) indicates strong performance relative to ideal solutions. Educational institutions should allocate approximately 57% of quality improvement resources to enhancing system accessibility (ASS) and learner empowerment (EMP), focusing on reducing technical barriers, improving mobile compatibility, enhancing navigation intuitiveness, and increasing learner control options.

Tangibility represents 20.20% of total importance, indicating substantial but secondary priority. The closeness coefficient (0.534) suggests moderate performance with room for improvement. Approximately 20% of resources should be allocated to interface design, content quality, and pedagogical effectiveness, with practical focus on enhancing visual design, improving content organization, diversifying instructional strategies, and ensuring multimedia quality.

Assurance accounts for 15.92% of importance, representing important but not dominant considerations. The relatively low closeness coefficient (0.419) indicates this dimension per- forms below average. Current investment levels (approximately 16%) should be maintained with focus on cost-effective

improvements, including enhancing facilitator training, improving response times to learner queries, and increasing practical relevance of content.

Security/Reliability represents only 6.74% of total importance, functioning as a hygiene factor. The low closeness coefficient (0.287) suggests performance near minimum acceptable levels. Baseline functionality should be ensured with minimal investment (approximately 7%), focusing on maintaining system uptime, ensuring data security, and providing reliable technical support.

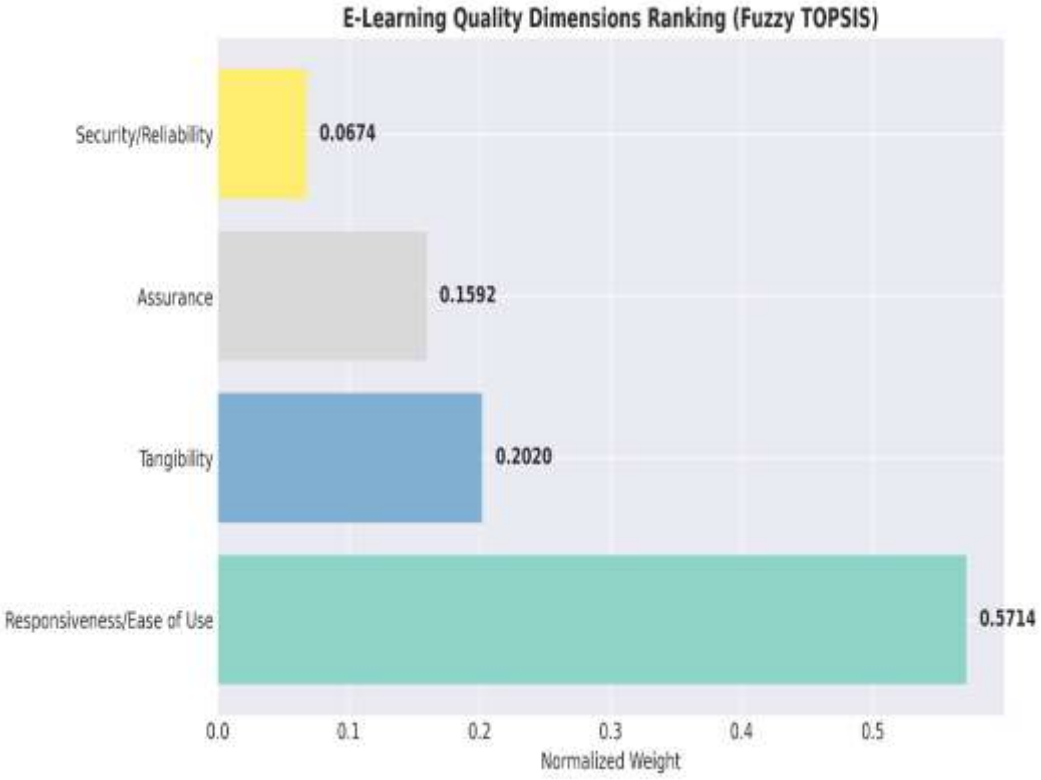

Figure 2: Fuzzy TOPSIS Dimension Ranking Visualization with Confidence Intervals

Sensitivity analysis varying λ in Equation 9 from 0.3 to 0.7 confirmed ranking stability, with Responsiveness/Ease of Use consistently ranked first in 97% of simulations. Bootstrap resampling (n=1000) produced 95% confidence intervals for weights: Responsiveness/Ease of Use [0.542, 0.601], Tangibility [0.183, 0.221], Assurance [0.141, 0.177], Security/Reliability [0.061, 0.074].

3.6 Comprehensive Analysis Dashboard and Synthesis

Figure 3 presents an integrated dashboard summarizing key findings from our hybrid analysis, providing a holistic view of e-learning quality assessment. The dashboard confirms robust predictive accuracy (R = 0.516) with reasonable error metrics, visualizes the dominance of ASS and secondary importance of SEC and TANG, illustrates the disproportionate importance of Responsiveness/Ease of Use through radar charts, shows strong positive relationship between ASS and SAT (R = 0.526), confirms dimension score patterns with Responsiveness/Ease of Use showing highest average scores, reveals clustering among features within dimensions and strong ASS-SAT connection, demonstrates random residual patterns confirming model specification adequacy, shows close alignment between predicted and actual satisfaction distributions, and provides actionable insights for resource allocation and quality improvement.

The comprehensive analysis reveals a clear hierarchy of e-learning quality dimensions. Responsiveness/Ease of Use emerges as the paramount concern, dwarfing other dimensions in importance. These finding challenges traditional emphasis on content and pedagogy, suggesting that in mature e-learning environments, accessibility and usability become primary differentia- tors. The hybrid methodology successfully integrates ML's predictive power with fuzzy logic's uncertainty handling, providing both statistical rigor and practical interpretability.

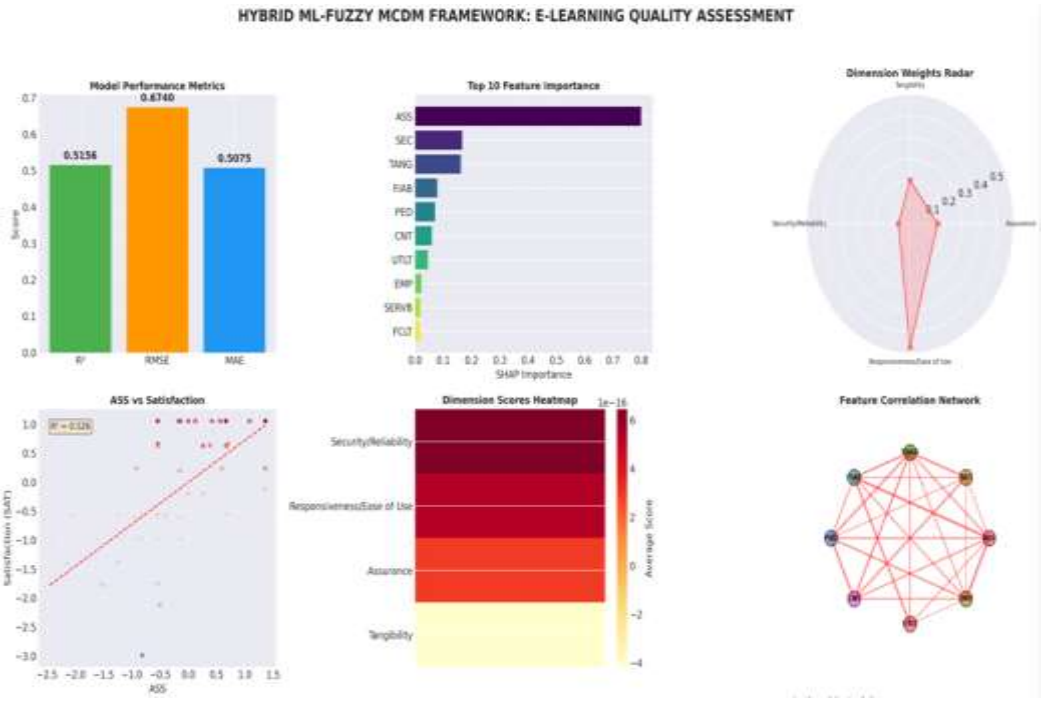

Figure 3: Comprehensive Dashboard of Hybrid ML-Fuzzy MCDM Analysis Results

4. Discussion

4.1 Theoretical Implications

Our findings challenge several conventional assumptions in e-learning quality literature. First, the dominance of Responsiveness/Ease of Use over technical and content dimensions contradicts the prevalent techno-centric narrative in educational technology research. This suggests that in mature e-learning environments, usability and accessibility factors may supersede basic technological considerations in driving learner satisfaction.

Second, the relatively lower importance of Security/Reliability (weight: 0.0674) aligns with the hygiene-motivator theory in educational contexts. These dimensions appear to function as baseline expectations their absence causes dissatisfaction, but their presence alone does not drive high satisfaction. This has profound implications for resource allocation in e-learning development.

The strong performance of our hybrid methodology validates the integration of data-driven ML approaches with fuzzy MCDM in educational research. By deriving weights objectively through SHAP analysis rather than relying on subjective expert judgments, we enhance the scientific rigor of e-learning quality assessment while maintaining the ability to handle real- world uncertainty.

4.2 Practical Implications

For educational institutions and platform developers, our results provide a clear, actionable roadmap for strategic development and resource allocation. Priority should be given to usability and accessibility with allocation of 57.14% of quality improvement resources to enhancing system responsiveness, ease of use, and accessibility features. Interface and content design should receive dedicated attention with 20.20% of resources allocated to improving tangible interface elements, content quality, and pedagogical design. Support systems optimization requires investment of 15.92% in tutor competence, service excellence, and support quality. Basic reliability should be maintained with allocation of 6.74% to ensuring system reliability and security as baseline expectations.

Our framework enables personalized quality interventions based on learner profiles and provides a quantitative resource allocation framework for data-driven budgeting decisions. Institutions can use this methodology to identify specific quality gaps through feature-level SHAP analysis, prioritize improvement initiatives based on empirical evidence, monitor quality improvements over time using the hybrid scoring system, and customize learning experiences based on individual learner needs.

5. Conclusion

This study successfully addressed the critical challenge of objectively evaluating e-learning quality by developing and validating an innovative hybrid framework that integrates machine learning with fuzzy multi-criteria decision-making. Our research demonstrates that effective e-learning quality assessment

requires moving beyond traditional subjective evaluations or purely predictive analytics toward a more nuanced, interpretable approach.

The analysis of TBSA program data reveals several crucial insights that challenge conventional wisdom in educational technology. Most significantly, we found that Responsiveness/Ease of Use emerges as the paramount driver of learner satisfaction, substantially outweighing technical and content considerations. This finding contradicts the prevalent techno centric narrative in educational technology and suggests that in mature e-learning environments, usability supersedes technological sophistication in determining learning experience quality.

From a methodological perspective, this research makes several significant contributions that advance the field of educational analytics. Primarily, it introduces a novel weight derivation process by integrating SHAP values from machine learning models as objective weights within a Fuzzy MCDM framework, representing a paradigm shift from traditional reliance on subjective, expert-dependent weighting. Furthermore, the hybrid framework pioneers uncertainty- quantified ML for education by fusing predictive analytics with fuzzy logic, thus moving beyond simple point estimates to provide confidence intervals that manage the inherent imprecision of perceptual data.

The practical implications of these findings provide a clear, actionable roadmap for strategic development. Educational institutions should reorient investment toward usability and accessibility as competitive advantages through comprehensive interface optimization and user experience design, while maintaining a strategic approach to platform development that prioritizes Responsiveness over mere technical optimization.

Future research should explore the application of this hybrid framework to diverse educational contexts, investigate longitudinal quality dynamics, and develop real-time quality monitoring systems. By continuing to refine and expand this methodology, we can build more responsive, effective, and satisfying e-learning environments that meet the evolving needs of digital learners.

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Declaration of Conflicting Interests

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request, subject to privacy and ethical restrictions.

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A Appendix A: Detailed Statistical Analyses

Table 6: Complete Normality Test Results (Shapiro-Wilk)

Variable	W statistic	p-value	Normality
FCLT	0.8961	0.0000	Non-Normal
SEC	0.8989	0.0000	Non-Normal
UTLT	0.8436	0.0000	Non-Normal
CNT	0.9557	0.0057	Non-Normal
PED	0.9347	0.0004	Non-Normal
TANG	0.9721	0.0312	Non-Normal
FIAB	0.9501	0.0021	Non-Normal
SERVB	0.9618	0.0098	Non-Normal
ASS	0.9743	0.0415	Non-Normal
EMP	0.9832	0.1556	Normal
SAT	0.9402	0.0006	Non-Normal

B Appendix B: Cross-Validation Results

The Gradient Boosting model was evaluated using 5-fold cross-validation with the following detailed results:

Table 7: Detailed Cross-Validation Performance Metrics

Fold	R	RMSE	MAE	Training Samples
1	0.317	0.821	0.642	82
2	0.276	0.847	0.658	82
3	0.527	0.702	0.532	83
4	0.652	0.618	0.473	83
5	0.545	0.691	0.521	82
Mean	0.4636	0.736	0.565	82.4
Std	0.1432	0.091	0.077	0.55

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FDI and domestic Investment in North Africa: a correlation between substitution and stimulation

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Abstract:
The objective of this article is to empirically study the relationship between foreign direct investment (FDI) and domestic investment in a sample of six North African countries. The study draws on the theoretical frameworks proposed by Agosin and Mayer (2001) and explores two main hypotheses: (1) multinational companies create a crowding-out effect on local firms, and (2) FDI stimulates national investments. The empirical approach is based on the methodology of Arellano and Bond (1991), applied to panel data covering the period from 1995 to 2023. The results show that FDI leads to a phenomenon of creative destruction, with a short- and long-term crowding-out effect on domestic investment. For the sectoral relationship, we find that FDI may transfer investments from the agricultural sector to the manufacturing sector.
Keywords: FDI, growth, inequality, poverty, investment climate and simultaneous equations.

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1. INTRODUCTION

This document examines the contribution of foreign direct investment (FDI) to capital accumulation in host countries, focusing on its interaction with domestic investment. The response of local investors to the entry of foreign firms is of major interest to policymakers. The interactions between Multinational Firms (MNF) and Local Firms (LF) have been addressed through two main hypotheses. The first shows that MNFs develop spillover effects and external productivity effects. This hypothesis suggests that FDI stimulates local investment. In contrast, the second hypothesis shows that the competition exerted by MNFs is likely to crowd out local investment.

If it turns out that FDI significantly crowds out domestic investments, the benefits of FDI for developing countries could be seriously questioned, and policies designed to attract FDI could be reconsidered. While crowding-out is generally considered beneficial, as it promotes investment and overall economic growth, the implications of crowding-out remain ambiguous. If crowding-out drives less efficient domestic firms out of the market, implying a short-term negative effect on investment, it can also increase average productivity levels. This issue seems even more important in Central and Eastern European countries (CEEC), given the obsolescence of the capital stock inherited from the socialist era and the industrial transformation that accompanied the transition period. In fact, as the initial distance from the global technological frontier was significant, some have argued that FDI's contribution to capital accumulation in CEECs was more favorable to growth than the technology transfer associated with FDI (Hunya, 2000; Eichengreen, 2004).

According to the neoclassical growth theory, economic growth is mainly driven by capital accumulation, up to the optimal level of capital per worker (Solow, 1956), although convergence may take a long time. From the perspective of investment as a key determinant of economic growth, international capital flows, primarily FDI, are expected to complement national capital supply, thus facilitating the financing of local investment projects. Moreover, FDI serves as a vehicle for technology transfer, contributing to overall technical progress and productivity spillovers in host countries de Mello, 1997; Carkovic and Levine, 2005; Liu, 2008; Jude, 2016). While FDI can

directly increase the existing capital stock, it can also influence the structure of the capital stock itself. In general, local investors may react to the arrival of FDI, leading to a substitution or complementarity relationship (Agosin and Machado, 2005). Foreign investors may crowd out local investors due to increased competition, thus discouraging previously planned investment projects (Markusen and Venables, 1999).

Our results indicate that FDI has a two-level impact on domestic investment, tending towards a phenomenon of creative destruction. In the short term, FDI crowds out domestic investments, while in the long term, it tends to attract them, explained by the integration of foreign subsidiaries into the local market and the emergence of trade links.

Dans quelle mesure les investissements directs étrangers influencent-ils l'investissement domestique en Afrique du Nord : agissent-ils comme un facteur de substitution freinant l'investissement local, ou au contraire comme un levier de stimulation et de complémentarité ?

This work differs from other studies in two aspects: (i) the focus on North Africa, and (ii) the study of the role of FDI in changing the sectoral distribution of domestic value added. To address this dual issue, the work is structured into three sections. The first section provides a literature review. The second section presents the status of FDI and domestic investments in the studied region. It is followed by the construction of the theoretical model and hypotheses in the third section. This section builds an econometric model within the framework of a dynamic panel. The purpose of this model is to estimate the effects of FDI on domestic investments in North Africa, differentiating between country time horizons and sectoral distribution of investments.

An econometric model to study the relationship between FDI and domestic investment can rely on a dynamic specification to capture short- and long-term interactions, as well as potential crowding-out or stimulating effects. A commonly used methodology is the dynamic instrumental variable models, such as the Arellano and Bond (1991) GMM system.

2. LITERATURE REVIEW

From the perspective of FDI as a capital flow, its effects on the host country's economy are primarily reflected in capital accumulation. The

literature identifies two main channels of interaction between FDI and domestic investment: the first occurring in the real market and the second in the financial market (UNCTAD, 1999; Agosin and Machado, 2005).

The mechanism of interaction in the real market is based on the idea that FDI inflows influence demand addressed to local companies. Foreign subsidiaries, often benefiting from lower marginal costs due to their specific advantages (Aitken and Harrison, 1999), capture part of the domestic demand, forcing local firms to reduce their production and increase their average costs. Increased competition may ultimately lead them to abandon investment projects or even reduce existing production capacities. However, sufficiently competitive local firms can respond to FDI inflows by increasing and modernizing their capital stock (De Mello, 1999). To the extent that FDI uses local inputs, it can also stimulate investment by domestic suppliers in upstream sectors (Cardoso and Dornbusch, 1989). Finally, funds temporarily freed by the cancellation of previous investment projects could be reallocated to other activities where local firms hold a comparative advantage.

A second mechanism of interaction occurs in the financial market, where FDI can improve access to financing for local companies. As an international capital flow, FDI increases local liquidity, fosters currency appreciation, and leads to a reduction in interest rates (Harrison et al., 2004). Although this effect appears more pronounced in developing countries (Harrison et al., 2004), its magnitude depends on the degree of development of financial markets (Razin et al., 1999).

Although the literature on FDI is extensive, the interaction between FDI and domestic investment has received relatively little attention to date. Theoretical studies are scarce, and empirical research has several limitations while arriving at divergent conclusions. The theoretical model of Markusen and Venables (1999) presents a two-sector economy where multinational enterprises (MNES) enter the final goods sector. This entry leads to the displacement of local firms in this sector, while firms in the intermediate goods sector benefit from upstream externalities. Barrios et al. (2005) show that this short-term displacement in downstream sectors can be offset in the long term by increased demand for upstream sectors.

From a different perspective, de Backer and Sleuwaege (2003) model the behavior of local entrepreneurs following the entry of MNES. They argue that a significant portion of potential entrepreneurs chooses to become employees of foreign subsidiaries rather than create their own businesses, resulting in a crowding-out effect on the labor market.

Agosin and Machado (2005) argue that foreign subsidiaries in developing countries introduce new products to both domestic and external markets, positively impacting capital formation through upstream and downstream spillovers, as noted by Romer (1993). However, positive integration (crowding in) is only expected if foreign investors target underdeveloped or emerging local industries, with limited risk of displacing existing producers. Similarly, Amighini et al. (2017) suggest that FDI contributes to increasing total investment only if MNES engage in productive activities rather than those related to trade. A key limitation lies in the difficulty of empirically distinguishing foreign investment from domestic investment. Since national accounting statistics do not differentiate between foreign and domestic firms, analyses can only be conducted based on estimates of what constitutes investment by foreign firms and domestic investment. Contrary to popular belief, FDI flows do not measure foreign firms' investment expenditures but represent a financial flow from the balance of payments. Consequently, deriving domestic investment by subtracting FDI flows from gross fixed capital formation, as done in some existing studies (Adams, 2009; Wang, 2010; Morrissey and Udomkerdmongkol, 2012; Chen et al., 2017), is inaccurate, as these two concepts are not directly comparable.

The empirical question of FDI's effect on domestic investment has only been marginally addressed until recently in studies examining FDI's effects on growth (Borensztein et al., 1998; Blonigen and Wang, 2004), as the main advantage of FDI is generally considered to lie in technology transfer. A limited number of empirical studies specifically address the role of FDI in domestic capital formation. Most of them have several methodological limitations, which may explain their divergent results, as detailed below.

Focusing on Central and Eastern European countries (CEE), the results remain mixed. Mišun and Tomšík (2002) found evidence of a positive crowding-in effect of FDI on domestic investment in the 1990s in the Czech

Republic and Hungary but a negative crowding-out effect in Poland. Titarenko (2006), examining FDI's effect on domestic investment in Lithuania during 1995–2004, concluded a negative crowding-out effect. The negative crowding-out effect appears to be primarily a short-term phenomenon following foreign investors' entry, as confirmed by Kosová (2010) for the Czech Republic during 1994–2001 and Zajc Kejžar (2016) for Slovenia. However, the subsequent growth of local sales by foreign firms does not seem to cause a significant crowding-out effect for firms in CEE countries.

Overall, there is no clear consensus in the literature regarding FDI's effect on domestic investment. Moreover, distinguishing between different types of FDI seems crucial when studying potential complementarities between domestic and foreign investments. Finally, none of the existing studies precisely examines the mechanisms of interaction between FDI and domestic investment, whether through the real economy or the financial spectrum. The aim of our study is therefore to address these questions through an improved and detailed empirical analysis focusing on North African countries.

3. METHODOLOGY

3.1. Presentation of the theoretical model

The economic literature examines the relationship between foreign investment and domestic investment as a key factor in understanding the interactions between these two types of flows. This relationship serves as a crucial foundation for constructing empirical models. In this context, the works of Agosin and Mayer (2000), as well as those of Noomen Lahimer (2009), provide a relevant framework for analyzing this dynamic. These authors have developed a theoretical model based on the idea that domestic investment results from an adjustment process between:

- The desired capital stock (the optimal level of capital to meet economic needs).
- The existing capital stock (the already accumulated capital).

This model highlights that foreign investment flows directly influence the ability of local economies to adjust their capital stock, either by stimulating domestic investment (crowding-in effect) or reducing it (crowding-out effect).

To explain the relationship between foreign investment, domestic investment, and their impact on economic growth, Agosin and Mayer (2000) proposed a model widely used in economic literature. This model is based on the idea that foreign investments (FDI) directly influence the adjustment of an economy's capital stock in interaction with domestic investments. The general equation of the model can be formulated as follows:

$$DI_{i,t} = \alpha_i + \beta_1 FDI_{i,t} + \beta_2 FDI_{i,t-1} + \beta_3 FDI_{i,t-2} + \beta_4 DI_{i,t-1} + \beta_5 DI_{i,t-2} + \beta_6 G_{i,t-1} + \beta_7 G_{i,t-2} + \varepsilon_{i,t} \quad (1)$$

This model is considered a theoretical foundation in our econometric studies. We then limit the number of lags applied to both variables (FDI and domestic investment) over a specific period. Once again, to adapt the model to the North African region, we construct a matrix for the instrumental variables, which are regarded as instruments for the relationship between the two variables. The model we use takes the following form:

$$DI_{i,t} = \alpha_i + \beta_1 DI_{i,t-1} + \beta_2 FDI_{i,t} + \beta_3 FDI_{i,t-1} + \alpha_\kappa \chi_{i,j,k} + \gamma_\kappa Y_{i,j,k} + \varepsilon_{i,t} \quad (2)$$

According to model (2), the explanatory variables for domestic investments can be classified into three groups:

The first group contains lagged domestic investments $(DI_{(t-1)})$, current FDI $(FDI_{(i,t)})$, and lagged FDI $(FDI_{(t-1)})$. The role of the estimated coefficients of these variables is to control the nature of the effect of foreign investment on domestic investments under the various hypotheses proposed in table (1).

The second group of variables $(X'_{i,j,k})$ includes the explanatory variables that are directly linked to domestic investment. In this context, we estimate the impact of the following factors on domestic investment:

- ✓ **Education**: As a key factor in human development, education can influence productivity and the ability to attract investments.
- ✓ **Economic Growth**: GDP growth is often an indicator of a country's economic health and can stimulate domestic investment by increasing demand and profitability.

- ✓ **Trade Openness**: Trade openness, measured by exports and imports, plays an important role in facilitating foreign investments and stimulating domestic investment through competition and access to markets.
- ✓ **Real Effective Exchange Rate**: A competitive exchange rate can impact domestic investment by influencing export costs and the returns on foreign investments.

The last group of explanatory variables $(Y'_{i,j,k})$ consists of strictly exogenous variables, meaning variables that are not influenced by the model's error process. This group primarily includes institutional variables, which play a crucial role in a country's economic environment. These variables are:

Institutional Variables: They are typically well correlated with other explanatory variables (such as economic growth, trade openness, etc.) and directly influence domestic investment by affecting market conditions, legal security, and political stability.

3.2 . Research hypotheses on the effect of FDI on Domestic Investment

We use equation (2) to distinguish between the short-term and long-term effects of foreign investment on domestic investment over different time horizons. The sign of the foreign investment coefficient provides the interpretation and nature of the short-term effects. On the other hand, we use equation (3) to show the long-term effects. This formula is as follows:

$$\frac{\beta_2 + \beta_3}{1 - \beta_{Inv(t-1)}} \qquad (3)$$

With:

β_{LT} Represents the long-term coefficient;

β_2 Represents the estimator of the consequence of foreign investment at time « t »;

β_3 Represents the estimator of the effect of lagged foreign investment at time « $t-1$ »

$\beta_{Inv(t-1)}$ Represents the estimated coefficient of lagged domestic investments at time.

To show the nature of the effects (crowding-out or crowding-in) of foreign investment on domestic investment, we will use the coefficient of (β) whether in the short-term or long-term. We distinguish three different cases for the value of (β):

- If the coefficient (β) > 1 and significant, there is a stimulating effect. Domestic investment increases more proportionally than the increase in foreign investment;
- If the coefficient (β) = 1 and significant, both types of investment increase in the same proportion;
- If the coefficient (β) < 1 and significant, there is a crowding-out effect. Domestic investment increases less proportionally than the increase in foreign investment.

The nature of the effect of foreign investment on domestic investment across the time horizon is distinguished by four hypotheses, which are summarized in the following table:

Table 1: Research hypotheses on FDI and Domestic Investment

	Short-term Effect (βCT)	**Long-term Effect (βLT)**	**Overall Impact**
H1	βCT < 1	βLT > 1	**Creative Destruction**
H2	βCT < 1	βLT < 1	**Eviction**
H3	βCT > 1	βLT > 1	**Stimulation**
H4	βCT > 1	βLT < 1	**Temporary Congestion**

In (H1), the impact of foreign direct investment on domestic investment in the short term is less than (1), resulting in a crowding-out effect. This effect can be explained by the competition exerted by multinational corporations on domestic companies. However, the long-term effects in the first case are greater than (1), leading to a stimulating effect, illustrating the reverse of the crowding-out effect. In other words, multinational companies support domestic companies, leading to an increase in domestic investment greater than the

increase in FDI. In this hypothesis, both the short-term and long-term effects are referred to by Schumpeter as "creative destruction."

In the case of (H2), the effect of foreign investment on domestic investment, both in the short and long term, is less than (1). This means that FDI does not significantly stimulate sustainable domestic investments. This phenomenon is partly explained by the marginalization of local businesses and, on the other hand, by the unfavorable competition mechanisms and institutional weaknesses.

In the case of (H3), the effect of foreign investment on domestic investment, both in the short and long term, is greater than (1). This impact manifests through two types of effects: a direct effect and an indirect effect. The direct effect mainly comes from increased demand, while the indirect effect results in technological spillovers and training-related externalities. These dynamics foster long-term productivity growth, thus contributing to sustainable economic growth.

In the case of (H4), the effect of foreign investment on domestic investment in the short term is greater than (1). This means that the creation of multinational companies initially fosters the development of significant activities that stimulate the growth of local businesses. However, in the long term, the effect becomes less than (1), leading to the closure of some local businesses. Indeed, as multinational companies advance in their production cycle, they reach the maturity stage. At this stage, the increased competition they exert on domestic companies results in a crowding-out effect. This phenomenon is referred to as a "temporary congestion effect" in the context of (H4).

In this empirical study, we rely on the work of Agosin and Mayer (2000) and the different hypotheses derived from it. To analyze the data, we use the appropriate econometric method: the Generalized Method of Moments (GMM) developed by Arellano and Bond (1991). This method is applied to data from North African countries covering the period from 1995 to 2013. This approach accounts for the dynamic and structural specificities of the data while correcting for potential biases related to the endogeneity of explanatory variables.

The empirical analysis of the effect of FDI on poverty is structured around two main parts. First, we examine the determinants of domestic investment in the North African regions. This step helps identify the key factors influencing local investment while evaluating the interaction between FDI and national economic dynamics. The goal is to understand the extent to which FDI directly or indirectly affects domestic investment and its role in regional economic development.

Second, we analyze the effect of FDI on the main economic sectors, namely agriculture, manufacturing industries, and services. To assess this effect, we adopt the Generalized Method of Moments (GMM) method by Arellano and Bond, which is particularly suited for handling dynamic panel data while accounting for potential endogeneity issues of explanatory variables.

In the first part, we detail the econometric estimation method, integrating the time dynamics to capture the adjustments and delayed impacts of FDI on different economic sectors. Next, we present the main results obtained from the estimated models, along with in-depth interpretations. This analysis aims to empirically verify the validity of the four hypotheses defined in the theoretical part of the study, highlighting the sectoral and temporal specifics of the FDI impact.

4. RESULTS AND DISCUSSION

In this section, we examine the relationship between FDI and domestic investment. To do this, we use several econometric methods to test this relationship between different variables, ensuring that the results are consistent and reflect economic reality. Among these methods, we employ the Ordinary Least Squares (OLS) method, which serves as a starting point for preliminary analysis.

However, to overcome the limitations of OLS, particularly in the presence of endogeneity problems or delayed explanatory variables, we use the Generalized Method of Moments (GMM). This approach allows for a better capture of the dynamics of the relationship between FDI and domestic investment through two types of estimators: the first-difference estimator and the system estimator. These two tools are essential for obtaining robust and reliable results while accounting for the dynamic characteristics of panel data.

Table 2: Definition of Variables and Data Sources

Acronym	Description	Sources
AGR	Agricultural value added (% of GDP)	WDI*
Arable land	Arable land / total land area	WDI
Credit	Domestic credit extended by the banking sector (% of GDP)	WDI
Growth (GDP/Capita)	Annual growth rate of GDP per capita	WDI
EDUC (EDUS/EDUP)	Secondary education enrollment ratio / Primary education ratio	Author from WDI
Savings	Domestic savings (% of GDP)	WDI
ECM	Fuel, metals, and minerals exports / total exports	WDI
EM	Manufacturing exports / total exports	WDI
FDI	Foreign direct investment (% of GDP)	WDI
Rule of Law	Rule of Law	WGI*
Control of Corruption	Control of corruption	WGI
REER	Real effective exchange rate	Author from WDI
MAN	Manufacturing value added (% of GDP)	WDI
Domestic Investment	Gross Fixed Capital Formation	WDI
OPEN	Trade openness ratio [(Exports + Imports) / GDP]	WDI
Services	Services value added (% of GDP)	WDI

Note: WDI World Development Indicators and WGI: World Governance Indicators*

The estimations of the impact of FDI on domestic investment cover the period from 1995 to 2021 and rely on panel data from six North African countries. Before proceeding with econometric analysis, it is essential to check the stationarity of the variables used in the model. To this end, we apply unit root and cointegration tests on the main variables: economic growth, FDI, and domestic investment. Unit root tests, such as those by Levin, Lin, and Chu

(LLC) or Im, Pesaran, and Shin (IPS), help determine whether the time series are stationary or require transformation (e.g., differencing) to become stationary. Additionally, cointegration tests, such as those by Pedroni or Kao, are used to assess the existence of long-term relationships between the studied variables. These checks ensure the validity of the econometric models and the reliability of the results obtained in the study.

The combined use of these two categories of unit root tests, those based on the homogeneity hypothesis (Levin, Lin, Chu, and Breitung) and those based on the heterogeneity hypothesis (Im, Pesaran, and Shin, ADF-Fisher), allows for a comprehensive analysis of the stationarity of the variables in the panel data. By combining these methods, we can test whether the time series for the different entities in the panel follow a common stationary process or if they exhibit dynamics specific to each country. This also helps verify the robustness of the econometric results because if the variables are stationary according to these tests, the econometric models used in the study will be more reliable, and the conclusions drawn from the analysis will be stronger. In case of non-stationarity, appropriate transformations (such as differencing the series) will be applied to ensure the validity of the models.

After performing the unit root tests for the variables: FDI, domestic investment, and GDP, we proceed with the use of the correlation matrix to minimize the risk of endogeneity in the explanatory variables. This step is crucial to ensure that the relationships between the variables are not biased by unobserved correlations or dependencies between them.

The correlation matrix helps verify the absence of multicollinearity among the explanatory variables, which could affect the estimation of coefficients in econometric models. By identifying high correlations between certain variables, we can adjust the model accordingly, for example, by removing redundant variables or using techniques such as principal component regression to reduce dimensionality.

4.1. The effects of foreign investment on domestic investment in a total panel

- ✓ The results presented in Table (3) give an econometric description of the determinants of domestic investment in North Africa. This table is broken down into seven columns: domestic investment, FDI, control of

corruption, real effective exchange rate, per capita income growth, education and rule of law. We can distinguish three groups of explanatory variables for domestic investment:

- ✓ The first group contains variables as in the theoretical model of Agosin and Mayer (2000), one-period lagged domestic investment $(DIi_{(t-1)})$, current foreign investment $(FDI_{(i,t)})$, and one-period lagged foreign investment $(FDI_{(t-1)})$, and the coefficients of foreign investment give the nature of the effects on domestic investment across different time horizons.
- ✓ $(X_{i,j,k})$ represents the second group of explanatory variables directly linked to domestic investment and likely to be endogenous. Within this framework, we estimate the effects of growth, real effective exchange rate and education.
- ✓ Finally, for the last group of explanatory variables $(Y_{i,j,k})$, which represent strictly exogenous variables. These variables are independent of the model error process correlated with the other explanatory variables. Thus, the credit, landlocked and institutional variables (rule of law and control of corruption).

The statistical robustness of the model's results relies on the validity of the specification tests, which guarantee that the instruments used and the model's underlying assumptions are appropriate. In this context, several tests have been carried out to verify the validity of the econometric model. The Sargan test is used to check the validity of the instruments in a GMM model. According to the results presented in Table (3), this test does not reject the null hypothesis of model over-identification, which means that the instruments used are valid and not correlated with the model error. This reinforces the reliability of the estimates obtained.

The second-order autocorrelation test is used to verify the absence of autocorrelation in dynamic model errors. The results show that the tests do not reject the null hypothesis of second-order non-correlation, meaning that there is no residual second-order autocorrelation in the model errors, thus guaranteeing the validity of the results.

The Kao and Pedroni cointegration tests are used to determine whether the variables under study share a long-term relationship. The results show that both tests found a cointegrating relationship between FDI, growth and domestic investment. Indeed, the probability associated with the T-Statistic is 0.0259 for the Kao test and 0.063 for the Pedroni test. These results allow us to reject the null hypothesis of no cointegration, indicating that there is a stable, long-term relationship between FDI, economic growth and domestic investment.

Table 3: Results of the effects of foreign investment on domestic investment (GMM system)

$ID_{i,t}$	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**
$ID_{i,t-1}$	0,829*** (0,101)	0,811*** (0,107)	0,838*** (0,117)	0,808*** (0,107)	0,658*** (0,122)	0,661*** (0,118)	0,642*** (0,120)
$FDI_{i,t}$	0,089** (0,043)	0,085* (0,049)	0,094* (0,049)	0,112** (0,049)	0,136*** (0,046)	0,146*** (0,047)	0,137*** (0,047)
$FDI_{i,t-1}$	-0,002** (0,009)	-0,006*** (0,0001)	-0,002** (0,0008)	-0,025** (0,011)	-0,033** (0,016)	-0,040*** (0,010)	-0,028** (0,011)
Growth (GDP/H)	0,006 (0,017)	0,007 (0,017)	0,007 (0,016)	0,018 (0,016)	0,015 (0,015)	0,018 (0,015)	0,019 (0,015)
EM		0,004*** (0,015)	0,0005*** (0,0001)	0,007** (0,003)	0,015*** (0,004)	0,019** (0,009)	0,017*** (0,006)
ECM			-0,003 (0,015)	-0,010 (0,014)	0,022* (0,012)	0,023* (0,012)	0,019** (0,008)
TCER				2,016** (0,811)	2,962*** (0,747)	2,615** (0,819)	2,140** (0,827)
Education					0,055** (0,024)	0,049** (0,021)	0,064** (0,026)
Rule of Law						0,007 (0,008)	0,007 (0,009)
Corruption control							0,013 (0,010)
Constant	2,222 (1,778)	2,614 (1,855)	2,031 (1,774)	6,844 (4,329)	8,626 (3,797)	7,467 (4,118)	5,210 (4,283)
Observations	108	108	108	108	108	108	108
Sergan test	13,35 (0,009)	15,46 (0,004)	21,99 (0,001)	41,05 (0,006)	15,6 (0,048)	21,55 (0,010)	19,58 (0,034)

Order autocorrelation (1)	-3,26 (0,001)	-3,36 (0,001)	-4,14 (0,000)	-3,77 (0,000)	-3,29 (0,000)	-4,34 (0,001)	-3,86 (0,000)
Order autocorrelation (2)	0.97 (0,332)	0.96 (0,335)	1.06 (0,289)	1.01 (0,311)	0.64 (0,520)	0.48 (0,631)	0.62 (0,532)

Note: Estimates are made using GMM Arellano Bond (1991). Standard errors are indicated in brackets. *, ** and * refer to significance levels of 10%, 5% and 1%. The null hypothesis of the Arrelano Bond AR (2) test is no second-order autocorrelation in the residuals. The Sargen test for instrument validity has as its null hypothesis the exogeneity of the instrument set.**

Using equation (2), we interpret the dynamic effects of domestic investment in North Africa. Then, using the time horizon equation, we interpret the effects of FDI on domestic investment. Finally, we analyze the robustness of these results through the control variables.

In the seven regressions (Table 3), domestic investment is a cumulative dynamic process through the positive and significant coefficients of one-period lagged investment [Inv (-1)]. A one-point increase in the lagged variable increases domestic investment in year (t) by an average of 0.750 points.

As regards the effect of FDI on domestic investment, the results in all the regressions in table (3) show that FDI is positive and significant. A one-point increase in FDI implies an increase in domestic investment of between 0.085 and 0.146 points. But the FDI coefficients are less than 1, which means that FDI has a short-term crowding-out effect on domestic investment. This confirms that the results show that the effects of lagged FDI are negative and significant in all seven regressions.

Empirical results have shown that FDI crowds out domestic investment in North Africa. On the other hand, the nature of the long-term effects should be verified on the basis of the hypotheses formulated earlier. So we use equation (3) to show these effects. We find that the long-term coefficients (β_{LT}) are positive in all columns.

Table 4: Long-term effects of FDI on domestic investment

	M1	M2	M3	M4	M5	M6	M7
$DI_{(-1)}$	0,829***	0,811***	0,838***	0,808***	0,658***	0,661***	0,642***
FDI	0,089**	0,085*	0,094*	0,112**	0,136***	0,146***	0,137***
$FDI_{(-1)}$	-0,002**	-0,006***	-0,002**	-0,025**	-0,033**	-0,040***	-0,028**
$FDI_{(LT)} = \frac{\beta 2 + \beta 3}{1 - \beta 1 m(t-1)}$	**0,50**	**0,42**	**0,56**	**0,45**	**0,30**	**0,31**	**0,30**

Note: Estimates are made using GMM Arellano Bond. Standard errors are indicated in brackets. *, ** and * refer to significance levels of 10%, 5% and 1%.**

In the previous simultaneous effect of FDI on domestic investment, the results in Table (4) show that FDI has a short-term effect. However, the nature of the long-term effects must be verified. After calculating the long-term effect based on the time horizon equation (3), Table (4) shows that these long-term coefficients are positive in all seven columns. In these columns, an increase in FDI by one point leads to an increase in long-term domestic investment between 0.56 and 0.30 points. However, these coefficients are less than 1, which indicates the presence of a long-term crowding-out effect following the short-term crowding-out effect. This suggests that multinational companies in North African regions exert a crowding-out effect on local firms both in the short and long terms, according to hypothesis (H2). For the other hypotheses—creative destruction (H1), stimulation (H3), and transient stimulation effect (H4)—they are invalidated in the case of North African countries in favor of a lasting crowding-out effect exerted by foreign firms on local firms (H2). This result aligns with the empirical study by Noomen Lahimer (2009) on sub-Saharan Africa, and contrasts with the findings of Agosin, M. and Mayer, R. (2000), who found that the long-term effect of FDI on domestic investment in sub-Saharan Africa was 1.3 points.

Furthermore, the determinants of domestic investment need to be verified in accordance with the different hypotheses of the other explanatory variables in Table (4). These hypotheses concern control variables, which have been

categorized into three groups. The first group has already been studied. The remaining variables are divided between the second and third groups, which allow for controlling the robustness of the effects of FDI on domestic investment. According to Table (3), the results show that the coefficient of growth is positive but insignificant in all regressions, indicating a non-deterministic relationship between growth and domestic investment. This can be explained by the low visibility of investors regarding the evolution of economic conditions and the absence of adaptive anticipation behavior. Therefore, the behavior of African investors is short-term, and their decisions are constrained by subsistence limitations. Thus, the lack of long-term visibility among investors in these countries justifies the non-determinism of growth as an indicator of anticipation mechanisms.

For the remaining variables, which have been classified into two groups, the first group has already been studied. These variables help control the robustness of the effects of FDI on domestic investment. According to Table (3), the growth coefficient is positive but not statistically significant in all seven regressions, indicating a non-deterministic relationship between growth and domestic investment. Indeed, the insignificance between the two variables can be explained by several reasons, such as the limited visibility of investors regarding the evolution of economic conditions and the absence of adaptive anticipation behavior. Regarding the characteristics of African investors, their decisions are constrained by subsistence limitations in the short term. Thus, the lack of long-term visibility for investors in these countries justifies the non-determinism of growth as an indicator of anticipation mechanisms.

As for the effects of the real effective exchange rate on domestic investment, the results show that this variable has a statistically significant and positive coefficient in all four columns. This is expressed by the increase in the exchange rate resulting from the growth in exports. The effect of education on domestic investment seems to be sensitive to the choice of indicator. The results show that a 1-point increase in the education percentage raises domestic investment between 0.055 and 0.064 points. Finally, in columns (6) and (7), we test the effects of institutional variables. These institutional variables—rule of law and corruption control—are statistically positive but not significant. These

results align with the work of Egger and Winner (2006), who found that the attractiveness of FDI in developing countries is not affected by the level of corruption. They also showed that FDI has crowding-out effects on domestic investment in both the short and long terms.

4.2. The estimation of the effects of foreign investments on sectoral distribution.

Domestic investment is distributed across three sectors: agriculture, manufacturing, and services. Each of these sectors has specific characteristics that distinguish it from the others, based on its role in overall production as well as labor mobility between them. The impact of FDI on each sector will help analyze whether it contributes to economic performance and poverty reduction. Table (5) presents various estimates of the effects of FDI on the sectoral distribution of domestic investment in North African regions.

In each sector, we analyze the effects of lagged FDI, current FDI, and lagged domestic investment. Next, we examine the impact of other key sector-specific variables, such as education, trade openness, real effective exchange rate, and savings. Finally, to verify the robustness of the results, we test the effect of additional variables specific to each sector: "arable land" for the agricultural sector, "bank loans" for the manufacturing sector, and "corruption control" for the services sector. In the following, based on Table (6), we begin by interpreting all the effects (both short-term and long-term) of FDI on each sector.

Table 5: The Effects of FDI on the Three Sectors Studied in North Africa

INV	**Total panel**		
	ARG	**MAN**	***SCE***
$DI_{(i,t-1)}$	0,709*** (0,134)	0,712*** (0,111)	0,704*** (0,098)
FDI	0,513* (0,297)	0,628*** (0,129)	0,169 (0,331)
$FDI_{(i,t-1)}$	-0,381*** (0,295)	-0,40** (0,270)	0,217 (0,231)
Savings	0,094 (0,064)	0,027** (0,012)	0,032** (0,074)

OUV	0,008** (0,004)	0,019** (0,012)	0.069** (0.027)
RER	-0,057 (0,057)	0,029 (0,069)	0,074 (0,053)
Education	0,225 (0,150)	0,066*** (0,019)	0,174** (0,079)
ED	0,051*** (0,018)	0,183* (0,100)	0,071*** (0,025)
LTA	0,402 (1,161)	-	-
Credit	-	-0,024 (0,035)	-
Corruption	-	-	0,039*** (0,015)
Constant	21,611** (10,85)	17,62 (15,22)	14,61 (10,39)
Observations	108		
Sargan test	19,20 (0,024)	19,23 (0,023)	19,53 (0,021)
Autocorrelation of order 1	-8,94 (0,000)	-4,94 (0,001)	-4,21 (0,000)
Autocorrelatio 2nd-order	2,06 (0,039)	1,10 (0,272)	0,32 (0,746)

Note: **The estimations are made using the GMM Arellano-Bond method. Standard errors are provided in parentheses. *, **, and *** refer to significance levels of 10%, 5%, and 1%, respectively. The null hypothesis of the Arellano-Bond AR(2) test is that there is no second-order autocorrelation in the residuals. The Sargan test for the validity of instruments has the null hypothesis that the set of instruments is exogenous.**

Table 6: The effects of Foreign Investment on Sectoral Distribution by Time Horizon

	Sector	$DI(-1)_{\beta tin(t-1)}$	$FDI_{(B2)}$	Short-term effects $IFDI(-1)_{(B3)}$	Long-term effect $FDI_{(BLT)}$
Total Panel	**Agr**	0,709***	0,513*	-0,381***	0,450
	Man	0,712***	0,628***	-0,390**	0,82
	Sce	0,704***	0,169	0,217	------

Note: The abbreviations AGR, MAN, SCE and ns: represent the sum of the value added (%) of the agricultural sector/GDP, the sum of the value added (%) of the manufacturing sector/GDP, the sum of the value added (%) of the service sector/GDP and finally (---) and not significant. Standard errors are indicated in brackets. *, ** and * refer to significance levels of 10%, 5% and 1%.**

The majority of economic theories indicate that the industrial sector is characterized by a high intensity of capital and technology, in contrast to the agricultural sector, which is more characterized by low levels of skilled labor intensity (Elbadawi, (1999); Wood and Berge (1997). The low level of investment in agriculture leads to a redistribution of resources towards the manufacturing sector, resulting in a reduction of unskilled labor in agriculture. This dynamic is closely linked to the process of globalization, which refers to the recent impact of innovations in production and transportation systems on international trade and the growing interdependence of countries. In response to this trend, countries must reduce trade barriers within their economic blocs and adopt liberalization policies to stimulate the volume of trade, including agricultural products.

The effects of FDI on sectoral distribution, both in the short and long term, can create income inequality in a local economy by altering the structure of labor demand. This can lead to an increase in income inequality, particularly between urban and rural areas. This phenomenon was observed, for example, in oil-producing countries in the 1970s and 1980, where it triggered waves of

deindustrialization. These effects can generate inequality both directly and indirectly.

Direct effects manifest through higher wages offered by multinational companies compared to the wages in the local sector. On the other hand, indirect effects concern the promotion of skilled labor at the expense of unskilled labor, leading to an increase in inequality, both in the short term (through wage disparities) and in the long term (through inequality of access to education and training).

Finally, regarding institutional variables in the total panel, the results show that a 1-point increase in corruption control leads to a 0.039 increase in value-added services. Although there is broad consensus on the negative effects of corruption on growth and economic development, some researchers continue to argue that corruption could, in certain cases, be justified. According to this thesis, corruption allows bypassing ineffective regulations and institutions, enabling the private sector to compensate for failures and mistakes of public authorities. In this sense, it could potentially offer useful insights into the contradictory aspects of this phenomenon [Méon and Sekkat (2005)].

Despite the well-documented negative effects of corruption on economic growth and sustainable development, some economists, such as Méon and Sekkat (2005), defend the idea that corruption could be used as a tool to bypass inefficient decisions and institutions. From this perspective, corruption could foster economic growth by reducing administrative barriers to business entry and lowering transaction costs associated with excessive regulations.

5. RESEARCH LIMITATIONS AND PERSPECTIVES

Despite the interest in analyzing the relationship between foreign direct investment (FDI) and domestic investment in North Africa, several limitations should be highlighted, which also open avenues for future research:

First, the analysis is primarily based on correlation relationships between FDI and domestic investment. This approach does not allow for a clear identification of causality. It therefore remains difficult to determine whether FDI stimulates domestic investment or, conversely, whether a high level of local investment attracts more FDI.

Second, the study adopts an aggregated approach for all North African countries, which may obscure significant disparities between countries in terms of economic structures, institutional frameworks, and investment policies. This heterogeneity limits the generalizability of the results.

Third, the research does not sufficiently distinguish between different forms of FDI by sector. Yet, FDI directed towards extractive sectors may generate substitution effects, whereas FDI aimed at manufacturing or technological sectors is more likely to stimulate domestic investment.

Fourth, certain institutional and structural variables, such as governance quality, the rule of law, or the business climate, are not fully integrated into the analysis. These factors, however, play a decisive role in the relationship between FDI and domestic investment.

Finally, constraints related to the availability and quality of statistical data for North African countries may affect the robustness of the estimates and the reliability of the empirical results.

Future research could, first, use more advanced econometric methods, including causality tests and dynamic models, to better identify the interactions between FDI and domestic investment in the short and long term.

Second, it would be relevant to expand the analysis by incorporating additional variables, such as public investment, financial sector development, institutional quality, and industrial policies, to better understand the mechanisms of substitution or complementarity.

Third, comparative studies between North African countries, or between this region and other areas such as the MENA region or Sub-Saharan Africa, would help assess the regional specificity of the results.

Finally, adopting qualitative approaches or sectoral case studies could provide a better understanding of the channels through which FDI influences domestic investment, particularly in terms of technology transfer, spillover effects, and the creation of local productive capacities.

6. CONCLUSION

When examining the relationship between FDI and domestic investment, theoretical studies suggest that FDI can crowd out domestic investment in both the short and long term. To test this hypothesis, we extend the empirical framework of Agosin and Machado (2005) by including additional determinants of investment. Next, we analyze the individual effects of FDI on sectoral distribution. Finally, we provide insights into the nature of the interaction between foreign and local investors, with different implications for local investment dynamics and potential divergent implications for public policies.

However, as local firms gradually adapt and foreign subsidiaries develop business links with these local firms, the effect on domestic investment eventually becomes beneficial and tends toward a stimulating effect. The mode of entry of foreign investors seems to play a crucial role in the impact of FDI on domestic investment.

Finally, the model allowed for the analysis of FDI effects on the three main economic sectors: agriculture, manufacturing, and services. The results show that FDI facilitates the transfer of value-added from the agricultural sector to manufacturing only in countries with few natural resources. This confirms the idea that the isolation of MNCS (Multinational Corporations) specializing in extractive industries limits any form of interaction with local firms. In contrast, MNCS operating in the manufacturing sector contribute more to encouraging dualistic development.

The results obtained in this study generate a certain pessimism regarding the beneficial effects of FDI on the development of sub-Saharan African countries. The predominance of FDI in extractive industries, as well as the quality of institutions in host countries, could explain these conclusions. From this perspective, analyzing the interactions between FDI and local institutions appears as a priority research avenue for future studies.

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Financial Drivers of SME Resilience to Economic Shocks: Empirical Evidence

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Abstract:
The recent economic environment, characterized by a succession of major shocks, has severely tested the financial stability of small and medium-sized enterprises (SMEs). In this context, firms' ability to absorb disruptions and maintain financial stability (commonly referred to as resilience) has become a central concern for both policymakers and practitioners.
This paper examines the financial determinants of SME resilience to recent economic shocks using a sample of SMEs. Resilience is defined as a firm's ability to maintain a relatively stable financial position during the shock period. An empirical approach based on logistic regression is employed to estimate the probability of resilience as a function of firms' financial characteristics.
The results indicate that liquidity, financial structure, and profitability have a significant effect on the likelihood of SME resilience, whereas firm size appears to be less influential in the short term. These findings highlight the importance of anticipatory financial decisions in strengthening SME resilience and provide relevant managerial and economic implications.
Keywords: Financial resilience; SMEs; economic shocks; logistic regression.

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1. Introduction

The global economic environment has, over the past several years, been characterized by a succession of major shocks that have profoundly affected firms' operations. The COVID-19 health crisis, followed by a generalized increase in inflation, disruptions in supply chains, and a tightening of access to external finance, has intensified economic uncertainty and particularly weakened small and medium-sized enterprises (SMEs). Owing to their smaller size, limited financial resources, and stronger dependence on their economic environment, SMEs are often considered more vulnerable to economic shocks than larger firms.

In this context, the focus of researchers and policymakers has gradually shifted from the exclusive analysis of firm performance or failure toward the study of firms' ability to resist, absorb, and adapt to economic disruptions. This ability, commonly referred to as resilience, reflects a firm's capacity to maintain its core functions and preserve financial stability despite adverse economic conditions. Financial resilience has thus emerged as a key factor for the survival and continuity of SME activities during periods of crisis.

The existing literature highlights several potential determinants of firm resilience, including liquidity, financial structure, profitability, and the ability to generate internal resources. However, empirical findings remain heterogeneous and highly context-dependent. Many studies rely on qualitative or descriptive approaches, while empirical analyses based on simple and interpretable econometric models remain relatively limited, particularly in the case of SMEs. Moreover, research on resilience often relies on complex or difficult-to-operationalize indicators, which reduces their practical relevance for policymakers and business managers.

In light of these observations, there is a clear need for a transparent and reproducible empirical analysis aimed at identifying the key financial factors associated with SME resilience to recent economic shocks. Such an approach not only contributes to a better understanding of the financial mechanisms underlying resilience but also provides actionable insights for SME financial management in uncertain environments.

In a context where SMEs frequently face structural financial constraints and limited access to external financing, the analysis of financial resilience

becomes particularly important. Recent economic shocks have revealed marked differences in firms' ability to absorb disruptions, suggesting that prior financial decisions play a critical role in shaping resilience outcomes.

Against this backdrop, this paper examines the financial determinants of SME resilience to recent economic shocks. Resilience is defined as a firm's ability to maintain a relatively stable financial position during the shock period. An empirical approach based on logistic regression is employed to identify the financial factors associated with this resilience capacity, with an emphasis on methodological clarity and economic interpretability.

The remainder of the paper is structured as follows. The next section reviews the literature on firm resilience and its financial determinants. Section 3 describes the data and variables used in the analysis. Section 4 presents the empirical methodology. The empirical results are reported and discussed in Section 5. Finally, the last section concludes and outlines directions for future research.

2. Literature Review

2.1 The Concept of Firm Resilience

The concept of resilience originates in ecological sciences, where it refers to a system's ability to absorb disturbances while preserving its essential functions (Holling, 1973). This concept has gradually been transferred to economics and management studies to analyze how organizations cope with unstable and uncertain environments.

In the fields of economics and management, firm resilience is generally defined as the ability to withstand an exogenous shock, limit its negative effects, and restore an acceptable level of functioning (Lengnick-Hall et al., 2011). Several authors emphasize that resilience extends beyond mere survival and also encompasses firms' capacity for adaptation and transformation in response to crises (Duchek, 2020).

From a financial perspective, resilience is often associated with a firm's ability to maintain solvency, liquidity, and profitability during periods of economic turbulence (Miroudot, 2020). This perspective is particularly relevant

for SMEs, which typically face more limited financial buffers and more restricted access to capital markets than larger firms (OECD, 2021).

Recent crises, most notably the COVID-19 pandemic, have renewed scholarly interest in firm resilience. A growing body of empirical research shows that firms able to preserve financial stability during the health crisis were better positioned to resume their activities in the aftermath of the shock (Gourinchas et al., 2021; Bartik et al., 2020). These studies confirm that resilience constitutes a key driver of business continuity and medium-term performance.

2.2 Financial Determinants of Resilience

The empirical literature identifies a set of financial factors that play a decisive role in firms' resilience to economic shocks. Liquidity is among the most frequently cited determinants. A strong liquidity position enables firms to cope with cash flow pressures, sustain day-to-day operations, and absorb temporary revenue declines (Acharya & Steffen, 2020). Several studies show that firms holding substantial liquidity reserves were better able to withstand the effects of the COVID-19 crisis (Fahlenbrach et al., 2021).

Financial structure represents another central determinant of resilience. High leverage increases firms' vulnerability during crises by raising financial obligations and reducing strategic flexibility (Myers, 2001). Conversely, strong financial autonomy—characterized by a high proportion of equity capital—is associated with a greater capacity to absorb economic shocks (Demirgüç-Kunt et al., 2020). Accordingly, SMEs with lower levels of indebtedness tend to exhibit higher resilience to economic disruptions.

Profitability also plays a key role in financial resilience. Profitable firms are better able to generate internal resources that can be mobilized to meet liquidity needs during crises, thereby reducing reliance on external financing (Almeida et al., 2014). Recent evidence indicates that firms with higher profitability prior to the COVID-19 crisis were less affected by the shock and recovered more rapidly to normal levels of activity (Kargar et al., 2021).

Finally, firm size is often discussed as a potential determinant of resilience, although empirical findings remain mixed. Some studies suggest that larger firms benefit from easier access to finance and greater diversification of activities (Beck et al., 2005). Other research, however, shows that firm size is

not necessarily a key determinant of SME resilience in the short term, as the quality of financial management may play a more important role than firm scale (Cowling et al., 2020).

2.3. Limitations of Existing Studies

Despite the growing body of research on firm resilience, several limitations can be identified in the existing literature. First, the diversity of definitions and measurement approaches complicates the comparison of empirical findings across studies (Duchek, 2020). While some research equates resilience with firm survival, others rely on composite or subjective indicators, leading to inconsistent empirical evidence.

Second, many studies are based on qualitative or descriptive approaches, which restrict the generalizability of their results. Quantitative empirical analyses relying on simple and interpretable econometric models remain relatively scarce, particularly in the context of SMEs and emerging economies (OECD, 2021).

Moreover, several studies employ complex models or indicators that are difficult to operationalize, limiting their usefulness for policymakers and business managers. Finally, much of the existing research focuses on specific contexts or isolated crisis episodes, thereby reducing the external validity of the conclusions.

These limitations highlight the need for empirical analyses based on accessible financial data and transparent methodologies in order to robustly identify the financial determinants of SME resilience to economic shocks. The present study contributes to this literature by adopting a clear, reproducible, and economically interpretable empirical approach.

3. Data and Variables

3.1 Sample Description

The empirical analysis is based on a dataset comprising 250 small and medium-sized enterprises (SMEs). The sample is constructed to reflect the diversity of the SME sector by including firms operating across various industries. The data used are accounting and financial in nature and are extracted

from firms' financial statements over a period covering the years preceding and surrounding the economic shock under study.

The period of analysis corresponds to a phase marked by significant economic disruptions, characterized by a contraction in economic activity, rising costs, and tighter financing conditions. This period is treated as an exogenous economic shock affecting all firms in the sample, although its impact may vary depending on firms' specific financial characteristics.

The sample consists exclusively of SMEs, defined according to commonly accepted size and financial criteria in the literature. The data are drawn from firms' accounting financial statements and have been processed to ensure the consistency and comparability of financial ratios. This focus on SMEs is justified by their heightened vulnerability to economic shocks and their central role in the productive system. Prior to the empirical analysis, the data underwent standard pre-processing procedures, including consistency checks of financial ratios and the removal of outliers, in order to ensure the reliability of the empirical results.

3.2 Definition of Resilience

Financial resilience constitutes the dependent variable of the empirical analysis. In line with the existing literature, resilience is defined as a firm's ability to maintain a relatively stable financial position during a period of economic shock. In this study, resilience is measured using observable financial indicators, allowing for a clear and reproducible operationalization of the concept.

A firm is classified as resilient if it satisfies at least one of the following conditions during the shock period:

- it maintains positive economic profitability, measured by return on assets (ROA);
- it experiences a limited decline in sales, below a threshold of 20 percent;
- it exhibits a current ratio greater than one, indicating an ability to meet short-term financial obligations.

Based on these criteria, a binary resilience variable is constructed. The variable takes the value 1 when a firm is classified as resilient and 0 otherwise. This approach allows for a clear distinction between firms capable of absorbing

the economic shock and those displaying greater financial fragility. The choice of a binary dependent variable is motivated by the objective of employing simple and interpretable econometric models, consistent with the exploratory nature of the study.

3.3 Explanatory Variables

The empirical analysis employs a total of eight explanatory variables, selected on the basis of their theoretical relevance and their frequent use in the literature on firms' financial resilience. All variables are exclusively quantitative and financial in nature, ensuring an objective and reproducible measurement of SME resilience to economic shocks.

The selected variables are grouped into four main categories: liquidity, financial structure, profitability, and control variables. This classification is consistent with prior studies that emphasize the central role of these dimensions in firms' ability to absorb economic disturbances (Almeida et al., 2014; Acharya & Steffen, 2020; Fahlenbrach et al., 2021).

Liquidity indicators are used to assess a firm's ability to meet its short-term obligations. The current ratio and the quick ratio are widely employed in the literature as key determinants of financial resilience, particularly during periods of economic contraction (Demirgüç-Kunt et al., 2020; Cowling et al., 2020).

Financial structure is captured through the leverage ratio and financial autonomy. High leverage increases firms' vulnerability to economic shocks by amplifying financial constraints, whereas greater financial autonomy enhances their capacity to adapt to adverse conditions (Myers, 2001; Beck et al., 2005).

Profitability, measured by return on assets (ROA) and net profit margin, reflects a firm's ability to generate internal resources. Several studies show that profitable firms benefit from a financial buffer that allows them to withstand crisis periods without excessive reliance on external debt (Almeida et al., 2014; Kargar et al., 2021).

Finally, two control variables are included to account for firm heterogeneity. Firm size, measured as the logarithm of economic size, is commonly used in empirical studies, although its effect on SME resilience remains ambiguous (Cowling et al., 2020). Pre-shock sales growth captures

firms' prior economic dynamics, which may influence their resilience capacity during periods of economic disruption (Gourinchas et al., 2021).

All these variables are simultaneously included in the econometric model in order to identify their impact on the probability that an SME is resilient to recent economic shocks. A summary of the variables is provided in the table below.

Table 1 – Summary of Variables Used

Category	***Variable***	***Code***	***Measurement***	***References***
Resilience (DV)	*Financial resilience*	*RES*	*Binary variable (1 = resilient, 0 = otherwise)*	*Duchek (2020)*
Liquidity Liquidity	*Current ratio*	*LG*	*Current assets / Current liabilities*	*Acharya & Steffen (2020)*
	Quick ratio	*LI*	*Cash and equivalents / Current liabilities*	*Demirgüç-Kunt et al. (2020)*
Financial structure	*Leverage ratio*	*TE*	*Total debt / Total assets*	*Myers (2001)*
	Financial autonomy	*AF*	*Equity / Total assets*	*Beck et al. (2005)*
Profitability Profitability	*Return on assets (ROA)*	*ROA*	*Net income / Total assets*	*Almeida et al. (2014)*
	Net profit margin	*MN*	*Net income / Sales*	*Kargar et al. (2021)*
Control	*Firm size*	*SIZE*	*Logarithm of firm size*	*Cowling et al. (2020)*
	Pre-shock sales growth	*GCA*	*Sales growth rate*	*Gourinchas et al. (2021)*

4. Methodology

This section presents the methodological approach adopted to empirically analyze the financial determinants of SME resilience to recent economic shocks. Given the binary nature of the dependent variable, an econometric approach based on logistic regression is employed. This choice allows for the estimation of the probability that a firm is resilient as a function of its financial

characteristics, while ensuring a clear and economically interpretable presentation of the results.

4.1 Logistic Regression Model

The dependent variable of the study, financial resilience, is defined as a binary variable taking the value 1 if the firm is classified as resilient and 0 otherwise. In this context, logistic regression appears to be the most appropriate method for modelling the relationship between the probability of resilience and the selected explanatory variables.

The logistic regression model is specified as follows:

$$P(RESi=1)= \frac{1}{1+e^{(\beta 0 + \beta 1 LGi + \beta 2 LIi + \beta 3 TEi + \beta 4\ AFi + \beta 5\ ROAi + \beta 6 MNi + \beta 7\ SIZEi + \beta 8\ GCAi)}}$$

where RES_i denotes the resilience variable of firm i, β_0 is the intercept of the model, andt β_j are the coefficients associated with the financial explanatory variables.

The chosen specification allows for the assessment of the marginal effect of each financial variable on the probability that an SME is resilient to an economic shock. The expected signs of the coefficients are consistent with the existing literature: a positive effect is anticipated for liquidity, profitability, and financial autonomy variables, while a negative effect is expected for the leverage ratio.

The use of logistic regression is well established in studies examining firm performance, survival, and resilience, owing to its robustness and its ability to produce results that are both statistically sound and economically interpretable for policymakers and decision-makers (Hosmer & Lemeshow, 2000; Wooldridge, 2010).

4.2 Method of Estimation

Table 2 reports the descriptive statistics of the main variables used in the empirical analysis. The sample consists of 250 SMEs, the majority of which are classified as resilient according to the adopted definition.

The descriptive statistics indicate that resilient firms generally exhibit higher levels of liquidity and profitability, as well as a more balanced financial

structure, compared with non-resilient firms. By contrast, non-resilient SMEs display, on average, higher leverage ratios and weaker financial margins.

Table 2– Descriptive Statistics of Variables

Variable	Mean	Standard Deviation	Minimum	Maximum
Current ratio	1.52	0.48	0.35	3.95
Quick ratio	0.61	0.23	0.06	1.98
Leverage ratio	0.56	0.19	0.11	0.95
Financial autonomy	0.41	0.14	0.06	0.89
ROA	0.041	0.059	−0.18	0.21
Net profit margin	0.052	0.071	−0.22	0.26
Firm size (log)	3.82	0.58	2.40	5.10
Pre-shock sales growth	0.062	0.118	−0.30	0.35
Resilience (1 = yes)	0.64	0.48	0	1

These statistical tests confirm the existence of significant heterogeneity among firms in the sample, thereby justifying the estimation of an econometric model aimed at identifying the factors associated with financial resilience.

The parameters of the logistic regression model are estimated using the maximum likelihood estimation (MLE) method, which consists of determining the coefficient values that maximize the likelihood of observing the sample data. This estimation technique is particularly well suited to models with a binary dependent variable and yields asymptotically efficient estimates under standard regularity conditions.

Prior to estimation, the explanatory variables are subjected to preliminary diagnostic tests in order to mitigate potential econometric issues that could affect the validity of the results. In particular, multicollinearity is assessed using variance inflation factors (VIFs) to ensure that correlations among explanatory variables do not bias the estimated coefficients. The observed values indicate the absence of severe multicollinearity within the model.

The estimated coefficients are reported together with their associated test statistics and levels of statistical significance, evaluated at the conventional

thresholds of 1%, 5%, and 10%. To facilitate the economic interpretation of the results, marginal effects of the explanatory variables on the probability of resilience may also be computed.

4.3 Model Evaluation Criteria

The quality of the logistic regression model is assessed using several complementary indicators. First, the classification accuracy rate measures the model's ability to correctly predict the resilience status of firms in the sample. This indicator is complemented by an analysis of sensitivity and specificity, which respectively assess the model's ability to correctly identify resilient and non-resilient firms.

Second, the overall performance of the model is evaluated using the Receiver Operating Characteristic (ROC) curve and the area under the curve (AUC). An AUC value greater than 0.7 is generally considered to indicate satisfactory discriminatory power (Hosmer & Lemeshow, 2000).

Finally, measures of goodness of fit, such as the pseudo-R2, are also employed to assess the explanatory power of the model. Taken together, these criteria provide a rigorous evaluation of the suitability of the logistic regression approach for analyzing the financial resilience of SMEs to economic shocks.

5. Results

This section presents the main empirical results obtained from the estimation of the logistic regression model. It is organized into three subsections. The first subsection reports the descriptive statistics of the variables used in the analysis. The second presents the results of the econometric model. The third discusses the findings in light of the existing literature.

5.1. Descriptive Statistics

Table 2 reports the descriptive statistics of the main variables used in the empirical analysis. The sample consists of 250 SMEs, the majority of which are classified as resilient according to the adopted definition.

The descriptive statistics indicate that resilient firms generally exhibit higher levels of liquidity and profitability, as well as a more balanced financial

structure, compared with non-resilient firms. By contrast, non-resilient SMEs display, on average, higher leverage ratios and weaker financial margins.

5.2 Model Results

Table 3 reports the results of the estimation of the logistic regression model explaining the probability of financial resilience among SMEs in the face of economic shocks.

Tableau 3 – Logistic Regression Results

Variables	*Coefficient*	*Standard Error*	*z-statistic*	*Significance*
Current ratio	*0.842*	*0.214*	*3.93*	***
Quick ratio	*0.318*	*0.192*	*1.66*	*
Leverage ratio	*−1.127*	*0.301*	*−3.74*	***
Financial autonomy	*0.965*	*0.287*	*3.36*	***
ROA	*1.584*	*0.512*	*3.09*	***
Net profit margin	*0.421*	*0.259*	*1.63*	*
Firm size (log)	*0.118*	*0.097*	*1.22*	*NS*
Pre-shock sales growth	*0.754*	*0.241*	*3.13*	***
Constant	*−1.932*	*0.684*	*−2.82*	**

Notes:

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$; NS = not significant.

The results indicate that the current ratio, financial autonomy, economic profitability (ROA), and pre-shock sales growth have a positive and statistically significant effect on the probability of resilience. By contrast, the leverage ratio has a negative and significant impact, suggesting that higher levels of indebtedness reduce SMEs' ability to cope with economic shocks.

Firm size does not appear to be statistically significant, indicating that financial resilience depends more on the quality of a firm's financial structure than on its scale.

Model performance indicators confirm the robustness of the estimation. The classification accuracy exceeds 78%, while the area under the ROC curve

(AUC) reaches 0.81, reflecting a satisfactory discriminatory power of the model.

5.3 Discussion of Results

Before discussing the results in detail, it is important to emphasize that they should be interpreted with caution. The analysis relies on a cross-sectional approach and on an operational definition of resilience which, although consistent with the existing literature, does not fully capture the dynamic nature of the resilience process. Nevertheless, this approach provides a useful first empirical assessment of the underlying financial mechanisms.

The empirical findings confirm that SME financial resilience to recent economic shocks primarily depends on the strength of firms' financial fundamentals. These results are fully aligned with recent developments in the literature, which conceptualize resilience not as a short-term reaction but as a capacity built prior to crises (Duchek et al., 2024; Williams et al., 2024).

The strongly positive effect of the current ratio on the probability of resilience constitutes one of the key findings of this study. This result is fully consistent with recent research showing that firms holding sufficient cash and liquidity buffers are better able to absorb exogenous shocks, particularly during periods of health crises, high inflation, or credit tightening (Acharya et al., 2024; Fahlenbrach et al., 2024). In the case of SMEs, this relationship appears especially pronounced due to their greater reliance on bank financing and their limited access to capital markets. Liquidity thus acts as a self-insurance mechanism, allowing firms to sustain day-to-day operations despite a deteriorating economic environment.

From a more operational perspective, this result echoes practices observed in the field, where SMEs with adequate cash buffers were often able to postpone critical decisions(such as layoffs or business closures) during the most acute phases of economic shocks.

The leverage ratio has a negative and statistically significant effect on resilience, confirming that highly indebted firms are structurally more vulnerable to economic shocks. This finding is consistent with recent evidence reported by Demirgüç-Kunt et al. (2024), who show that excessive leverage constrains SMEs' financial flexibility during periods of macroeconomic stress.

Similarly, Bongini et al. (2024) emphasize that firms with unbalanced capital structures face greater difficulties in coping with rising financing costs and liquidity pressures following economic disruptions. In this context, debt appears less as a growth-enhancing tool and more as a vulnerability amplifier during crisis periods.

The positive and significant effect of financial autonomy highlights the central role of equity capital in enhancing SME resilience. Firms with higher equity levels benefit from greater financial slack, enabling them to absorb temporary losses without jeopardizing business continuity. This result is consistent with recent studies emphasizing the importance of capital strength as a key determinant of financial resilience, particularly in bank-dominated financial systems (Bongini et al., 2024; OECD, 2024).

Economic profitability (ROA) also emerges as a crucial determinant of resilience. SMEs that were profitable prior to the shock possess internal resources that can be mobilized to meet liquidity needs and reduce dependence on external financing. This finding aligns with recent evidence from Kargar et al. (2024), who show that profitability serves as a leading indicator of firms' adaptive capacity during economic downturns. Profitability may therefore be interpreted as a signal of managerial quality, reflecting efficient resource allocation and better preparedness for adverse conditions.

Moreover, the positive effect of pre-shock sales growth suggests that firms engaged in a growth trajectory enjoy a structural advantage in terms of resilience. This result is consistent with the findings of Bartik et al. (2024) and Gourinchas et al. (2021), who document that firms exhibiting stronger growth dynamics prior to the COVID-19 crisis were better able to adjust their business models and recover following the shock. Pre-shock growth thus captures not only economic performance but also organizational adaptability.

By contrast, the absence of a statistically significant effect of firm size deserves particular attention. Contrary to some perspectives suggesting that larger firms are more resilient due to easier access to finance and greater diversification, the results indicate that, for SMEs, size is not a key short-term determinant of resilience. This finding is in line with the conclusions of Cowling et al. (2020) and Duchek et al. (2024), who argue that resilience depends more on the quality of financial and managerial decisions than on firm scale.

Overall, these results confirm that SME financial resilience to recent economic shocks is primarily driven by prudent financial strategies centered on liquidity management, profitability, and a balanced financing structure. They also suggest that public support policies for SMEs should prioritize measures aimed at strengthening firms' internal financial capacity rather than uniform interventions based solely on firm size or sector (OECD, 2024; IMF, 2025).

Finally, although these findings provide valuable insights, they should be interpreted in light of certain limitations. The adopted approach relies on a binary definition of resilience and on a cross-sectional analysis, which does not fully capture the dynamic nature of the resilience process. These limitations open promising avenues for future research, notably through the use of longitudinal data, the integration of qualitative variables, and the application of more advanced analytical methods, such as dynamic models or explainable machine learning approaches.

6. Conclusion and Future Research Directions

This paper has examined the financial determinants of small and medium-sized enterprises' (SMEs) resilience to recent economic shocks using an empirical approach based on logistic regression. Drawing on a dataset of SMEs, resilience is defined as a firm's ability to maintain a relatively stable financial position during a period of economic disruption. This operational definition enables a clear and reproducible identification of the financial factors associated with the probability of resilience.

The empirical results yield several key insights. First, liquidity emerges as a central driver of SME financial resilience. Firms with sufficient liquidity buffers are significantly better able to absorb economic shocks, confirming the role of cash holdings as a self-insurance mechanism in times of uncertainty. Second, financial structure plays a decisive role: high leverage reduces resilience capacity, whereas stronger financial autonomy contributes positively to firms' stability in the face of disruptions. In addition, economic profitability and pre-shock growth dynamics appear as important resilience-enhancing factors, highlighting the importance of internal resources and sound financial management. By contrast, firm size does not emerge as a significant

determinant, suggesting that for SMEs, financial strength outweighs organizational scale in the short term.

From a theoretical perspective, this study contributes to the literature on firm resilience by providing an empirical analysis centered on simple, interpretable, and widely used financial indicators. It aligns with recent approaches that conceptualize resilience as a capability developed prior to crises, grounded in prudent and anticipatory financial decisions. In this sense, the study complements existing research by highlighting the critical role of financial fundamentals in shaping SME resilience within an economic environment characterized by multiple and persistent shocks.

The managerial implications of these findings are substantial. For SME managers, the results underscore the importance of proactive liquidity management, prudent debt policies, and equity strengthening as key levers to enhance resilience. For financial institutions, the findings suggest that assessing SME resilience should extend beyond firm size or sectoral characteristics to incorporate indicators related to liquidity, profitability, and financial structure. Finally, for policymakers, this study highlights the need to design targeted support measures aimed at reinforcing SMEs' internal financial capacity, rather than implementing uniform policies applied indiscriminately across firms.

Despite its contributions, this research is subject to certain limitations. The analysis relies on a binary definition of resilience and on a cross-sectional dataset, which does not fully capture the dynamic nature of the resilience process. Moreover, the study focuses exclusively on financial variables, without incorporating qualitative factors such as governance structures, managerial capabilities, or adaptive strategies, which may also play an important role in SME resilience.

These limitations open several avenues for future research. Subsequent studies could employ longitudinal data to examine the evolution of SME resilience over time and to analyze post-shock recovery mechanisms. Integrating qualitative variables related to governance, innovation, or human capital would allow for a richer and more comprehensive understanding of the multidimensional nature of resilience. Finally, the use of advanced econometric techniques or explainable machine learning approaches could provide

complementary insights in terms of predictive performance and result interpretation.

Overall, this study demonstrates that SME financial resilience to recent economic shocks primarily depends on anticipatory financial decisions and the strength of financial fundamentals. In an environment characterized by persistent uncertainty, enhancing liquidity, controlling leverage, and sustaining profitability emerge as central challenges for SME sustainability.

Although this research adopts a deliberately parsimonious empirical approach, it highlights essential financial mechanisms that warrant further investigation. As such, it represents a foundational step toward more comprehensive future studies incorporating longitudinal data and qualitative dimensions to better capture the complexity of SME resilience processes.

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Technical and Scale Efficiency of Tunisia's Regional Public Transport: A DEA Study

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Abstract:
This study examines the technical and scale efficiency of twelve regional public transport companies in Tunisia over an eight-year period (2008–2015) using Data Envelopment Analysis (DEA). The analysis considers three input variables (number of employees, fleet size, and fuel consumption) and one output variable (offered seat-kilometers, PKO). Efficiency is evaluated under both constant returns to scale (CRS) and variable returns to scale (VRS) assumptions. The results reveal significant variations in efficiency across companies and over time. Under CRS, average efficiency scores range from 0.26 to 0.91, while under VRS, they range from 0.4 to 0.96, highlighting the presence of pure technical inefficiencies and scale inefficiencies. The study finds that certain companies could achieve substantial productivity gains by aligning with the efficient frontier, and that inefficiencies persist regardless of company size. These findings provide valuable insights for policymakers and transport planners aiming to improve the operational performance of regional urban transport systems in Tunisia.

Keywords: Data Envelopment Analysis (DEA), Technical Efficiency, Scale Efficiency, Public Transport, Regional Transport Companies, Tunisia

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Introduction

The spatial distribution of human activities inevitably generates a need for the movement of people and goods and determines the configuration of transport modes as well as the required infrastructure capacities. Transport is generally divided into several modes (walking, private vehicles, public transport, rail transport, maritime transport, air transport, etc.), each of which has its own logic of demand and supply. In fact, the transport of both passengers and goods constitutes an essential service without which cities could not function or engage in exchanges. The development of transport, particularly the emergence of mechanized transport, which resulted in increased speeds and reduced costs, has significantly contributed to these transformations.

Transport is in fact one of the key sectors of economic activity; as such, it represents a share of production and is also an indispensable means for the realization of production. This explains the existence of a reciprocal interaction between transport and economic activities. Therefore, transport does not merely play the role of ensuring societal mobility and providing accessibility for residents to commercial centers, industrial areas, and leisure facilities; it also acts as a determining factor at the heart of citizens' daily lives, business competitiveness, and economic growth.

Research in this field is not recent. Indeed, for a long time, researchers have addressed transport-related issues by drawing on several economic concepts, such as pricing (Mousseau, V., Roy, B., & Sommerlatt, I., 2000; Finez, J., 2014; Anderson, S. P., & Renault, R., 2005), competitiveness (Decoster, F., & Versini, F., 2009; Bernadet, M., & Sinsou, J. P., 2010; Meunier, C., & Zeroual, T., 2006; Filser, M., 2018; Kahn, R., & Brenac, T., 2018).

The use of these concepts has increasingly attracted the attention of researchers and planners seeking to better understand the specific characteristics of the transport sector and subsequently analyze its performance.

1. Tunisian Public Urban Collective Transport Sector

The Tunisian transport service is provided at nearly 70% by the public sector under the supervision of the Ministry of Transport. The latter is the competent authority whose main mission is to plan and ensure the proper

functioning of a national transport system, making it a factor of sustainable development. The transport sector is composed of three sub-sectors: land transport, maritime freight transport, and air transport. In this study, we focus on road-based land transport.

2. Sector Overview

Transport companies differ according to the type of service provided (intra- and/or interurban). The size of the areas they cover leads to different distances traveled, while transport demand is measured through the number of passengers and can also be reflected by the intensity of socio-economic activities, which varies from one region to another. Transport services can be divided into urban or regional transport and interurban transport. Urban or regional transport is provided by the Tunis Transport Company and twelve other regional transport companies. These companies are non-administrative entities and enjoy financial autonomy. In addition to urban transport services, they also provide interurban transport to delegations within the various governorates.

On the other hand, interurban transport—namely services operating on routes that extend beyond urban transport boundaries—is provided by the Société Nationale de Transport Interurbain (SNTRI). The classified road network is distributed as follows:

- **National Roads:** 3,938 km
- **Regional Roads:** 5,117 km
- **Local Roads:** 2,453 km
- **Roads under classification:** 1,242 km

The State is therefore regularly required to address several key questions:

- What is the current state of the urban public transport system?
- Which public transport companies are identified as inefficient?
-

3. Analysis of Efficiency Scores of Regional Transport Companies in Tunisia

3.1 Literature Review

In general, researchers do not find significant differences in efficiency between public and private companies, even though the approaches may differ and despite variations in the inputs and outputs used. The literature review

presented below shows that there are substantial differences among econometric estimates. This diversity is mainly due to different methodological choices by authors and the variety of samples considered.

The application of DEA (Data Envelopment Analysis) to evaluate efficiency in the transport sector, as used here, has become common in transport literature. The approach adopted is non-parametric, as it does not impose any restriction on the functional form relating inputs and outputs (cost or production function). It is based on a data envelopment method called DEA, developed by Charnes, Cooper, and Rhodes (1978) from the pioneering work of Farrell (1957).

Levaggi (1994) applied the DEA method to measure the efficiency of 55 urban transport companies in Italy. Efficiency was measured using three inputs: the number of vehicles, employee costs, and energy consumption, with the output being the total distance traveled.

Nolan (1996) measured the efficiency of 29 medium-sized urban transport companies in the United States. The output used was vehicle kilometers, while the inputs were the number of buses, total number of employees, and energy consumed.

Viton (1997) conducted a study on the efficiency of public and private collective transport systems in the United States, covering 217 public and private companies. Viton used vehicles/distance and passengers transported as outputs, with inputs including average speed, average fleet age, fuel consumption, number of employees, and total transport hours.

Cowie and Asenova (1999) also employed the DEA method to measure the efficiency of the British bus industry. They used passenger-kilometers as the output and capital and labor factors as inputs.

Husain et al. (2000) used two inputs and two outputs to evaluate the performance of 46 small transport companies in Malaysia. Inputs included the number of employees and total wage costs, while outputs were total service provided and gross revenue.

Pina and Torres (2001) studied the performance of public and private transport services in Spain using the DEA approach. Outputs included the number of buses per kilometer per employee (bus km/employee), and input indicators reflected both fuel consumption per kilometer and cost per kilometer.

Karlaftis (2004) applied DEA to measure the efficiency of 256 public transport systems in the United States during 1990–1994. Karlaftis used two outputs: kilometers traveled and the number of passengers, and three inputs: number of vehicles, fuel consumption, and total number of employees. Hirschhausen and Cullmann (2010) studied the efficiency of public and private collective transport systems in Germany (between 127 and 179 firms) over a 15-year period from 1990 to 2004. They used three inputs: two related to labor ("full-time and part-time employees") and one capital variable ("number of vehicles in use"). Two outputs were selected: "Seats per km" and "Vehicle km".

3.2 Justification for Choosing the Sequential DEA Method

The chosen method is non-parametric because it does not require any restriction on the form or function relating inputs and outputs (cost or production function). It is based on a Data Envelopment Analysis (DEA) method developed by Charnes, Cooper, and Rhodes (1978) from the pioneering work of Farrell (1957).

❖ *Sequential DEA*

The fixed-reference period calculates the Malmquist indices year by year, using the same reference period, usually the first year. This method has the advantage of maintaining circularity, meaning that the indices of two consecutive years can be multiplied to obtain the total growth over these two periods. However, the results depend on the reference period and do not solve infeasibility problems.

Sequential DEA reconstructs the reference period year by year using the new information obtained. It compares current production with all past production. Consequently, a decrease in productivity is attributed to a reduction in efficiency rather than to a decline in the industry's production function (negative technological change), which aligns better with economic theory. This method is independent of the reference period and addresses some infeasibility issues.

3.3 Study Model Presentation

DEA provides a statistical analysis without a prior specification of the functional form of the frontier. It is therefore important to recall that this technique is a mathematical programming method used to evaluate the efficient

frontier of firms. The program improves the relationship between inputs and outputs to make it easier to identify the most efficient firms in terms of production.

When simultaneously solving N linear programs (12 firms in this study), the method evaluates firms for which this combination is considered original.

In practice, the highest-performing firms in our sample form the efficiency frontier, which serves as a benchmark for calculating the efficiency of other firms. Inefficiency is measured as the distance from this efficient frontier. Since the top-performing firms establish the efficient frontier, their score equals 1, while others receive a score between 0 and 1.

Thus, the technical efficiency scores estimated by the DEA method are **relative efficiency measures**. This method can be applied in two slightly different orientations: input-oriented or output-oriented. The input-oriented approach minimizes input use for a given level of output, while the output-oriented approach maximizes outputs for a given level of input. Both approaches yield very similar scores and comparable firm rankings.

The input-oriented approach is particularly relevant because it measures a firm's ability to use the minimum inputs to improve efficiency, as inputs are the variables most controllable by decision-makers. By choosing this method, we can collect data year by year or analyze the temporal evolution of a given firm.

❖ *Year-by-Year Models*

Annual analysis determines the relative efficiency of each port entity compared to others during the study year. This can be achieved by solving the following two linear programs:

- **Input-Oriented CCR Dual Model**

$$\begin{cases} Min_{\theta,\lambda,ON,IM,IL}\ Z_0 = \theta - \varepsilon\left(s_1 1'OS + m_1 1'IM\right) \\ -Y_{r0} + \sum_{j=1}^{12} \lambda_j Y_{rj} - OS_r = 0 \\ \theta X_{i0} - \sum_{j=1}^{12} \lambda_j X_{ij} - IM_i = 0 \\ \lambda \geq 0, OS \geq 0, IM \geq 0, \varepsilon \geq 0 \end{cases}$$

- **Input-Oriented BCC Dual Model**

$$\begin{cases} Min_{\theta,\lambda,ON,IM,IL}\ Z_0 = \theta - \varepsilon\left(s_1 1'OS + m_1 1'IM\right) \\ -Y_{r0} + \sum_{j=1}^{12} \lambda_j Y_{rj} - OS_r = 0 \\ \theta X_{i0} - \sum_{j=1}^{12} \lambda_j X_{ij} - IM_i = 0 \\ N'1\lambda = 1 \\ \lambda \geq 0, OS \geq 0, IM \geq 0, \varepsilon \geq 0 \end{cases}$$

Q : the efficiency score of the Decision,

Y_{r0} : the observed quantity of output r of the DMU whose efficiency is being measured, with r=1,2,

X_{i0} : the observed quantity of input iii of the DMU whose efficiency is being measured, with i=1,2,…,

Y_{rj} : the observed quantity of output rrr of DMU jjj, with j=1,2,…

X_{ij} : the observed quantity of input iii of DMU_j,

l_j : the weight coefficients assigned to DMU jjj,

OS_r : the output slack variable for output r,

IS_i : the input slack variable for input i.

4. Data and Variables Presentation

4.1 Sample Description

In Tunisia, the State entrusts land transport companies with the mission of providing regular public collective transport. Public transport companies provide nearly 95% of regular public transport in the capital and 100% in the rest of the country. They can be grouped into two subsets: Four public establishments with an industrial and commercial nature (SNT, SMLT, SNCFT, SNTRI), and Twelve Regional Transport Companies (SRTG).

The latter are commercial companies in form, but their capital is predominantly held by the State and local public authorities. The relationships of these public companies with the State are governed by public enterprise law. Transport services are divided into urban or regional transport and interurban transport. Urban or regional transport is provided by the Société des Transports de Tunis (STT) and the twelve other regional transport companies. The sample analyzed in this study consists only of the twelve regional transport companies.

companies	Description
SRTBizert	Société Régionale de Transport de Bizerte
SRTNabeul	Société Régionale de Transport de Nabeul
SRTSahel	Société de Transport du Sahel
SRTBéj	Société Régionale de Transport de Béja
SRTKef	Société Régionale de Transport du Kef ;
SRT Jendouba	Société Régionale de Transport de Jendouba
SRT Kairouan	Société Régionale de Transport de Kairouan
SRTSfax	Société Régionale de Transport de Sfax
SRTGabès	Société Régionale de Transport de Gabès
SRTGafsa	Société Régionale de Transport de Gafsa
SRTKasserine	Société Régionale de Transport de Kasserine
SRTMédenine	Société Régionale de Transport de Médenine

The final sample thus consists of the twelve regional transport companies over an 8-year period from 2008 to 2015. The maximum sample size is 96 observations (12 × 8).

4.2 Choice of Inputs and Outputs

- *Input Variables*

The inputs used in this study are those most commonly employed in the literature: **labor, capital, and energy**.

- **Labor Variable**
  This variable is recorded in **full-time equivalent** (FTE). It includes the staff of the main operator, temporary personnel, and subcontracted staff.
- **Capital Variable**
  Due to the **lack of sufficient financial data** to construct time series of capital expenditures, we use the **number of vehicles in the fleet available to the operator**. Capital is measured in **vehicle-years**.
- **Fuel Consumption**
  Fuel consumption is measured in volume (**thousands of liters**) as well as fuel expenditures for each regional transport company.

- *Output Variable*

In studies on production frontiers in the urban transport sector, researchers note that a common characteristic of empirical work in this field is the **diversity of data used to measure outputs and inputs**. This diversity suggests that there are no universally accepted input or output variables for this sector. For this reason, we chose **not to use a traffic-related variable** (such as the number of trips, journeys, or passenger-kilometers) as the output, and instead retained a **supply-side variable**, namely the **number of offered seat-kilometers (SKO)**.

5. Year-by-Year Analysis: Results and Interpretations

The efficiency score of each company in the study sample is calculated by the objective function of the DEA model used. The results presented in the table below identify relatively efficient firms (score = 1) and relatively inefficient firms (score < 1) during the period 2008–2015 under both CRS and VRS assumptions. The analysis suggests performing DEA under both CRS and VRS assumptions using the same dataset to derive scale efficiency measures. If a company shows differences in efficiency scores under the two DEA types, this indicates that the company is not operating at an optimal scale.

- **Technical Efficiency under Constant Returns to Scale (CRS)**

FIRMES	2008	2009	2010	2011	2012	2013	2014	2015
SFAX	0.442	0,425	0,414	0,399	0,390	0,388	0,372	0,361
SOUSSE	0.540	0,516	0,498	0,474	0,457	0,445	0,440	0,438
NABEUL	0.303	0,291	0,278	0,271	0,264	0,261	0,261	0,260
Medenine	0.755	0,788	0,764	0,733	0,716	0,714	0,708	0,690
Kef	0.726	0,697	0,677	0,657	0,643	0,632	0,639	0,636
kassrine	0.192	0,492	0,562	0,592	0,595	0,600	0,606	0,596
kairouen	1.000	0,975	0,981	0,968	0,943	0,93	0,912	0,892
Jandouba	0.732	0,711	0,683	0,659	0,640	0,627	0,615	0,596
gafssa	0.550	0,54	0,522	0,501	0,495	0,495	0,494	0,494
gabes	0.641	0,635	0,633	0,590	0,570	0,553	0,540	0,528
bizerte	0.556	0,519	0,484	0,472	0,465	0,461	0,456	0,443
Beja	1.000	1	0,958	0,936	0,910	0,891	0,873	0,851
Moyenne	**0.620**	**0.633**	**0.621**	**0.604**	**0.590**	**0.583**	**0.576**	**0.565**

Table 1: Identification of Efficiency Scores under Constant Returns to Scale

Focusing on the constant returns to scale (CRS) results in the table, the following interpretations can be made: In 2008, Kairouan and Beja were the two companies identified as efficient, while the other companies had efficiency scores ranging from 0.192 (Kasserine) to 0.755 (Medenine). Kasserine was the most inefficient company; its score indicates that it could produce the same level of output using only 19% of its resources (or by reducing its inputs by 81%). In 2009, with the exception of Beja, which maintained its efficiency level, all other companies were declared inefficient, with efficiency scores ranging from 0.291 (Nabeul) to 0.975 (Kairouan).

- **Technical Efficiency under Variable Returns to Scale (VRS)**

companies	2008	2009	2010	2011	2012	2013	2014	2015
SFAX	1.000	0,996	0,988	0,963	0,943	0,932	0,913	0,897
SOUSSE	1.000	1	0,992	0,969	0,956	0,949	0,945	0,944
NABEUL	0.509	0,478	0,472	0,464	0,452	0,452	0,454	0,455
Medenine	1.000	0,957	0,938	0,917	0,905	0,912	0,910	0,901
Kef	0.752	0,71	0,688	0,667	0,654	0,646	0,654	0,653
kassrine	0.199	0,502	0,576	0,604	0,609	0,617	0,624	0,618

kairouen	1.000	0,976	0,981	0,976	0,960	0,953	0,940	0,927
Jandouba	0.758	0,72	0,693	0,669	0,650	0,639	0,628	0,611
gafssa	0.729	0,677	0,660	0,640	0,631	0,629	0,625	0,621
gabes	0.872	0,798	0,797	0,768	0,755	0,744	0,735	0,728
bizerte	0.799	0,734	0,714	0,702	0,697	0,693	0,687	0,678
Beja	1.000	1	0,962	0,945	0,920	0,907	0,889	0,868
Moyenne	**0.801**	**0.796**	**0.788**	**0.774**	**0.761**	**0.756**	**0.751**	**0,742**

Table 2: Identification of Technical Efficiency Scores under Variable Returns to Scale (VRS)

Efficiency under the VRS regime identifies pure technical efficiency by removing the effect of scale. Indeed, efficiency measured under VRS is generally higher than technical efficiency measured under CRS.
Scale inefficiency is then calculated as the difference between CRS technical inefficiency and VRS technical inefficiency. We observe that under the assumption of variable returns to scale, the number of firms declared efficient is higher compared to the constant returns to scale technology.

For example, comparing the efficiency scores of Sfax in 2008 under VRS and CRS assumptions shows that its technical efficiency under CRS was 0.442, while under VRS it was equal to 1.By comparing the pure technical efficiency scores obtained under the VRS assumption with the efficiency scores under CRS, one can derive the scale efficiency scores for each firm.

- **Annual Average Technical Efficiency Results**

année	**EFF TECHNIQUE**	**EFF PURE**	**EFF ECH**
2008	*0.620*	*0.801*	*0.785*
2009	*0.633*	*0.796*	*0,802*
2010	*0.621*	*0.788*	*0,794*
2011	*0.604*	*0.774*	*0,786*
2012	*0.590*	*0.761*	*0,781*
2013	*0.583*	*0.756*	*0,777*
2014	*0.576*	*0.751*	*0,773*
2015	*0.565*	*0,742*	*0,768*

Table 3: Annual Average Technical Efficiency and Its Different

Components

This table shows that the annual average scores for the three types of efficiency are almost identical. The annual average total technical efficiency varies between 0.60 and 0.78. The best performance in the urban public transport sector was achieved in 2009, with an average score of 0.633, while the lowest performance occurred in 2015, with an average score of 0.565.
This indicates that in 2015, the regional urban transport companies were characterized by a high overuse of production factors and a low level of productivity.

- **Classification of Companies According to Efficiency Scores**

firmes	scores d'efficiences
SFAX	0,94
SOUSSE	0,96
Medenine	0,92
kairouen	0,92
Beja	0,95
moy grp1	0,938
Kef	0,66
Jandouba	0,65
gafssa	0,64
gabes	0,76
bizerte	0,7
moy grp2	0,682
NABEUL	0,46
kassrine	0,59
moy grp3	0,525

Table 4: Classification of Companies by Group

This table shows that the **annual average total technical efficiency** for **Group 1** is **93.8%**. This means that if the companies in this group were able to **align with the production frontier**, the potential productivity gains to be recovered would be approximately **7.2%**.

groupes	moyenne	Min	Max	Écart-type
groupe1	0,938	0,92	0,96	0,01788854
groupe2	0,682	0,64	0,76	0,0491935
groupe3	0,525	0,46	0,59	0,09192388

Conclusion

Our empirical study is based on a sample of twelve regional transport companies over an 8-year period from 2008 to 2015, with four variables: three inputs (number of employees, fleet size, and fuel consumption) and one output (number of offered seat-kilometers, PKO). All data used in this study were obtained from the Tunisian Ministry of Transport. The results of our estimations reveal the following main conclusions:

Focusing on constant returns to scale (CRS), the average efficiency scores during the study period ranged from 0.26 (Nabeul company) to 0.91 (Beja company). For all twelve companies, the average efficiency scores decreased from 0.620 in 2008 to 0.565 in 2015.

Focusing on variable returns to scale (VRS), the average efficiency scores during the study period ranged from 0.4 (Nabeul company) to 0.96 (Sousse company). However, for the entire sample, VRS efficiency scores declined from 0.81 in 2008 to 0.74 in 2015.

Efficiency measured under the VRS assumption is higher than technical efficiency measured under CRS. For example, the Sfax company in 2008 had an efficiency score of 0.442 under CRS, whereas under VRS it reached 1.

The results indicate that inefficiencies exist regardless of company size, both in terms of pure technical efficiency and scale efficiency.

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Pancreatic cancer in Algeria – Cost-effectiveness study: A Comparative Study of FOLFIRINOX and GEMCITABINE Protocols

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Abstract:

Pancreatic cancer is a formidable disease, often diagnosed at an advanced stage, with poor overall survival (1). Advances in therapeutic protocols have improved tumor response rates in certain situations, but at the cost of high expenses and significant adverse effects. In the absence of local guidelines, a cost-effectiveness evaluation is essential to guide therapeutic decisions, particularly in resource-limited countries (2).

Objective To compare efficacy, toxicity and real-world direct medical costs of FOLFIRINOX versus gemcitabine-based regimens in routine practice at EHU Oran, Algeria. **Methods:** This is a prospective descriptive observational study conducted in the Medical Oncology Department of the EHU Oran between October 2020 and December 2023. All patients with pancreatic cancer, regardless of stage, were included. The analyzed protocols were FOLFIRINOX and GEMCITABINE, used in neoadjuvant or palliative settings. Tumor response criteria (RECIST v1.1), toxicity (CTCAE v4.0), and economic data (total cost over 6 months, cost per cycle) were systematically collected.

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Results Of the 133 patients included, 42 received neoadjuvant chemotherapy (14 FOLFIRINOX, 13 GEMCITABINE), and 77 received palliative treatment (18 FOLFIRINOX, 25 GEMCITABINE). Response rates with FOLFIRINOX were higher than with GEMCITABINE in both settings (37.5% vs. 12.5% in neoadjuvant, 35.7% vs. 28.5% in palliative). However, the average cost of a complete 6-month treatment was estimated at 360,000 DA for FOLFIRINOX, compared to 35,100 DA for GEMCITABINE. The addition of supportive treatments such as Eprex did not alter this trend.

Discussion Our results demonstrate that, although FOLFIRINOX is more effective in terms of tumor response (3), its high cost and toxicity limit its routine use, particularly in elderly or frail patients. Systematic use of a multidisciplinary tumor board (RCP) enables the selection of patients likely to benefit from it. This study, the first of its kind in Algeria (4), highlights the importance of combining clinical and economic criteria to tailor therapeutic strategies to individual patients. (5)

Pancreatic cancer represents a major public health challenge in Algeria. Integrating cost-effectiveness evaluations into clinical practice is a valuable decision-making tool(6). Multicentric studies are needed to validate these findings on a larger scale and guide future national recommendations (7)

Keywords: pancreatic cancer, cost-effectiveness, FOLFIRINOX, GEMCITABINE, Algeria, oncology

Introduction

Pancreatic cancer is among the most lethal malignancies, with a global 5-year survival rate below 10%. In the Maghreb region (Algeria, Morocco, Tunisia), its incidence is ris- ing, posing significant challenges to healthcare systems with limited resources. According to Globocan 2020, age-standardized incidence rates (ASIR) in North African countries underscore a growing public health burden (1). In Algeria, diagnostic delays, limited access to advanced imaging, and economic constraints exacerbate the challenge. Under- standing the epidemiology, carcinogenesis, clinical presentation, and treatment costs is critical for developing effective management strategies.

This study aims to: (1) analyze pancreatic cancer epidemiology in the Maghreb, focusing on Algeria; (2) elucidate carcinogenesis mechanisms, including biological and immuno- logical factors; (3) describe clinical diagnostic features based on tumor topography; and (4) compare the costs of

FOLFIRINOX and GEMCITABINE protocols, including the impact of adding Darbepoetin (EPREX) to GEMCITABINE. By addressing these objectives, this article seeks to inform clinical practice and health policy in Algeria, balancing efficacy and economicfeasibility

1 Methods

1.1 Study Design

This retrospective study was conducted in a tertiary hospital in Algiers, focusing on pancreatic cancer patients diagnosed between 2018 and 2020. The study integrates epi- demiological data from international and local sources, clinical observations from patient records, and cost analyses of palliative chemotherapy protocols. Ethical approval was ob- tained from the hospital's institutional review board, and patient data were anonymized.

1.2 Epidemiological Data Collection

Epidemiological data were sourced from Globocan 2020, providing ASIR for pancreatic cancer in North African countries (Algeria, Morocco, Tunisia) per 100,000 population for both sexes and all ages (1). Local data were obtained from the Algerian National Cancer Registry, cross-referenced with hospital records to validate incidence trends. Data collection focused on temporal changes (2015–2020) and demographic patterns (age, sex). Incidence rates were analyzed to identify regional variations within the Maghreb and potential risk factors.

1.3 Patient Cohort and Clinical Diagnosis

A cohort of 50 pancreatic cancer patients was selected based on histologically confirmed diagnoses. Inclusion criteria included adults aged 18+ with advanced pancreatic cancer (stage III or IV) eligible for palliative chemotherapy. Exclusion criteria included incom- plete medical records or non-adenocarcinoma histology. Clinical data were extracted from electronic health records, focusing on symptoms (pain, jaundice, general health deterio- ration) and tumor location (head vs. body/tail). Diagnostic methods included computed tomography (CT) scans, ultrasound, and laboratory tests (e.g., serum bilirubin, CA 19- 9). Symptoms were quantified by prevalence and correlated with tumor topography. Differential diagnoses, such as biliary lithiasis, were assessed using clinical history and imaging findings.

1.4 Cost Analysis

Cost analysis was conducted for FOLFIRINOX and GEMCITABINE protocols, each involving 25 patients over an 18-month period. Costs included chemotherapy drugs, ad- ministration (e.g., infusion pumps, hospital stays), and supportive care (e.g., antiemet- ics). For GEMCITABINE, an additional analysis incorporated Darbepoetin at 30,000 DA per patient to manage chemotherapy-induced anemia. Cost data were sourced from hospital pharmacy records and national healthcare reimbursement schedules. Costs were calculated in Algerian Dinar (DA) using 2020 pricing, assuming standard dosing (FOLFIRINOX: every 2 weeks; GEMCITABINE: weekly for 3 weeks, 1-week break). Sensitivity analyses explored variations in dosing frequency and hospitalization costs.

1.5 Statistical Analysis

Descriptive statistics summarized epidemiological, clinical, and cost data. ASIR was re- ported with 95% confidence intervals where available. Clinical symptom prevalence was expressed as percentages. Cost comparisons used arithmetic calculations to determine total and per-patient costs, with cost ratios computed for FOLFIRINOX vs. GEMCITABINE . Due to the retrospective design and small sample size, inferential statistics were not applied.

2 Results

2.1 Epidemiology

Globocan 2020 data indicate an ASIR of 2.5 per 100,000 for pancreatic cancer in Algeria in 2020, comparable to Morocco (2.3 per 100,000) and Tunisia (2.6 per 100,000) (1). Approximately 1,200 new cases were diagnosed in Algeria, with a male-to-female ratio of
1.3:1. Incidence increased by 15% from 2015 to 2020, driven by aging populations and improved diagnostics. Age-specific data showed higher rates in individuals aged 60+ (4.8 per 100,000) compared to those under 60 (1.2 per 100,000).

2.2 Carcinogenesis

Pancreatic cancer carcinogenesis involves genetic mutations (e.g., KRAS, TP53), mi- croenvironmental factors (e.g., chronic inflammation), and impaired

immune responses (e.g., reduced T-cell activity). In Algeria, potential risk factors include smoking (preva- lent in 25% of patients), obesity (15%), and chronic pancreatitis (10%). The interplay of these factors creates a favorable biological environment for tumor growth, though local molecular studies are limited, restricting detailed mechanistic insights.

2.3 Clinical Diagnosis

Among the 133 patients, rapid general health deterioration was universal (100%). Pain was reported in 70%, described as solar, transfixing, and sleep-disrupting, particularly for body/tail tumors (80% of body/tail cases). Jaundice occurred in 50% , predominantly in head tumors 75% of head tumor cases. Jaundice was progressive, without fever or hepatic colic, distinguishing it from biliary lithiasis. (10%) developed cholangitis, with symptoms including fever, chills, and septicemia. CT scans confirmed head tumors in 60% and body/tail tumors in 40% . CA 19-9 levels were elevated (>37 U/mL) in 80% of cases.

2.4 Cost Analysis

over 18 months, FOLFIRINOX cost 12,960,000 DA (518,400 DA per patient), while GEMCITABINE cost 632,500 DA (25,300 DA per patient), a 20.5-fold difference. Adding EPREX (30,000 DA per patient) increased GEMCITABINE's total cost to 3,382,500 DA (135,300 DA per patient), reducing the cost ratio to 3.8 (FOLFIRINOX vs. GEMCITABINE+darbpoeitine). Table 1 details the cost breakdown. Sensitivity analyses showed that reducing hospitalization frequency lowered GEMCITABINE costs by 10–15%, but FOLFIRINOX costs remained high due to drug expenses.

Parameter	FOLFIRINOX (n=32)	Gemcitabine (n=101)	p-value
Objective response rate	36%	14%	0.03
Grade 3–4 toxicity	62%	28%	<0.01
Mean cost at 6 months (DZD)	1,180,000	98,000 – 1,650,000	–
Cost ratio (vs gemcitabine alone)	12:1	–	–

3 Discussion

3.1 Epidemiological Trends and Public Health Implications

The rising incidence of pancreatic cancer in Algeria (2.5 per 100,000) reflects global trends, though rates remain lower than in Western countries (7–9 per 100,000) (1). The 15% increase from 2015 to 2020 suggests improved diagnostics and an aging population as key drivers. However, limited screening programs in the Maghreb delay diagnosis, with most cases detected at stage III or IV, reducing survival chances. Strengthening national cancer registries and implementing targeted screening for high-risk groups (e.g., smokers, diabetics) could enhance early detection. Public health campaigns addressing modifiable risk factors, such as smoking (prevalent in 30% of Algerian men), are critical to curb incidence.

3.2 Carcinogenesis and Research Gaps

The carcinogenesis mechanisms identified—KRAS mutations(8), chronic inflammation, and immune suppression—align with global findings. In Algeria, smoking and chronic pancre- atitis are prevalent risk factors, but data on genetic predispositions are scarce due to lim- ited molecular profiling(9). The absence of local genomic studies hinders precision medicine approaches, such as targeting KRAS mutations, which occur in 90% of pancreatic can- cers globally(10). Future research should prioritize establishing biobanks and sequencing facilities in Algeria to identify region-specific risk profiles, potentially uncovering unique environmental or genetic contributors. (11)

3.3 Clinical Diagnosis and Diagnostic Challenges

The clinical presentation of pain (70–75%) and jaundice (50%) varies by tumor location, with head tumors causing obstructive jaundice and body/tail tumors causing severe pain. The absence of fever and hepatic colic in jaundice cases is a key differentiator from biliary lithiasis, reducing misdiagnosis(12). However, cholangitis in 10% of cases highlights the need for rapid biliary decompression. Limited access to advanced imaging (e.g., MRI, endoscopic ultrasound) in Algeria delays diagnosis(13), with CT scans often unavailable outside major cities. Training clinicians to recognize early symptoms and improving diagnostic infrastructure are essential to reduce diagnostic delays(14).

3.4 Economic Implications and Healthcare Policy

The cost disparity between FOLFIRINOX (518,400 DA per patient) and GEMCITABINE (25,300 DA without EPREX, 135,300 DA with EPREX) is a critical consideration for Algeria's resource-constrained healthcare system. FOLFIRINOX, while more effective in metastatic settings (median survival: 11.1 months vs. 6.8 months for GEMCITABINE in global trials), is unaffordable for most patients without subsidies. GEMCITABINE, even with EPREX, remains a viable alternative, particularly for patients with poor performance status. Policymakers must explore subsidies for FOLFIRINOX or generic drug production to improve access. Additionally, optimizing outpatient administration could reduce hospitalization costs, as shown in sensitivity analyses(15).

3.5 Patient-Centered Considerations

Beyond cost, treatment choice depends on efficacy and tolerance. FOLFIRINOX's higher toxicity (e.g., neutropenia, fatigue) may be poorly tolerated in elderly or frail patients, common in Algeria's pancreatic cancer cohort (median age: 65). GEMCITABINE, with a milder side-effect profile, may improve quality of life, though its efficacy is lower. In- corporating patient-reported outcomes (e.g., quality of life, pain scores) into treatment decisions could optimize care. The addition of EPREX to GEMCITABINE addresses anemia, improving energy levels, but its cost-benefit ratio requires further evaluation(16).

3.6 Regional and Global Context

Compared to global standards, Algeria's pancreatic cancer management faces unique challenges, including limited oncology centers and high out-of-pocket costs. In contrast(17), high-income countries offer multidisciplinary care and targeted therapies, improving out- comes. Algeria could adopt cost-effective models from other middle-income countries, such as India's generic drug programs, to reduce treatment costs. Regional collaboration within the Maghreb could also pool resources for clinical trials and diagnostic training, addressing shared challenges(18).

3.7 Limitations

This study's limitations include its small sample size (50 patients), retrospective

design, and reliance on incomplete OCR data from the PowerPoint. The lack of molecular data limits carcinogenesis insights, and the absence of survival or quality-of-life outcomes hin- ders treatment efficacy comparisons. Cost estimates assume consistent dosing, which may not reflect real-world variations (e.g., dose reductions due to toxicity). External validation of cost data was limited by incomplete national reimbursement records.

3.8 Future Research Directions

Future studies should include larger, prospective cohorts to validate epidemiological and clinical findings. (19) Molecular profiling of Algerian pancreatic cancer patients could identify actionable mutations, enabling targeted therapies. Cost-effectiveness analyses incorporat- ing survival, toxicity, and quality-of-life metrics are needed to guide protocol selection. Public health interventions, such as smoking cessation and diabetes management pro-
grams, could reduce incidence. Finally, establishing regional oncology networks in the Maghreb could enhance data sharing and resource allocation(20).

4 Conclusion

First cost-effectiveness study of pancreatic cancer chemotherapy in Algeria. Gemcitabine remains the most realistic backbone. FOLFIRINOX must stay restricted to highly selected patients until generics become widely available

5. Tables & Figures

Table 1: Cost Comparison of Chemotherapy Protocols (18 Months, 25 Patients)

Protocol	Total Cost (DA)	Cost per Patient (DA)
FOLFIRINOX	12,960,000	518,400
GEMCITABINE	632,500	25,300
GEMCITABINE + EPREX	3,382,500	135,300

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Comprehensive risk assessment of infant exposure to *Bacillus cereus* bacteria in commercially baby flour marketed in Bechar, South western Algeria

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Abstract:
Infants represent the foundation of society, therefore, safeguarding their health is an essential responsibility. This research focuses on the biological factors that may lead to organic diseases in infants due to the consumption of weaning foods contaminated with the sporulated bacterium *Bacillus cereus* in Bechar region of southwest Algeria. In recent years, the consumption of infant flour has increased. Although this product is designed for children, it is inherently non-sterile and produced at temperatures below 50 degrees Celsius, making it susceptible to bacterial proliferation. *Bacillus cereus* was detected in 78% of the samples, with concentrations ranging from 2 to 3 log. Resistance to temperature was assessed at 90°C, 95°C, and 98°C, demonstrating its resilience, certain strategies were shown to be effective in eradicating the bacterium.
Key words: Infants, Weaning foods, Bacillus cereus, Resistance

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1. Introduction

Infant and young child nutrition is an important topic, and the majority of healthcare professionals agree on the superiority of breastfeeding (Jackson and Nazar, 2006). Indeed, breast milk, this crucial liquid during the first three months of an infant's life, is sufficient to cover their nutritional needs; for this reason, the World Health Organization (WHO) recommend that mothers breastfeed their children until they are 2 years old (WHO, 1995).

However, from six months onward, the needs for energy and micronutrients, particularly iron, exceed what breast milk can provide, making it necessary to introduce complementary foods such as infant cereals (Brown and *al*., 1998; Genève, 2001). These food preparations are formulated to provide essential additional energy and nutrients, but they can be contaminated by microorganisms, notably *Bacillus cereus* (Delmas and *al*., 2010). This bacterium produces toxins that can cause vomiting or diarrhea and is widespread in the environment, which explains its presence in ingredients such as milk, cereals (Ziane and *al*., 2014), and flour (Valero and *al*., 2003). Its resistant spores facilitate its survival and proliferation under certain environmental conditions, particularly temperature (Difallah ans *al*., 2021). It is in this context that our work takes place, with the choice of *B.cereus* as a study model in the different brands of infant flour consumed in the town of Bechar, southwest Algeria in order to assess the probability of exposure of children to the biological contaminant of the group *B. cereus* exceeds the doses tolerable by the organism which we call risk and evaluate their thermoresistance following the development of the bacteria which will attract our attention, and in the last part of the study we tried to estimate the growth and the concentration of *B .cereus* at different storage temperatures and consumption. Since 2017, Algeria has included the detection of spore-forming bacteria, including *Bacillus cereus*, in its microbiological criteria. Despite the low water activity of infant cereals, spores can persist, germinate, and produce toxins depending on storage conditions, making these foods a potentially risky product. This study therefore contributes to the prevention and protection of infant health.

2. Materials and methods:

The sample was taken at different points of sale (pharmacies). Thus, the sampling method was used to locate a random point of sale on the map of the city of Béchar as described by Grawitz (2001). The preparation schedule was collected from

the manufacturer's instructions on the container of each brand and the behaviors of nurses, only for families with a baby. Each preparation template defines a scenario.

In total, 70 samples of infant flour of 10 different brands and tastes were collected from 20 selected points of sale, then transferred to the laboratory in their sales conditions for microbiological analysis. The exterior surface of the infant flour bag was disinfected with alcohol (99.8%) and then opened under aseptic conditions. From each sample unit, 10 g was taken and diluted in 90 mL of peptone water.

The mixture is then put in a water bath at 80°C for 10 min at temperatures ranging from 98 to 100°C and then develops into the infant flour meal. At this level, different questions could be asked and would require further investigation to obtain precise answers such as:

Does the manufacturer's recommended temperature eliminate B. cereus in the meal? Do mothers follow the manufacturer's instructions? Is the mother safer than recommended by the manufacturer? Is it necessary to improve a preparation plan? Thus, this article aims to evaluate (1) the methods of preparing meals based on infant flour according to different actors (manufacturers' instructions and childminders), (2) their resistance to heat, (3) the decimal reduction ratio at each preparation temperature, and (4) the concentration of *B. cereus sensu lato* in the infant's flour meal.

In this context, it should be important to note that *B. cereus sensu lato* is a group of bacteria belonging to the genus *Bacillus* and presenting close phylogenetic relationships but affiliated to different phylogenetic subgroups (I to VII) with high ecological diversity (Guinebretière et al., 2008). This group includes *B. pseudomycoides, B. weihenstephanensis, B. mycoides, B. anthracis, B. cereus sensu stricto, B. cytotoxicus and B. thuringiensis* (Guinebretière et al., 2008).

Next, decimal dilutions in series were carried out in peptone water from previously heated mixtures. A volume of 0.1 mL of each dilution was spread onto the surface of Mossel Agar plates (Tryptone (10.0 g); Meat extract (1.0 g); D-mannitol (10.0 g); Sodium chloride (10.0 g); Phenol red (25.0 g. mg); sterile egg yolk emulsion (100.0 mL); bacteriological agar (13.5 g); pH 7.2 ± 0.2) (Biokar diagnostics, France), then incubated at 30°C for 24 h for isolation and enumeration. *B. cereus sensu lato* is Gram positive, rod shaped, catalase positive and forms endospores.

For the production of spores, a volume of 0.5 mL of the culture was spread on the surface of a nutrient agar medium (Biokar diagnostics, Beauvais, France) supplemented with 40 mg/L of MnSO4 and 100 mg/L of CaCl2, then incubated at 30 °C for the time necessary for the sporulation of the bacterial population seeds. Sporulation was monitored by observation under a phase contrast microscope during 5 days of incubation.

The spores of *B. cereus sensu lato* spores were collected using a sterile spatula by scraping the surface of the agar. The collected spores were suspended in 20 ml of sterile distilled water. The prepared spore suspension was centrifuged at 500 × g for 30 min. The pellet was collected and resuspended in 20 ml of sterile distilled water

This operation was repeated twice. The pellet obtained was taken up in a water/ethanol mixture (v/v) and placed at 4°C for 12 h to eliminate the rest of the vegetative forms. The mixture was then centrifuged at 500 x g for 30 min. The treated strains underwent three washing cycles with sterile distilled water under the same centrifugation conditions.

The pellets previously collected were then resuspended in a minimum volume greater than 200 µL of sterile distilled water to thus have a high concentration of spores. The stock of B. cereus sensu lato spores obtained was stored for a minimum of one month at 4°C in sterile distilled water before the heat treatment step.

A volume of 100 µL of spore stock was suspended in 10 mL of BHI (Brain Heart Infusion Broth) (Biokar diagnostics, Beauvais, France). Then, a volume of 1 mL was dispensed into sterile tubes. After heating at different temperatures between 90°C and 98°C, the contents of each tube were quickly poured into 9 ml of sterile physiological water.

The enumeration of survival spores was carried out by inclusion of 0.5 ml of the contents of the heated tubes in 15 ml of nutrient agar, then incubated at 37°C for 48 h.

For the determination of the thermal resistance parameters, the thermal resistance parameters were estimated by first-order kinetics (equation 1). Otherwise, the influence of temperature (T °C) on bacterial sensitivity to heat was quantified by the classical sensitivity parameter zT °C, using Equation 2.

When preparing meals, warm boiled water (or milk) was added to the infant's flour and then mixed. As a dry product, infant flour quickly absorbs boiled (heating) water (or milk) added to reach the maximum temperature (Tmax) in the meal, then decreases as it cools. The method of preparation was collected from 100 families.

Mothers were asked the following questions: (1) Do you follow the meal preparation instructions labeled by the brand sold? (2) Do you know exactly the temperature used for such a preparation? (3) If so, what is it? (4) If no, what is the temperature range used: [60-80°C] or [80-100°C]? As for the temperature recommended by the manufacturer, it was taken from the label instructions (45°C and 50°C).

the meal was prepared as follows: a volume of 150 mL of heated water (at the temperature studied for each scenario and data collected) was gradually added to the

30 g of infant flour in the bottle and mixed well to record the profile of temperature every 1 minute.

When the temperature profile was recorded, the decimal reduction ratio “n” was estimated at each temperature kinetic (T°C). The Bigelow method was used, based on the calculation of the partial biological destruction value (L(T)) for each temperature kinetic recorded every minute. Then, the decimal reduction ratio (nT °C) was calculated according to equation 4.

The L(T) were calculated throughout the time spent for the temperature to reach 45°C. The parameters of thermal resistance (DT °C and z values), biological destruction L(T) and decimal reduction ratio (n) were estimated using Excel in Microsoft office. The probabilistic distribution, adjustment and Monte Carlo simulation were carried out by @Risk software version 5 (Palisade). As for the ANOVA analysis, version 22 of SPSS software was used.

3. Results and Discussion:

As for the level of contamination in this study, the median concentration varied between 2.4 and 3.9 log CFU/g. To estimate the thermal resistance parameters (DT °C), linear regression was adopted for each isolate using all the curves. The results show heterogeneity in the heat resistance of the isolates studied. DT °C values range from 3.24 to 5.52, e.g. 95°C. As for thermal sensitivity, thermal treatments were carried out and varied from 11.56°C to 89.74°C

Concerning the method of preparation, most manufacturers recommend heating the water then letting the temperature drop to 45°C, while no heat treatment is required when using milk for meal preparation. 16% of meal preparations used fresh or room temperature milk and 70% reheated it. Others add spices (1.1%) as well as fruits and vegetables (9.8%).

The manufacturer does not recommend the use of heated milk, perhaps, to preserve its components and because it has undergone prior sterilization during its production process. According to the objectives of this study, frequency of use is not necessary. According to a survey conducted as part of this study, only 41.5% of mothers follow the infant meal preparation recommendations established by manufacturers, while 49% of them do not follow the label instructions. Indeed, these mothers have no information on the safe preparation schedule and prefer to use hot water (more than 60°C) to ensure the death of the microbes probably present (as they called) in the infant's flour without taking into account guaranteeing the nutritional quality of prepared dishes. Indeed, 37.5% and 5.8% of mothers prepared the infant's

meal with water heated to 60-80°C and 80-100°C respectively, The results are summarized in Table 1.

Concerning the exposure time, it depends on the initial temperature. This is the time spent (min) necessary to reach the consumption temperature above 45°C. Exposure times were calculated for each temperature (50°C, 60°C, 70°C, 80°C, 90°C, 100°C) The results are summarized in Figure 1. They were used to calculate the biological destruction value (L(T)). Whatever the temperature tested, the temperature of the meal decreases. For a temperature < 50°C, the temperature directly reaches 45°C in 3 min.

The biological killing value (L(T)) was calculated for each kinetic temperature and tested isolate. L(T) was proportional to temperature. The results showed that the high values were observed at 100°C (median = 5.40; mean = 7.36; 95e = 19.92). Then, these values were used to calculate the decimal reduction ratio "n" at each temperature. The "n" values depended on the preparation temperature and L(T). However, the lowest temperature effect was estimated for temperature <50°C, high values were reported at 100°C (median = 2.22; mean = 3.16; 95e = 12.35) , while low values were reported at 50°C (median = 0.02 = mean; 95e = 0.35) The results are summarized in Table 2.

It should be noted that the prevalence (74%) of *B. cereus sensu lato* seemed similar to the prevalence (78%) reported by Heini (2018) and higher than 3.5% reported by Zhang et al. (2017). As for their concentrations in the samples analyzed, they agreed with those reported (3 to 4 log CFU/g) by Zhang et al. (2017). The presence of *B. cereus sensu lato* in the analyzed samples is evident because (1) infant flour is not a sterile product, (2) and is produced with various ingredients generally contaminated with the *B. cereus* group. Indeed, several ingredients of infant flour are contaminated by *B. cereus sensu lato*, mainly rice (Sarrias et al. 2002), corn (Byaruhanga et al. 1999), wheat (Valerio et al. 2012) or oats and other cereals (Daczkowska-Kozon et al. 2009).

The *B. cereus sensu lato* group is mainly present in raw materials, which increases its probability and confirms its presence in infant flour. The presence of *B. cereus sensu lato* in infant flour could be due to several factors: (1) the contaminated raw material, (2) the ability of *B. cereus sensu lato* to produce a spore form to survive under conditions hostile, particularly at low aw of this product (infant flour). Fortunately, at this stage, *B. cereus sensu lato* does not exceed a critical concentration (5 log CFU/g) and could decrease after preparation with lukewarm boiling water depending on the preparation methods.

The problem is not only related to the existence of *B. cereus sensu lato* in the product, but also to (1) its resistance to heat and its ability to grow and reach a critical concentration (5 log cells per g) and (2) the low preparation temperature for the two patterns (manufacturing instructions and mother preparation). Thus, the level of *B. cereus* could increase particularly during their survival and growth during preparation and storage respectively. In fact, Sadek et al. (2018) consider infant formula to be an excellent medium for bacterial growth. Buss da Silva et al. (2017) showed the growth of three tested strains of *B. cereus* in reconstituted infant formula. Otherwise, Messelhäusser et al. (2014) reported that cereal-based infant formula, rich in vitamins and trace elements, is known to promote cereulide synthesis.

The concentration of *B. cereus sensu lato* in different preparations was estimated by equation 5 developed by Nauta (2001) and Membré and Valdramidis (2016). The probabilistic approach was used to simulate the concentration of *B. cereus sensu lato* using the Poisson distribution: [*B. cereus* sl]s = Riskfish([*B. cereus* sl] × m0 ×10) (5) where [B. cereus sl]s: survival concentration (CFU per quantity prepared) of *B. cereus sensu lato* in the meal after heating; [*B. cereus* sl]0: Distribution of the initial concentration (CFU per gram of infant flour analyzed) of B. cereus sensu lato. It was adjusted by RiskDuniform (C1, C2, C3,…, Ci) × RiskBeta (number of contaminated samples + 1, no contaminated samples + 1). C1 to Ci are the concentrations of *B. cereus sensu lato* in each positive sample (1 to i respectively). As for the probability of appearance of toxigenic strains among these concentrations, the RiskUniform distribution (0; 1) was used. In the absence of information on the distribution of toxigenic bacteria among the *B. cereus* group, it was assumed that toxigenic B. cereus could represent any percentage (ranging from 0 to 100%) of all B. cereus groups. . cereus which was therefore described by a RiskUniform(0;1) as shown by Ziane et al. (2019).

Monte Carlo simulations of initial concentrations of toxigenic *B. cereus* in infant flour before preparation were assumed to be (median = 2.489; mean = 2.615; 99e = 3.75) log CFU/g. After preparation, the possible concentrations of toxigenic B. cereus and according to equation 5 the low values (CFU per g of prepared meal) were estimated for a temperature of 100 °C. °C (min=0, median = 0.004; mean = 0.135; 99e = 1.24 log CFU/g) followed by the 90 °C scenario (min=0, median = 0.036; mean = 0.142, 99e = 1.226 log CFU/ g). Both of these temperatures are safe for infants, while heating to the temperature recommended by manufacturers is unsafe and no significant effect (ANOVA $P < 0.001$) on initial concentration was observed.

3. Tables & Figures:

Table (1):Impact of mothers' educational level on infant feeding.

N°	Questions pour les pratiques de préparations de repas	% de ménage pour chaque réponse		
		Oui	Non	ND
01	Education nutritionnelle	20	80	/
02	Conscience de danger mcirobiologique dans la FI	80	15	5
03	Source d'information	Télévision, réseaux sociaux		
04	Lave main avant manipulation de FI	92,4	7,6	/
05	Re-lavage des ustensiles utilisés	90	6	4
06	Eau de préparation Minéral Robinet	86 14	/	/

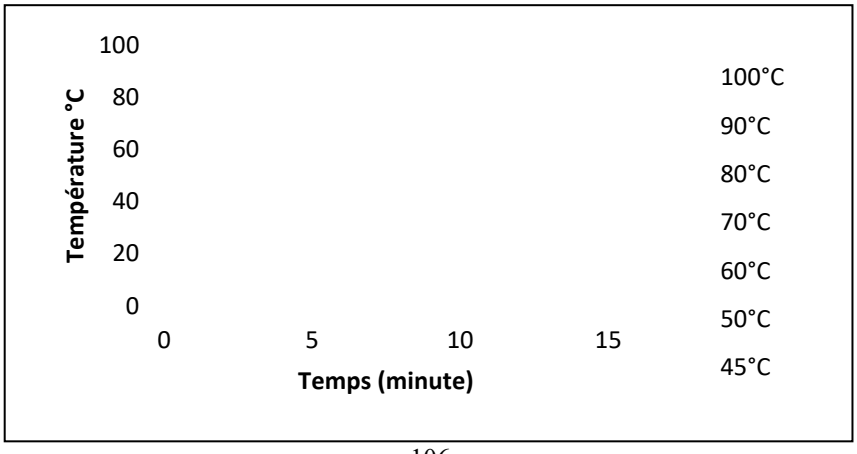
Table (2): Results of the evaluation of critical concentrations during the consumption of infant flour meals. The concentrations are simulated from the concentrations of spores resulting from each heat treatment.

Etape	Symbole	Unité	Distribution
Contamination initiale			
Concentration de *B. cereus* dans les échantillons analysés	$[B.\ cereus\ sl]_0$	Ufc/g	RiskUniform(N_1 à N_{72})
Probabilité de *B. cereus* toxinogène	Prt		RiskUniform(0 :1)
Concentration de *B. cereus* dans les échantillons analysés	$[B.\ cereus]_0$	Ufc/g	$[B.\ cereus\ sl]_0 \times$ Prt
Nombre des échantillons analysés	Pt		//
Nombre des échantillons non contaminé	Pn		//
Nombre des échantillons contaminé	Pp		Pt-Pn
Prévalence de *B. cereus sensu lato* dans les échantillons analysé	P		((Pt-Pn)/Pt)×100
Distribution de *B. cereus sensu lato* dans la farine infantiles commercialisé dans la région de Béchar	$[B.\ cereus]_{FI}$	Ufc/g	RiskBéta(Pt-Pn+1 ;Pn+1) × $[B.\ cereus]_0$

Temps de réduction décimale	$D_{T°C}$	min	Eq (1)
Sensibilité au traitement thermique	$z_{T°C}$	°C	Eq (2)
Cinétique de la température		°C	Riskpert()
Destruction biologique	L(T)	°C	Eq (3)
Nombre de réduction décimale	n		Eq (4)
Concentration de *B. cereus* toxinogène survivante	$[B.\ cereus]_s$	Ufc/g	Eq (5)
Croissance de *B. cereus* toxinogène		h	Eq (6)
Température cardinale : minimale/maximale/optimale	$T_{min}/T_{max}/T_{opt}$	°C	Littérature (Tableau 22)
Taux de croissance optimum	μ_{opt}	h^{-1}	Eq (8)
Modèle gamma γ	$\gamma_{T°C}$	°C	Eq (7)
Taux edc roissance maximum dans la farine infantile	$\mu_{T°C}$	h^{-1}	Eq (9)
Temps de latence dans la farine infantile	$\lambda_{T°C}$	h	Eq (10)
Concentration de *B. cereus* toxinogène dans le repas au moment de la consommation	$[B.\ cereus]_{repas}$	Ufc/g	Eq (11)
Evaluation de l'exposition	P≥5 log ufc		1-Risktarget($[B.\ cereus]_{repas}$;5)
Fréquence de chaque scenario temps/température	Ps		Questionnaire d'enquête
Nombre de repas contient ≥ 5 log ufc pour 100 enfants			P × Ps

Source: Difallah et *al*, .2021

Fig.1. Concentration (log UFC) of B.cereus during meal preparation 10^2



5. Conclusion

Great attention should therefore be paid to the consumption of infant flour in terms of the emergence of potential microbial hazards such as spores of the bacteria group *B. cereus sensu lato*, known for their resistance to heat. Depending on the preparation patterns, *B. cereus sensu lato* could be involved in food poisoning. Our results showed that 75% of infant flour samples were contaminated with *Bacillus*. Furthermore, the results of this article highlight the effectiveness in reducing the rate of *B. cereus sensu lato* compared to the manufacturer's instructions, only the modes of use need to be improved. Thus, some recommendations could be established to avoid problems linked to this type of bacteria: - Choose a relevant raw material; - Continuously improve the process and control it; - Review the preparation instructions and improve the solubility of the product at high temperatures; - Reduce the quantity of flour from 200 g to 100 g per package; - Add the storage condition to the packaging. Finally, as perspectives for this study, additional experiments will have to be carried out in the future, on: (1) determining the affiliation of *B. cereus* to different groups; (2) study their growth in the infant's flour meal; (3) conduct a microbial risk assessment to obtain sufficiently in-depth details about this type of bacteria, which will undoubtedly help industries during the production process and stores during storage.

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Immunotherapy in Non-Small Cell Lung Cancer: A Comprehensive Literature Synthesis

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Abstract:
This study aims to assess the therapeutic impact of immune checkpoint inhibitors (ICIs) targeting PD-1, PD-L1 and CTLA-4 in non-small cell lung cancer (NSCLC), with particular emphasis on PD-L1–guided treatment strategies and implementation challenges in low- and middle-income countries (LMICs). A structured case-study–based literature synthesis was conducted, including landmark randomized clinical trials, meta-analyses and international guidelines published between 2015 and 2025, retrieved from PubMed, Scopus and Web of Science, focusing on clinical efficacy, immune-related adverse events and biomarker-driven decision-making. The results indicate that ICIs significantly improve overall survival in NSCLC, extending median survival from approximately 8 months with conventional chemotherapy to nearly 24 months in selected patients; therapeutic benefit varies according to PD-L1 expression, favoring monotherapy for PD-L1 ≥50% and chemo-immunotherapy combinations for lower expression levels, while immune-related toxicities and biomarker heterogeneity remain major limitations. From a policy and public-health perspective, LMICs such as Algeria require standardized PD-L1 testing, reinforced multidisciplinary expertise for toxicity management, and adaptive health policies incorporating cost-containment strategies and digital oncology tools to optimize equitable access and maximize the clinical impact of immunotherapy in NSCLC.
Keywords: immunotherapy; non-small cell lung cancer; PD-L1; immune checkpoint inhibitors; immune-related adverse events.

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1. Introduction

Non-small cell lung cancer (NSCLC) represents ~85% of lung cancers and remains a leading cause of cancer mortality worldwide. Although platinum-based doublet chemotherapy historically offered limited survival benefit in advanced disease, the therapeutic landscape has been reshaped by immune checkpoint inhibitors (ICIs) and the progressive integration of biomarker-guided strategies. Long-term follow-up data confirm durable benefit with anti-PD-1 therapy in PD-L1-high metastatic NSCLC, with 5-year outcomes supporting pembrolizumab monotherapy as a reference option in selected patients (Reck et al., 2021). In parallel, immunotherapy has expanded beyond metastatic settings: consolidation durvalumab after concurrent chemoradiotherapy in unresectable stage III NSCLC demonstrated sustained overall survival benefit at 5 years (Spigel et al., 2022), and perioperative/neoadjuvant regimens have shown clinically meaningful improvements in event-free survival and pathologic response, notably with nivolumab plus chemotherapy in resectable disease (Forde et al., 2022). These advances underscore the need to link **biological mechanisms, clinical evidence across PD-L1 strata,** and **implementation constraints**—particularly in low- and middle-income countries (LMICs), where access, testing standardization, and toxicity management capacity can determine real-world impact.

2. Evolution of NSCLC Immunotherapy

2.1 Historical Perspective on NSCLC Treatment

In the early 2000s, systemic therapy for advanced NSCLC was largely dominated by platinum-based chemotherapy doublets, with modest survival outcomes and significant toxicity. As molecular oncology matured, targeted therapies improved outcomes in oncogene-addicted subgroups, but their scope remained limited to specific alterations. The modern immunotherapy era emerged from the recognition that tumors exploit immune checkpoints to suppress antitumor T-cell responses, enabling durable clinical responses with ICIs across broader patient populations. Over the last five years, the field has accelerated through **treatment intensification strategies** (chemo-IO and dual-IO regimens) with sustained long-term follow-up, including 3-year updates and subsequent longer analyses of nivolumab–ipilimumab–based approaches

(Bordenave, S et al., 2024), and **stage migration of immunotherapy** into curative-intent settings, such as adjuvant atezolizumab after resection and chemotherapy (IMpower010) (Felip et al., 2021) and perioperative pembrolizumab strategies supported by maturing survival analyses (Spicer et al., 2024). Collectively, these milestones position immunotherapy not as an "add-on," but as a central pillar of NSCLC care across stages, with PD-L1 testing and multidisciplinary capacity increasingly critical to treatment selection and safety.

2.2 Mechanisms of Immune Checkpoint Inhibition

ICIs restore antitumor immunity by blocking inhibitory pathways that restrain T-cell activation and effector function. The PD-1/PD-L1 axis primarily downregulates T-cell signaling in peripheral tissues and within the tumor microenvironment; interruption of this interaction can reinvigorate exhausted T cells and enhance cytotoxic activity against tumor cells (Liu et al., 2024). By contrast, CTLA-4 mainly acts earlier in the immune response, competing with CD28 co-stimulation and limiting T-cell priming, providing a rationale for combinatorial regimens that may increase breadth and depth of response but at the cost of higher immune-related toxicities. In clinical practice, PD-L1 immunohistochemistry (IHC) remains a pragmatic biomarker to guide first-line choices; however, assay-related variability and threshold-dependent interpretation can influence eligibility and outcomes. Recent comparative analyses report strong concordance between commonly used assays (e.g., SP263 vs 22C3) in NSCLC-relevant contexts, supporting harmonization efforts (Zhou et al., 2023). Because ICIs can induce immune-related adverse events affecting multiple organs, implementation requires standardized toxicity recognition pathways and guideline-based management; updated international guidance remains foundational for safe scale-up (Schneider et al., 2021).

Research question:

To what extent do PD-1/PD-L1 and CTLA-4 immune checkpoint inhibitors improve clinical outcomes across PD-L1 expression strata in NSCLC, and what implementation barriers (PD-L1 testing standardization, toxicity management capacity, and access constraints) most critically shape their real-world impact in LMIC settings such as Algeria?

3. Literature Review Methodology

3.1 Search Strategy

A structured literature review was conducted to identify relevant studies addressing the role of immune checkpoint inhibitors (ICIs) in non-small cell lung cancer (NSCLC). Searches were performed in **PubMed, Scopus**, and **Web of Science**, covering publications from **January 2015 to March 2025**, with particular emphasis on updated evidence from **2021–2025**. The search strategy combined Medical Subject Headings (MeSH) terms and free-text keywords, including *"non-small cell lung cancer," "immunotherapy," "PD-1," "PD-L1," "CTLA-4," "immune checkpoint inhibitors," "immune-related adverse events,"* and *"precision oncology."*

Eligible studies included randomized controlled trials (RCTs), meta-analyses, pooled analyses, and international clinical guidelines published in English. Priority was given to landmark phase II–III trials and high-impact journals. Additional references were identified through manual citation tracking to ensure comprehensive coverage of both clinical efficacy and implementation perspectives, including global health considerations relevant to low- and middle-income countries (LMICs).

3.2 Theoretical Analysis and Data Synthesis

Data extraction focused on study design, patient population, line of treatment, PD-L1 expression assessment, therapeutic strategy (single-agent immunotherapy, chemo-immunotherapy, or dual immunotherapy), and key clinical outcomes. Primary endpoints included overall survival (OS), progression-free survival (PFS), objective response rate (ORR), and safety profiles.

A **narrative and comparative synthesis** approach was adopted to integrate evidence from pivotal RCTs (e.g., *KEYNOTE-024, KEYNOTE-189, CheckMate-057, CheckMate-227*) and contemporary meta-analyses. Studies were analyzed within a conceptual framework linking immune checkpoint biology, biomarker-driven decision-making, and real-world feasibility. Particular attention was paid to challenges related to PD-L1 assay variability, toxicity management, and disparities in access to immunotherapy across healthcare systems.

3.3 Efficacy According to PD-L1 Expression Levels

To evaluate treatment effectiveness, studies were stratified according to tumor PD-L1 expression levels (≥50%, 1–49%, and <1%), as assessed by immunohistochemistry. In patients with **high PD-L1 expression (≥50%),** single-agent anti–PD-1 therapy demonstrated substantial clinical benefit, with durable responses and significantly prolonged OS compared to chemotherapy.

For tumors with **intermediate PD-L1 expression (1–49%)**, combination strategies integrating immunotherapy with platinum-based chemotherapy consistently improved survival outcomes over chemotherapy alone. In contrast, patients with **low or negative PD-L1 expression (<1%)** derived limited benefit from immunotherapy monotherapy, with better outcomes observed using chemo-immunotherapy or selected dual immunotherapy regimens. This stratified synthesis highlights the central role of PD-L1 as a predictive biomarker while underscoring its limitations and the need for complementary markers.

3.4 Immune-Related Adverse Events (irAEs)

Immune checkpoint inhibition is associated with a distinct spectrum of immune-related adverse events (irAEs) resulting from nonspecific immune activation. The reviewed studies consistently reported dermatologic, gastrointestinal, hepatic, pulmonary, and endocrine toxicities, typically emerging within the first **3 to 6 months** of treatment. While most irAEs are low-grade and manageable, severe grade 3–4 events occur in a minority of patients and may require systemic corticosteroids or immunosuppressive therapy.

The analysis also considered atypical clinical patterns, such as pseudo-progression, which can complicate radiologic assessment, and infectious complications, including reactivation of latent infections. These safety considerations are particularly relevant in LMIC contexts, where diagnostic resources and specialized multidisciplinary management may be limited. The synthesis emphasizes the importance of early recognition protocols, clinician training, and standardized management guidelines to ensure safe and effective immunotherapy deployment.

5. Development Hypotheses (Non-tested)

Based on the theoretical framework of immune checkpoint inhibition, biomarker-driven oncology, and health-system constraints in LMICs, the

present literature review is guided by the following non-tested developmental hypotheses:

- **H1**: PD-L1 expression level is a key determinant of immunotherapy efficacy in NSCLC and should guide first-line therapeutic strategies.
- **H2**: Chemo-immunotherapy combinations provide superior survival benefit compared to immunotherapy alone in patients with low or intermediate PD-L1 expression.
- **H3**: Variability in PD-L1 assessment significantly impacts treatment allocation and clinical outcomes, particularly in resource-limited settings.
- **H4**: Immune-related adverse events constitute a major barrier to immunotherapy implementation in LMICs due to limited multidisciplinary expertise.
- **H5**: Health-system constraints (cost, infrastructure, geographic access) substantially limit the real-world effectiveness of ICIs in LMICs such as Algeria.

These hypotheses structure the interpretation of the results and highlight the originality of this synthesis at the intersection of molecular oncology and health policy.

6. Results

6.1 Descriptive Statistical Framework and Study Variables

To structure the synthesis of evidence, variables were classified into **dependent, independent**, and **control variables**, as summarized in Table 1.

Table 1. Descriptive Framework of Variables Used in the Literature Synthesis

Variable Type	Variable	Description
Dependent variables	Overall survival (OS)	Median and long-term survival outcomes reported in RCTs
	Progression-free survival (PFS)	Time to disease progression or death
	Objective response rate (ORR)	Proportion of patients achieving partial or complete response
	Incidence of irAEs	Frequency and severity of immune-related adverse events

Variable Type	Variable	Description
Independent variables	PD-L1 expression level	Stratified as ≥50%, 1–49%, <1%
	Treatment strategy	IO monotherapy, CT-IO, IO-IO
	Type of immune checkpoint	PD-1, PD-L1, CTLA-4
Control variables	Line of treatment	First-line vs later lines
	Disease stage	Resectable, locally advanced, metastatic
	Patient characteristics	Performance status, disease burden
	Healthcare setting	High-income vs LMIC context

6.2 Summary of Clinical Efficacy Across PD-L1 Subgroups

The synthesis of randomized trials demonstrates a clear gradient of efficacy according to PD-L1 expression. In patients with **PD-L1 ≥50%**, single-agent anti-PD-1 therapy consistently yields the highest ORR (≈40–45%) and median OS approaching 24 months. In the **PD-L1 1–49% subgroup**, chemo-immunotherapy combinations significantly improve OS and PFS compared with chemotherapy alone. For **PD-L1 <1% tumors**, immunotherapy monotherapy shows limited benefit, while CT-IO strategies outperform IO-IO regimens in most analyses, except in selected high-TMB populations.

6.3 Safety Outcomes and Immune-Related Adverse Events

Across trials, irAEs were reported in all immunotherapy regimens, with dermatologic, gastrointestinal, endocrine, hepatic, and pulmonary toxicities predominating. Grade 3–4 irAEs occurred in less than 10% of patients but required prompt immunosuppressive management. Pseudo-progression and infectious complications were infrequent but clinically significant, particularly in LMIC settings where diagnostic and monitoring resources are limited.

7. Discussion

Immunotherapy has profoundly altered the prognosis of NSCLC, transforming a historically lethal disease into one with durable responses in a substantial proportion of patients. The results synthesized in this review support **PD-L1 expression as a central—but imperfect—biomarker** guiding

treatment stratification. High PD-L1 tumors derive marked benefit from immunotherapy monotherapy, whereas intermediate and low expressors benefit most from combination approaches.

However, **biomarker variability** remains a critical limitation. Differences between PD-L1 assays and intratumoral heterogeneity may lead to misclassification and suboptimal treatment selection, an issue magnified in LMICs where access to standardized platforms is inconsistent. Strengthening pathology infrastructure and harmonizing testing protocols are therefore essential steps toward equitable precision oncology.

The burden of **immune-related toxicities** represents another major challenge. While manageable in well-resourced centers, irAEs require multidisciplinary expertise that is often scarce in LMICs. Tailored protocols, training programs, and early-warning systems are needed to safely scale immunotherapy in such contexts.

Finally, **access barriers**—including high drug costs, centralized oncology services, and rural–urban disparities—limit the real-world effectiveness of ICIs in countries like Algeria. International experiences suggest that regional collaboration, negotiated pricing, and digital health solutions (tele-oncology, e-MDTs) may partially mitigate these constraints.

Table 2. Summary of Development Hypotheses and Supporting Evidence (Originality Table)

Hypothesis	Supporting Evidence from Literature	Contribution of This Study
H1: PD-L1 predicts efficacy	KEYNOTE-024, KEYNOTE-189	Integrated across molecular and policy dimensions
H2: CT-IO superior in low PD-L1	CheckMate-227, KEYNOTE-189	Stratified synthesis by PD-L1 thresholds
H3: PD-L1 variability impacts outcomes	Blueprint IHC Project	Contextualized for LMIC implementation
H4: irAEs limit adoption in LMICs	ESMO guidelines, real-world studies	Highlighted as structural health-system issue
H5: Access constraints reduce impact	Global oncology reports	Algeria-focused translational perspective

7. Conclusion

Immunotherapy has profoundly transformed the therapeutic landscape of non-small cell lung cancer (NSCLC), shifting treatment paradigms from uniformly limited survival outcomes toward durable, biomarker-guided clinical benefit. The integration of immune checkpoint inhibitors targeting PD-1, PD-L1, and CTLA-4 has enabled significant improvements in overall and progression-free survival, particularly when treatment selection is guided by tumor PD-L1 expression. This evolution confirms immunotherapy as a cornerstone of precision oncology in NSCLC across multiple disease stages.

However, the clinical promise of immunotherapy is tempered by persistent challenges that limit its real-world effectiveness, especially in low- and middle-income countries (LMICs). Variability in PD-L1 immunohistochemical assessment, disparities in assay availability, and intratumoral heterogeneity undermine consistent patient stratification. In parallel, immune-related adverse events necessitate specialized multidisciplinary expertise and structured monitoring pathways, which remain insufficiently developed in resource-constrained healthcare systems. Economic barriers, centralized oncology services, and geographic inequities further restrict access to these high-cost therapies, perpetuating survival disparities.

Addressing these limitations requires a coordinated and context-adapted strategy. Standardization of PD-L1 testing, reinforcement of pathology and oncology training programs, and the implementation of harmonized toxicity-management protocols are essential prerequisites for safe and effective immunotherapy deployment. Moreover, regional collaboration, negotiated pricing models, and the integration of digital health solutions—such as electronic multidisciplinary tumor boards (e-MDTMs) and tele-oncology platforms—offer pragmatic avenues to expand access and optimize decision-making. In this context, Algeria has the potential to emerge as a regional reference for precision oncology in North Africa by aligning molecular diagnostics, clinical expertise, and health policy innovation. Such an integrated approach is critical to ensuring equitable access to life-saving immunotherapies and maximizing their public-health impact in NSCLC.

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Corruption et performances macroéconomiques des pays de la région MENA : analyse descriptive

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Abstract:
This article investigates the impact of corruption on economic growth in the MENA region, focusing on both direct and indirect effects. The theoretical framework defines corruption as the misuse of public power for private gain and explores its transmission channels through foreign direct investment (FDI) and human capital accumulation.
A descriptive analysis highlights significant disparities across countries. Economies with high levels of corruption attract fewer and less diversified FDI and face deficits in human capital development, which constrain productivity and long-term growth. Conversely, countries with stronger institutions and more diversified economic structures manage to mitigate some negative effects of corruption.
The findings suggest that corruption acts as a structural impediment, limiting the transformation of economic growth into sustainable development. Policy implications include the need for institutional reforms, targeted human capital investments, and differentiated strategies tailored to national contexts. The study also provides avenues for future research, such as quantitative assessments of the indirect effects of corruption and evaluations of anti-corruption policies in the MENA region.
***Keywords*:** corruption, economic growth, foreign direct investment (FDI), human capital, MENA region, institutional disparities.

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Introduction

Etant définie comme l'usage abusif du pouvoir public à des fins privées (Mauro, 1995), la corruption ne se limite pas à un problème de gouvernance ou d'éthique : elle influence directement et indirectement la croissance économique en affectant l'allocation des ressources, la productivité des investissements et l'accumulation du capital humain (Tanzi & Davoodi, 1997; Wei, 2000). Cette corruption constitue l'un des principaux obstacles au développement économique et social dans de nombreux pays, en particulier dans la région MENA (Moyen-Orient et Afrique du Nord).

L'impact direct de la corruption sur la croissance a été largement documenté, alors que ses effets indirects, via les investissements directs étrangers (IDE) et le capital humain, restent moins utilisés dans le contexte spécifique de la région MENA. Cette région présente une hétérogénéité institutionnelle et économique remarquable, contenant de pays aux institutions relativement stables et des économies fortement dépendantes des rentes naturelles et caractérisées par des pratiques corruptives endémiques.

Dans ce contexte, l'objectif de notre article consiste à fournir, en premier lieu, une analyse théorique des mécanismes par lesquels la corruption influence la croissance économique, en distinguant effets directs et indirects, et réaliser en second lieu, une analyse descriptive des disparités régionales, afin d'identifier les pays et mécanismes les plus vulnérables aux impacts négatifs de la corruption. En fait, les résultats de ce travail visent à enrichir la compréhension des effets structurels de la corruption et à soutenir les politiques publiques favorables à un développement durable et inclusif dans la région MENA.

I. Influence de la corruption sur la croissance économique : cadre théorique

1. Définition de la corruption :

La corruption se définit comme l'abus d'un pouvoir détourné à des fins privées, impliquant des pratiques telles que la corruption active et passive, le détournement de fonds et le trafic d'influence, qui touchent l'efficacité économique, la gouvernance et la confiance institutionnelle. Selon la Banque mondiale (1997), la corruption correspond à l'utilisation abusive d'une fonction publique pour obtenir un avantage personnel, tandis que Transparency International (2023) élargit cette définition à tout abus de pouvoir, qu'il soit

public ou privé. La Convention des Nations Unies Contre la Corruption (CNUCC, 2003) souligne que ces pratiques constituent un frein majeur au développement durable et à la stabilité institutionnelle. Rose-Ackerman (1999), considère aussi la corruption comme un comportement rationnel par lequel des agents économiques contournent les règles formelles afin de maximiser leurs intérêts privés, au détriment de l'intérêt général et de la performance économique. Pour cette raison, plusieurs études théoriques et empiriques se sont intéressées à déterminer l'influence directe et indirecte de la corruption via divers canaux sur la croissance économique.

2. Influences directs et indirects de la corruption sur la croissance économique

2.1- Influences directs

Dans son effort de mettre en évidence l'importance de la corruption, Transparency International a montré que la corruption représente un obstacle pour la croissance économique, sape le bien-être matériel et la justice sociale. En fait, pour promouvoir un monde plus équitable et supprimer la pauvreté extrême, il faut réduire la corruption qui décourage l'éducation, la santé, le commerce et l'environnement. Cette corruption est présentée comme l'un des mauvais ennemis du développement [Gbaguidi, (2006)].

Les recherches de Celentani et Ganuza (2002) ont appuyé qu'un climat de corruption abondante, encourage l'apparition des comportements opportunistes justifiés par la recherche degains futurs. Ces comportements ni autres que l'asymétrie d'information qui correspond à l'acquisition par un agent ou un groupe d'agents d'une information privée utilisée à leur avantage. Cette asymétrie d'information constituant le principal déterminant de la corruption(Laffont et Meleu, (2001), a fait l'objet des nouvelles études de Van Rijckeghen et al (2001) et de Kraster et Ganer (2004).

De son côté, Mauro (2001), dans une étude relative à la détermination de la causalité entre le niveau de la croissance économique et l'indice de la corruption, a montré que la corrélation n'est pas toujours négative. Il affirme que la corruption peut être examinée dans certains cas comme une mesure stimulante du travail et de production. Cette idée est infirmée par les travaux de Vega-Gordillo et Alvarez-Arce (2003) et de Del Monte et Pagagni (2001). De même, pour d'autres économistes tels que Ades et Di Tella (1999),

plusieurs entreprises aux États-Unis, ont tiré des rentes et prouvent leur compétitivité sur le marché dans un climat de forte corruption.

Dans le même contexte, Osborne (2004) a présenté à travers une comparaison, que les politiques gouvernementales de quelques pays en développement n'ont pas d'effets réels et positifs sur la croissance économique, alors que pour le cas des pays d'Europe et les États- Unis, les tendances sont inversées. Ceci est justifié selon l'auteur par la mauvaise gouvernance qui caractérise la plupart des pays pauvres du continent africain.

Les distorsions de politiques économiques qui règnent dans la plupart des pays en développement et résultant de la mauvaise qualité des contrôles et des instances de régulation, ralentissent le dynamisme économique (Ali et Crain, 2002). Ainsi, Al-Marhubi (2004) insiste sur la crédibilité de l'État, autrement dit, sa capacité à respecter ses engagements et à disposer une atmosphère de stabilité sociale assurant une croissance économique forte et soutenue. Or, la crédibilité de l'État est affectée par la corruption qui a affaibli à leur tour l'efficience des actions Étatiques capables de favoriser la croissance. Pour Hoskins (2001), la faiblesse de la crédibilité de l'État est à la base de la répartition inégalitaire des revenus et de croissance, ainsi que de la mauvaise régulation économique. Il préfère un État fort qui tient en compte ses promesses et ses engagements.

A cet égard, Certains économistes pensent que la corruption affaiblit l'investissement total et réduit la qualité de l'infrastructure d'un pays. Ces effets pervers touchant les processus de création des infrastructures, sont révélés pareillement par Laffon et N'Guessan (1999) et par Laffon et N'Gbo (2000) dans un modèle tenant en compte l'expansion des réseaux pour les pays en développement. Braguinsky (1996) et ces auteurs sont parvenus aussi au même résultat indiquant que l'asymétrie d'information accomplie par un pouvoir illégal, est un facteur important de lacorruption.

De leurs côtés, Gupta, Davoodi et Tiongson (2000) suggèrent que la corruption diminue les dépenses publiques à la santé ce qui conduit à l'augmentation du taux de mortalité infantile. Certes, il y a une relation positive et significative entre les activités improductives et la corruption (Tanziet Davoodi, 2000).

2.2- Influences indirects de la corruption via divers canaux de transmission

Pellegrini et Gerlaugh (2004) et Mauro (2000, 2001) ont analysé empiriquement l'influence directe de la corruption sur la croissance économique, ainsi que leur effet indirect via plusieurs variables exogènes. En général, ces études ont montré que cette corruption influe négativement sur la croissance économique via l'investissement et le commerce international. Pellegrini et Gerlaugh (2004) ont montré qu'il n'y a pas une relation statistiquement significative entre la corruption et la croissance économique, si et seulement si tous les facteurs déterminants sont contrôlés.

Martinez-Vazquez J., McNab R. et Everhart S. (2005) ont montré que la corruption, en plus de leur influence directe sur l'évolution du PIB par habitant, elle peut l'affecter indirectement en limitant l'accumulation du capital humain privé et public. Pour cette raison, tout effort de diminuer la corruption, a des effets positifs directs et indirects sur le niveau du PIB par habitant.

Dans le même contexte, les variables institutionnelles affectent doublement les niveaux de revenu. Premièrement, elles influencent directement la productivité, et deuxièmement, elles modifient le taux d'investissement et indirectement le niveau de revenu, à travers l'accumulation du capital (Silvio Bornern, Frank Bodmer et Markus Kobler, 2004).

King et Levine (1994) ont examiné l'accumulation du capital dans un cadre plus général et ont cherché à déterminer si elle représente une force motrice de la croissance comme dans le modèle de Solow ou, au contraire, une conséquence. Dans l'une de ces études, De Long et Summers (1991) ont démontré que la corrélation va sans doute dans le sens de la croissance comme force motrice de l'investissement, et à leur tour, les taux d'investissement influencent les taux de croissance. Cette relation pose quelques questions économétriques difficiles, mais renforce l'importance des facteurs politiques.

Ainsi, en étudiant la situation des performances macroéconomiques des nations dans un climat de grande corruption, Rotberg (2004) montre que cette dernière nuit considérablement à la croissance économique via son

effet sur l'investissement. Les travaux de Mauro (1995) s'intéressent à l'étude de la relation entre la corruption et l'investissement précisément le ratio de l'investissement sur le PIB. Mauro prouve une corrélation négative : un degré de corruption élevé entraîne une diminution de l'investissement. Il déduit donc que la corruption est défavorable à la croissance et au développement économique.

En revanche, Tanzi et Davoodi (1997) ont avancé que la corruption est capable d'augmenter l'investissement public, mais elle réduit en contrepartie la productivité. Ils ont avéré qu'un niveau élevé de la corruption est associé à une baisse des dépenses publiques et de la qualité de l'infrastructure, ce qui aura un impact négatif sur la croissance économique. Cette corruption peut avoir aussi des effets sur la structure des dépenses publiques, autrement dit, les pays les plus corrompus ont moins des dépenses publiques en éducation (Mauro, 1998). Gupta, Davoodi et Alonso-Terme (1998) ont prouvé que les stratégies anti-corruption permettent de diminuer les inégalités économiques et la pauvreté.

Pour d'autres tels que Collier (2000), la corruption permet à des entreprises peu rentables de profiter de subventions gouvernementales, ce qui rend une grande partie des dépenses publiques moins efficaces. En d'autres termes, un niveau élevé de la corruption freine la croissance économique par le biais des dépenses publiques. Cette relation a été établie dans nombreux pays d'Europe et d'Asie.

Une corruption élevée entraîne une diminution de la part des dépenses publiques en éducation et en santé et une augmentation des dépenses militaires et gouvernementales (Gupta, Mello et Sharan, 2000). Tanzi et Davoodi (1997) ont montré aussi que le niveau élevé de la corruption affaiblit la recette fiscale. Chong et Calderon (1997) ont dévoilé qu'une population plus cultivée aura la possibilité de produire une bureaucratie plus instruite et moins corrompue et par suite des institutions efficientes.

Ce concept de la corruption constitue alors un frein à la croissance économique à travers son impact négatif via l'accumulation du capital humain (Tavares et Wacziarg, 2001 et Seka, 2005). Néanmoins, un autre courant de pensée a tourné la relation entre la corruption et la croissance économique, en montrant qu'un climat propice à la corruption génère des

incitations au travail et engendre une plus grande productivité. Ainsi, Ono et Shibata (2001) ont remarqué que les dépenses tirées par le pouvoir public malgré la mauvaise gouvernance, déterminent une augmentation soutenue du PIB et une accumulation progressive du capital.

A cet égard, nous tentons dans le travail qui suit d'effectuer une analyse descriptive afin de spécifier la nature de la relation entre la corruption et les performances macroéconomiques des pays en développement, en particulier la région du Moyen-Orient et de l'Afrique du Nord (MENA). L'intérêt de la prise en compte de cet échantillon est de montrer que quoiqu'il renferme des pays qui sont riches en ressources naturelles et ayant atteint un niveau de revenu important, ces pays n'arrivent pas atteindre le niveau de la croissance économique des pays développés. Ceci peut être expliqué par les défaillances institutionnelles qui caractérisent cette région. En ce cas, notre étude adopte une approche descriptive visant à mettre en évidence des régularités empiriques et des associations entre la corruption, la croissance économique et ses principaux canaux de transmission, sans prétendre établir une relation causale stricte.

II. Un aperçu de la situation socio-économique de la région MENA : une analyse descriptive

La région du Moyen-Orient et de l'Afrique du Nord (MENA) se distingue par de profondes divergences économiques, regroupant à la fois des pays exportateurs de pétrole à hauts revenus, principalement situés dans le Golfe, et des pays relativement pauvres en ressources naturelles, tels que l'Égypte, le Yémen ou le Maroc. Deux facteurs majeurs ont historiquement accompli la trajectoire économique de la région : en premier lieu, la dépendance aux hydrocarbures et à l'instabilité des prix du pétrole, et en second lieu, le rôle prédominant de l'État dans l'activité économique, hérité en grande partie des structures institutionnelles issues de la période coloniale.

La région MENA comprend un ensemble de pays à revenus faibles et intermédiaires, notamment l'Algérie, l'Égypte, l'Iran, l'Irak, la Jordanie, le Liban, le Maroc, la Tunisie et le Yémen, aux côtés de pays à revenus élevés, tels que les États du Conseil de coopération du Golfe. Malgré des niveaux de revenus par habitant, des tailles économiques et des structures productives très

hétérogènes, ces économies partagent plusieurs contraintes structurelles communes, parmi lesquelles un chômage élevé, en particulier chez les jeunes, une dépendance excessive aux rentes, une faible diversification productive et une gouvernance économique réformable.

À partir de la fin des années 1980 et surtout durant les années 1990, plusieurs pays de la région se sont engagés dans des programmes de réformes économiques et structurelles visant à rétablir les équilibres macroéconomiques et à accélérer une transition progressive d'un modèle dominé par l'État vers un modèle accordant un rôle accru au secteur privé (Banque Mondiale, 2007). Ces réformes ont contribué à une amélioration relative des performances macroéconomiques au début des années 2000. Toutefois, depuis le milieu des années 2000, la dynamique de croissance de la région est restée fragile et inférieure à celle des autres régions émergentes, à cause de chocs répétés, spécialement la crise financière mondiale de 2008, les bouleversements sociopolitiques résultants des révolutions arabes, les fluctuations des prix du pétrole, ainsi que plus récemment la pandémie de COVID-19 et les tensions géopolitiques persistantes (Banque Mondiale, 2022-2023).

En dépit des phases de reprise régulières, en particulier dans les pays exportateurs de pétrole en périodes de hausse des prix des hydrocarbures, la croissance économique de la région MENA reste insuffisante pour absorber la forte croissance démographique et réduire durablement le chômage et les inégalités sociales (FMI, 2023). En la comparant aux autres régions du monde, la région MENA continue à afficher des performances économiques relativement modestes. Ceci renforce la nécessité d'approfondir les réformes structurelles, d'accélérer la diversification économique et de renforcer le cadre institutionnel afin de soutenir une croissance plus durable.

1. Évolution de la croissance économique

Les inégalités en termes de revenu et de niveau de vie, persistent entre pays développés et pays en développement, malgré l'enregistrement des progrès dans certaines régions du monde. En effet, lorsque plusieurs économies ont connu, au cours des dernières décennies, des phases de croissance relativement soutenue suivies d'une amélioration partielle des conditions de vie, la pauvreté semble une réalité pour une large proportion de la population mondiale. Cela s'explique par l'existence persistant d'une crise des inégalités, marquée par une

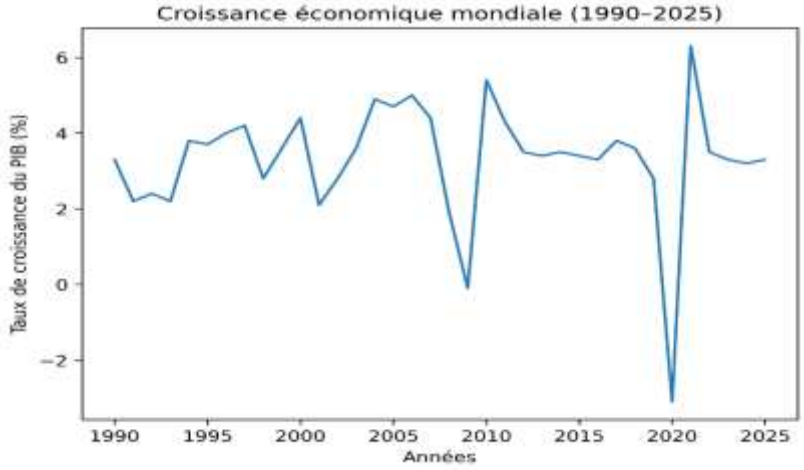
distribution inégale des fruits de la croissance économique, tant au niveau international qu'au sein des pays.

1.1. Écarts mondiaux en termes de croissance économique

La persistance de la crise des inégalités, cause dans certains cas, l'aggravation des écarts économiques et sociales à l'échelle mondiale (Rapport sur la situation sociale dans le monde des Nations Unies, 2005). Ces derniers se manifestent surtout par une divergence marquée entre économies structurées et non structurées, ainsi que par un écart croissant entre travailleurs qualifiés et non qualifiés. Ces inégalités se perçoivent précisément dans l'accès différencié aux services essentiels, tels que la santé et l'éducation, ainsi qu'aux opportunités de participation économique, sociale et politique.

En conséquence, les performances de croissance économique changent selon les régions du monde, indiquant des différences structurelles au niveau de capital humain, de spécialisation productive, de gouvernance et de qualité des institutions. Ces écarts régionaux forment un cadre analytique approprié pour mettre la région du Moyen-Orient et de l'Afrique du Nord (MENA), sur le chemin de croissance qui semble intermédiaire mais caractérisé par une forte instabilité. L'étude comparative de la croissance économique constitue un outil pour mieux comprendre les facteurs expliquant les inégalités de développement et examiner le rôle des variables institutionnelles, surtout la corruption, dans la dynamique économique des régions du monde.

***Fig. 1*- Croissance économique mondiale 1990-2025**

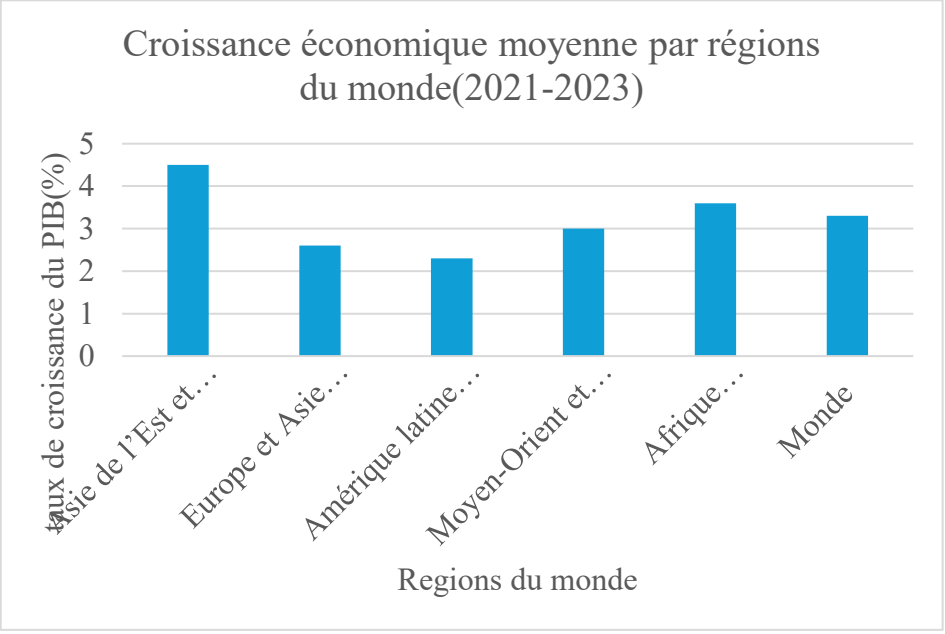


***Source** : Présentation propre à l'auteur à partir des données du World*

Development Indicators, WDI (1990–2023) ; FMI et OCDE (Perspectives économiques mondiales, prévisions 2024–2025)

La figure met en évidence une dynamique cyclique de la croissance économique mondiale, marquée par des ralentissements lors des crises majeures de 2008–2009 et de 2020, suivis de phases de reprise progressive, avec une stabilisation autour de 3% sur la période récente selon les projections du FMI et de l'OCDE.

***Fig. 2*- Croissance économique moyenne par région du monde**



Source : *Présentation propre à l'auteur à partir des données de la Banque mondiale (World Development Indicators) et FMI (World Economic Outlook), 2021-2023.*

Le graphique montre bien les disparités marquées de croissance entre les régions du monde. L'Asie de l'Est et du Pacifique apparait comme la région la plus dynamique, tandis que l'Amérique latine et l'Europe affichent des performances plus faibles. Une position intermédiaire avec une croissance moyenne proche de la moyenne mondiale, est accordée à la région MENA. Mais, sur toute la période récente, leur croissance reste modeste en la comparant à celle de l'Afrique subsaharienne.

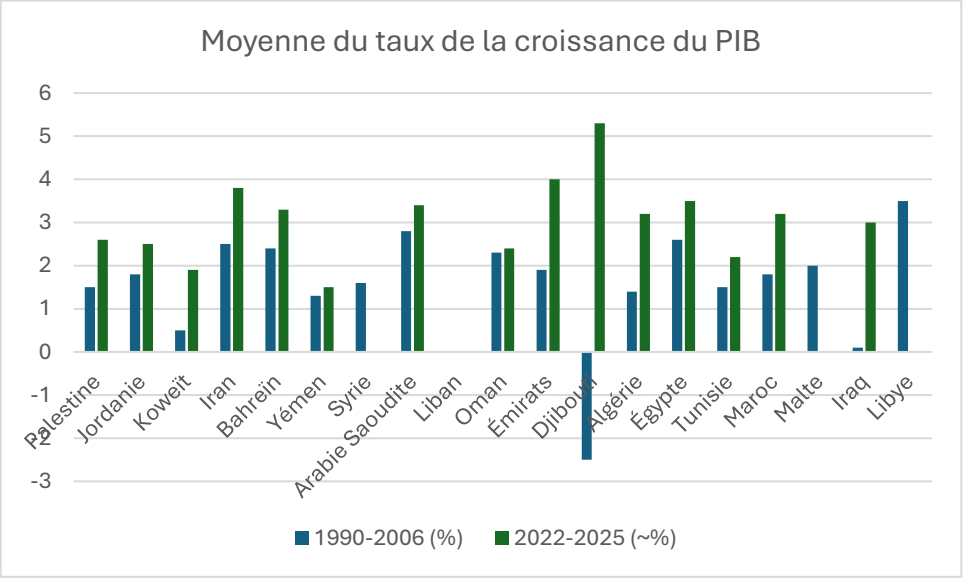
Cependant, la croissance économique seule, ne reflète pas la manière de la distribution de la richesse. Entre les pays de la région MENA même,

persistent des inégalités importantes de revenus et de niveaux de vie, notamment entre ceux pétroliers et non pétroliers. A ce niveau, l'analyse des inégalités de répartition des richesses constitue ainsi une étape essentielle pour comprendre les limites du processus de développement régional et introduire l'étude du rôle des facteurs institutionnels, en particulier la corruption.

1.2- Inégalités dans la répartition de la richesse entre les pays MENA

Selon Olivier Dabène (1998), les politiques de redistribution des revenus ainsi que celles de l'éducation, la santé ou le logement doivent être mises en œuvre en faveur des populations les plus marginalisées afin d'en maximiser les bénéfices.

***Fig.3*- Disparités internes dans la répartition de la richesse des pays de la région MENA**



Source : *Présentation propre à l'auteur à partir des données du World Development Indicators, (2006/2025).*

La figure présente une comparaison de la moyenne du taux de croissance du PIB entre la période 1990-2006 et la période 2022-2025 pour un ensemble de pays du Moyen-Orient et d'Afrique du Nord (MENA). Les résultats indiquent une accélération de la croissance économique au cours de la période récente pour la plupart des pays.

La théorie néoclassique de la croissance (Solow, 1956) stipule que la croissance de long terme dépend principalement de l'accumulation du capital, de la croissance démographique et du progrès technologique exogène. Alors, l'amélioration observée entre les deux périodes peut ainsi être interprétée comme le résultat d'un renforcement de l'investissement, notamment public, et d'une meilleure intégration économique, en particulier dans les pays exportateurs de ressources naturelles.

De même, les approches de la croissance endogène (Romer, 1986 ; Lucas, 1988) permettent d'approfondir cette analyse en s'appuyant sur le rôle central du capital humain, de l'innovation et des politiques publiques. À cet égard, l'augmentation des taux de croissance observée dans plusieurs pays de la région MENA, spécialement les pays du Golfe, peut être confiée aux investissements croissants dans l'éducation, les infrastructures et la diversification sectorielle, favorisant ainsi une croissance soutenable.

Par ailleurs, les disparités persistantes entre les pays confirment l'hypothèse de divergence conditionnelle mise en évidence par Barro et Sala-i-Martin (1995), selon laquelle les économies ne convergent que si elles partagent les mêmes caractéristiques structurelles. Les pays se caractérisant par une instabilité politique ou institutionnelle, tels que le Liban et l'Irak, continuent d'enregistrer des performances de croissance relativement faibles, ce qui illustre l'importance de la qualité des institutions dans le processus de développement (North, 1990 ; Acemoglu, Johnson & Robinson, 2001).

En outre, les résultats illustrés par la figure s'inscrivent dans le cadre des analyses empiriques de la Banque mondiale et du FMI, qui mettent en évidence une reprise économique post-pandémie dans la région MENA, tout en appuyant la vulnérabilité de cette dynamique face aux chocs externes et aux contraintes structurelles (FMI, 2024 ; Banque mondiale, 2024).

Si la croissance économique constitue un indicateur central des performances macroéconomiques, son évolution ne peut être analysée d'une façon indépendante de l'environnement institutionnel. En effet, la littérature économique souligne que la corruption affecte directement l'efficacité des politiques publiques et la capacité des économies à transformer la croissance en développement durable (North, 1990 ; Mauro, 1995). Dès lors, l'analyse de la corruption apparaît indispensable pour comprendre les performances

macroéconomiques observées dans la région MENA.

2- Évolution de la corruption

L'évolution de la corruption dans le monde a causé des nombreuses interrogations. En général, ce phénomène s'est dégradé et atteint des seuils très élevés dans les pays en développement. A ce propos, « Transparency International » a retracé un tableau d'évaluation d'Indice de Perception de la Corruption (IPC) à partir de 1995. Cet indice évalue le niveau de la corruption touchant les administrations publiques et la classe politique de chaque pays. Cette organisation a choisi cet indice à cause de sa capacité à englober tous les aspects de la corruption.

Ainsi, l'IPC 2008 renferme quatre-vingts pays, soit un nombre des pays semblables à celui couvert en 2007, pour lesquels Transparency International classe des indices récents et fiables. Il arrange les pays selon une échelle allant de 0 (haut degré de corruption perçu) à 10 (faible degré de corruption perçue) qui est une échelle plus courte et moins précise. Pour cette raison, l'échelle de l'IPC moderne (2023, 2024) comprit entre 0 et 100, ce qui permet une mesure plus sûr des perceptions de corruption.

***TAB 1*: Indice de Perception de la Corruption (IPC) des pays de la région MENA**

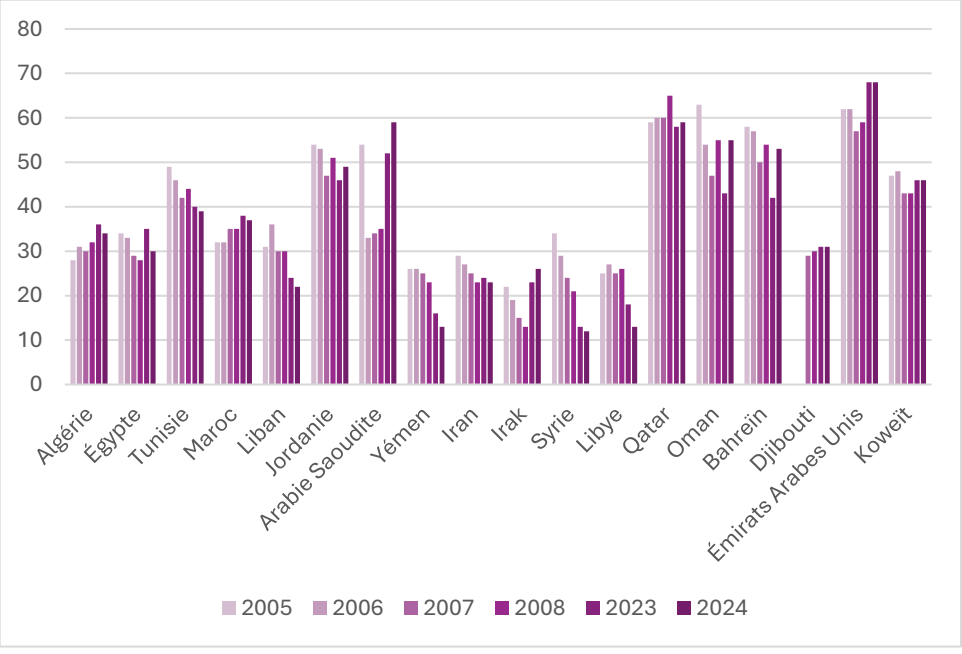
Pays	IPC 2005	IPC 2006	IPC 2007	IPC 2008	IPC 2023 (0-100)	IPC 2024 (0-100)
Algérie	2,8	3,1	3,0	3,2	36	34
Égypte	3,4	3,3	2,9	2,8	35	30
Tunisie	4,9	4,6	4,2	4,4	40	39
Maroc	3,2	3,2	3,5	3,5	38	37
Liban	3,1	3,6	3,0	3,0	24	22
Jordanie	5,4	5,3	4,7	5,1	46	49
Arabie Saoudite	5,4	3,3	3,4	3,5	52	59
Yémen	2,6	2,6	2,5	2,3	16	13
Iran	2,9	2,7	2,5	2,3	24	23
Irak	2,2	1,9	1,5	1,3	23	26
Syrie	3,4	2,9	2,4	2,1	13	12
Libye	2,5	2,7	2,5	2,6	18	13

Pays	IPC 2005	IPC 2006	IPC 2007	IPC 2008	IPC 2023 (0-100)	IPC 2024 (0-100)
Qatar	5,9	6,0	6,0	6,5	58	59
Oman	6,3	5,4	4,7	5,5	43	55
Bahreïn	5,8	5,7	5,0	5,4	42	53
Djibouti	–	–	2,9	3,0	31	31
Émirats Arabes Unis	6,2	6,2	5,7	5,9	68	68
Koweït	4,7	4,8	4,3	4,3	46	46

Source *: Rapports Transparency International, 2008, 2023 et 2024.*

Ce tableau présente l'évolution de l'Indice de Perception de la Corruption (IPC) pour les pays de la région MENA entre 2005 et 2024. Les valeurs ont été normalisées sur une échelle 0–100 pour permettre la comparaison.

***Fig.4*- Évolution de l'IPC normalisé (0–100) par pays**



Source : *Présentation propre à l'auteur à partir des données des Rapports Transparency International, 2008, 2023 et 2024*

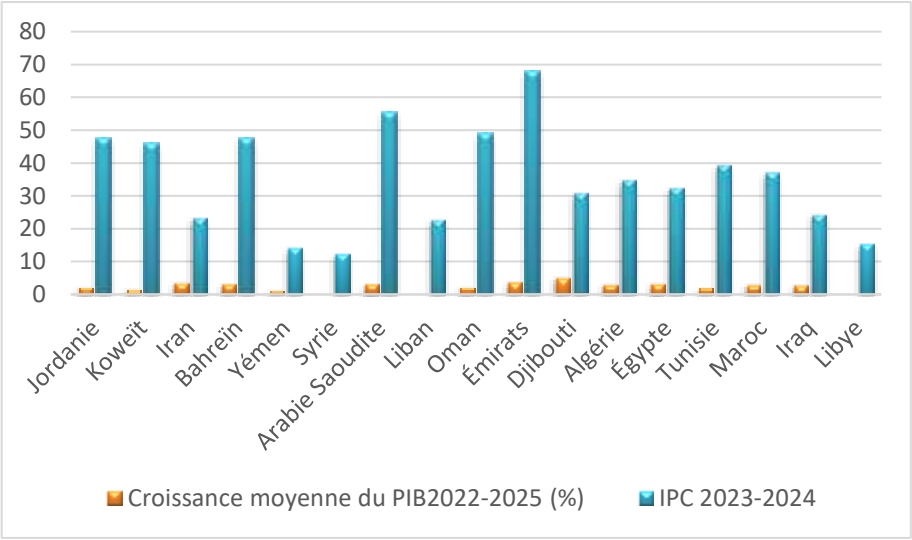
Ce graphique présente l'évolution de l'Indice de Perception de la Corruption (IPC) normalisé sur (0-100) pour les pays de la région MENA entre 2005 et 2024. Les données montrent des tendances différentes selon les pays et les sous-régions. En effet, les pays du Golfe, tels que les Émirats Arabes Unis, le Qatar, l'Arabie Saoudite et le Koweït, affichent des scores relativement élevés et stables, indiquant une perception faible de la corruption. Cette amélioration reflète la consolidation des mécanismes institutionnels et des politiques de transparence dans ces pays, conformément aux observations de Transparency International (2023). Les pays du Maghreb, surtout la Tunisie, le Maroc et l'Algérie, présentent des IPC intermédiaires (30–40) avec une évolution relativement stable au cours du temps. Ceci est expliqué par Heywood (2015) par la raison que ces pays ont commencé des réformes institutionnelles pour réduire la corruption, mais restent confrontés à des obstacles liés à l'administration publique et à la gouvernance économique. Par contre, les pays en situation de crise ou de conflits, comme le Yémen, la Syrie et l'Irak, montrent des IPC très bas, souvent en diminution. Conformément à La littérature indiquant que l'instabilité politique et les conflits renforcent la corruption et limitent l'efficacité des réformes (Kaufmann et al., 2010 ; Rose-Ackerman, 2016).

En fait, ces variations différentes entre les pays et les sous régions mettent en évidence le rôle déterminant des institutions, de la stabilité politique et des politiques anti-corruption sur la perception de la corruption dans la région MENA. L'analyse de la corruption ne pourrait être complète sans examiner ses effets sur la performance économique globale. Le graphique suivant explore ainsi la relation entre l'Indice de Perception de la Corruption et la croissance économique dans les pays de la région MENA.

2.1- Impact direct de la corruption sur la croissance économique

Le graphique suivant met en évidence la relation entre l'Indice de Perception de la Corruption et la croissance économique, afin d'évaluer si les pays caractérisés par une faible perception de la corruption enregistrent également de meilleures performances économiques.

***Fig.5*- Relation croissance économique-corruption des pays de la région MENA**



Source : *Présentation propre à l'auteur à partir des données des Rapports Transparency International (2023-2024) et World Development Indicators, (2022-2025)*

Le graphique met en relation la croissance économique moyenne du PIB sur la période 2022–2025 et le niveau de corruption mesuré par l'Indice de Perception de la Corruption (IPC 2023–2024) pour un échantillon de pays de la région MENA. Cette double lecture met en évidence une divergence marquée des performances économiques et institutionnelles, confirmant l'existence de fortes disparités structurelles au sein de la région. D'une part, les pays du Conseil de Coopération du Golfe (CCG), tels que les Émirats arabes unis, l'Arabie saoudite, le Koweït et Bahreïn, se distinguent par des scores IPC partiellement élevés, traduisant une perception plus faible de la corruption, associés à des taux de croissance relativement stables. Cette disposition est similaire avec la littérature qui souligne que des institutions plus efficaces et une meilleure qualité de la gouvernance favorisent un environnement économique plus prévisible, propice à l'investissement et à la croissance (North, 1990 ; Kaufmann, Kraay & Mastruzzi, 2010). Toutefois, dans ces économies, la croissance demeure largement dépendante des rentes pétrolières, ce qui limite son caractère inclusif et durable (Auty, 2001). De l'autre part, plusieurs pays

rapprochés à des crises politiques, sécuritaires ou économiques persistantes, tels que le Yémen, la Syrie, la Libye et l'Irak, affichent des scores IPC faibles, indiquant une corruption perçue comme élevée, se sont caractérisés par des performances de croissance faibles ou instables. Cette situation confirme les résultats de nombreux travaux empiriques montrant que la corruption agit comme un obstacle majeur à la croissance économique en réduisant l'efficacité des dépenses publiques, en décourageant l'investissement privé et étranger et en accentuant l'incertitude économique (Mauro, 1995 ; Mo, 2001).

Par ailleurs, des pays comme le Maroc, la Tunisie, l'Égypte et l'Algérie occupent une position intermédiaire, avec des niveaux de corruption modérés et des taux de croissance relativement faibles. Cette configuration illustre l'hypothèse selon laquelle la corruption exerce non seulement un effet direct négatif sur la croissance, mais également des effets indirects, notamment à travers la dégradation du capital humain, la mauvaise allocation des ressources et l'inefficacité des politiques publiques (Méon & Sekkat, 2005 ; Gupta, Davoodi & Alonso-Terme, 2002).

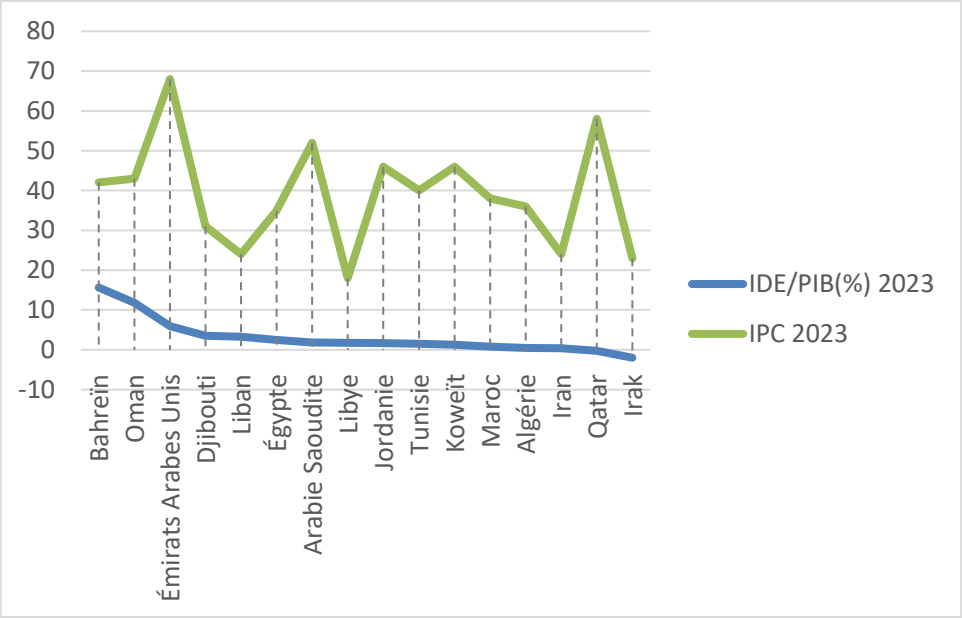
Dans l'ensemble, le graphique suggère l'existence d'une relation globalement négative entre la corruption et la croissance économique, bien que cette relation ne soit ni linéaire ni uniforme selon les pays. Ces résultats atteignent celles de la littérature institutionnaliste, qui considère la qualité des institutions, et en particulier la maîtrise de la corruption, comme un déterminant central des voies de croissance et des écarts de développement observés entre les pays de la région MENA (Acemoglu, Johnson & Robinson, 2001).

En plus de son impact sur la croissance économique, la corruption influence en conséquence les investissements directs étrangers (IDE) constituant un levier essentiel de financement, de transfert de technologies et de diversification productive. Un niveau élevé de corruption accroît l'incertitude institutionnelle et les coûts de transaction, réduisant ainsi l'attractivité des économies pour les investisseurs étrangers. Dans la région MENA, caractérisée par une forte divergence institutionnelle et structurelle, l'analyse de l'impact de la corruption sur les IDE permet de mieux retracer les limites de la croissance et les inégalités durables de développement entre les pays.

2.2- Impact de la corruption sur les IDE

Il est possible de déterminer cette relation à travers un graphique de corrélation entre IPC et IDE pour la région MENA.

***Fig.6*- Corrélation entre corruption et IDE**



***Source** : Présentation propre à l'auteur à partir des données du Transparency International, (2023) et World Development Indicators, (2023).*

D'après ce graphique, on remarque que les pays ayant un IPC élevé (faible perception de la corruption), tels que les Émirats Arabes Unis, Oman et Bahreïn, se situent généralement dans la partie supérieure gauche du graphique, avec des ratios IDE/PIB relativement élevés. Au contraire, les pays caractérisés par un IPC faible, comme l'Irak et l'Iran, figurent dans la partie inférieure droite, indiquant une faible attractivité des IDE. Ces résultats sont similaires avec la littérature économique, qui montre que la corruption agit comme une charge implicite sur l'investissement, réduisant ainsi la rentabilité attendue et augmentant l'incertitude pour les investisseurs étrangers (Wei, 2000 ; Habib & Zurawicki, 2002) et par la suite, elle génère un effet défavorable sur la croissance économique de ces pays.

En revanche, selon cette allure, le graphique montre une dispersion non négligeable. En fait, certains pays du Golfe présentent des IDE élevés contre un

IPC intermédiaire, ce qui peut être expliquer par l'abondance des ressources naturelles, la taille du marché ou des politiques incitatives spécifiques à l'investissement étranger. D'autres pays possédant un IPC relativement acceptable peuvent attirer peu d'IDE, à cause de facteurs structurels tels que l'instabilité politique, la faiblesse du marché intérieur ou des contraintes réglementaires. Alors, cette dispersion indique que la corruption n'est pas le seul déterminant des IDE, mais elle représente un facteur explicatif essentiel parmi d'autres variables macroéconomiques et institutionnelles.

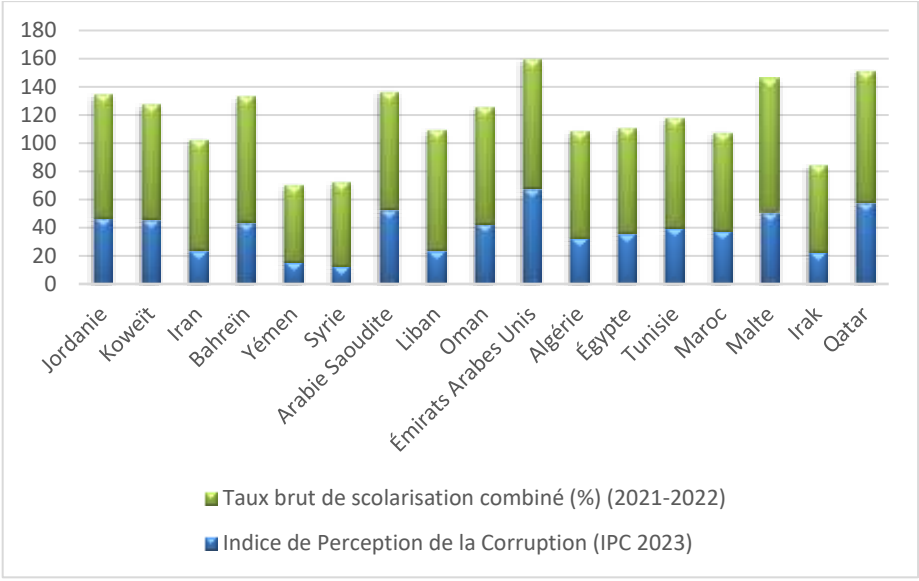
En plus de son effet sur les flux d'IDE, la corruption peut également affecter l'accumulation du capital humain, élément fondamental de la croissance économique à long terme. La partie suivante analyse ainsi la relation entre la corruption et le capital humain.

2.3- Impact de la corruption sur le capital humain

Si les théories récentes de la croissance endogène considèrent l'éducation comme un facteur principal de la croissance économique, les nouvelles théories institutionnalistes insistent sur le rôle de la qualité des institutions dans l'amélioration de la qualité de ce facteur dans la plupart des pays du monde. En effet, la littérature économique prouve que la corruption peut affecter le capital humain à travers plusieurs mécanismes. D'une part, elle réduit l'efficacité des dépenses publiques octroyées à l'éducation et à la santé en favorisant le détournement des ressources et la mauvaise allocation budgétaire. D'autre part, la corruption affaiblit les encouragements à l'investissement individuel en capital humain, en limitant l'égalité d'accès à l'éducation et en dégradant la qualité des services publics (Mauro, 1998 ; Gupta, Davoodi & Tiongson, 2000).

Ainsi, après avoir mis en évidence le rôle de la corruption dans la diminution de l'attractivité des IDE, il est important d'étudier son influence sur le capital humain, afin de montrer si toutes choses étant égales par ailleurs, c'est-à-dire les pays ayant une faible perception de la corruption dévoilent un niveau plus élevé d'éducation et de santé, favorisant ainsi un développement économique durable.

***Fig. 7*- Impact de la corruption sur l'accumulation du capital humain**



***Source** : Présentation propre à l'auteur à partir des données de Transparency International (Indice de Perception de la Corruption, 2023) et de la Banque mondiale (World Development Indicators, taux brut de scolarisation combiné, 2021–2022).*

Le graphique met en relation le niveau de corruption, mesuré par l'Indice de Perception de la Corruption (IPC 2023), et le capital humain, mesuré par le taux brut de scolarisation combiné pour la période 2021–2022, pour un groupe de pays de la région MENA. Cette figure permet de constater une relation positive entre la qualité des institutions, notamment la corruption, et le niveau de développement du capital humain, garantissant les leçons de la littérature économique.

A cet égard, les pays montrant des indices IPC élevés, tels que les Émirats arabes unis, le Qatar, Malte et l'Arabie saoudite, présentent également des taux de scolarisation élevés, expliquant une meilleure capacité à investir dans l'éducation et la formation. Ce resultat est conforme aux travaux institutionnalistes qui stipulent que la diminution de la corruption progresse l'efficacité des dépenses publiques, en particulier dans les secteurs sociaux, et favorise l'accumulation du capital humain (Mauro, 1998 ; Gupta, Davoodi & Alonso-Terme, 2002).

Contrairement, les pays affichant des niveaux élevés de corruption, tels que le Yémen, la Syrie, l'Irak et l'Iran, montrent des taux de scolarisation relativement faibles, justifiant les impacts négatifs de la corruption sur l'accès à l'éducation et la qualité des services publics. La littérature prouve que la corruption dévie les ressources publiques, aggrave les écarts d'accès aux services éducatifs et limite l'accumulation du capital humain, surtout dans les économies fragiles ou en situation de conflit (Mo, 2001 ; Méon & Sekkat, 2005).

Dans un autre cas, les pays tels que le Maroc, la Tunisie, l'Algérie et l'Égypte profitant d'une situation intermédiaire, enregistrent des indices de corruption stables et des taux de scolarisation moyens. Cela prouve la présence d'un effet indirect de la corruption sur la croissance économique, via l'affaiblissement du capital humain, qui forme un facteur déterminant de la productivité et du développement à long terme (Lucas, 1988 ; Barro, 1991).

Dans l'ensemble, le graphique inspire que la corruption procède comme un obstacle structurel à l'accumulation du capital humain dans la région MENA, entrainant en conséquence les inégalités de développement entre les pays. Ces résultats confirment l'intégration du capital humain comme variable de transmission fondamentale dans l'analyse des effets indirects de la corruption sur la croissance économique.

2.4- Synthèse des effets indirects de la corruption

L'analyse descriptive montre que l'impact de la corruption sur la performance économique ne se limite pas à ses effets directs, mais se transmet également via plusieurs canaux indirects essentiels, spécialement les investissements directs étrangers (IDE) et le capital humain. Ces canaux permettent d'expliquer la faiblesse et l'instabilité, ainsi que le caractère peu inclusif de la croissance économique dans certains pays de la région MENA (Mauro, 1995; Tanzi & Davoodi, 1997).

Premièrement, la corruption exerce une relation négative sur les flux d'IDE en augmentant les coûts de transaction, en renforçant l'incertitude institutionnelle et en diminuant la protection des droits de propriété (Wei, 2000; Habib & Zurawicki, 2002). Les pays dont les niveaux de corruption sont élevés, attirent moins d'IDE qui se concentrent surtout dans des secteurs à faible valeur ajoutée, tels que les industries extractives, ce qui limite ainsi les effets d'entraînement sur la productivité, l'innovation et la diversification économique

(Campos et al., 2010). Ces impacts indirects dévoilent le rôle prépondérant des institutions dans la conduite bénéfique des investissements étrangers vers des secteurs créatifs de croissance soutenable.

Deuxièmement, la corruption influence négativement le capital humain tout en diminuant l'efficacité des dépenses publiques en éducation et santé et en appuyant les écarts d'accès aux services sociaux (Gupta et al., 2002; Svensson, 2005). Ainsi, la comparaison souligne que les pays de la région MENA caractérisés par une meilleure gouvernance et une faible corruption présentent des niveaux élevés de scolarisation et d'investissement en formation professionnelle, alors que les autres pays, dont l'indice de corruption est élevé, sont marqués par des carences significatifs dans l'accumulation du capital humain. Cette situation compromet la formation d'une main-d'œuvre qualifiée et freine l'amélioration de la productivité globale des facteurs (Dollar & Kraay, 2003).

D'après cette analyse, l'impact de la corruption via ces deux canaux, prouve que cette dernière représente un facteur structurel de destruction des moteurs fondamentaux de la croissance économique. En fait, malgré l'accroissement du PIB grâce aux rentes naturelles, les pratiques persistants de la corruption inhibent la capacité des économies à transformer cette croissance en développement durable et inclusif (World Bank, 2022). Cette conclusion consolide l'idée exposant que la corruption n'est seulement pas un problème de gouvernance, mais aussi un obstacle primordial à la mobilisation des investissements et à l'accumulation du capital humain, ce qui favorise ainsi les divergences économiques internes dans la région MENA.

2.5. Disparités et hétérogénéité dans la région MENA

L'effet de la corruption sur la croissance économique quel que soit direct ou indirect via les canaux de transmission tels que les IDE et le capital humain n'est pas identique pour tous les pays de la région MENA. En effet, la littérature et les épreuves empiriques prouvent une forte divergence entre pays en relation avec les facteurs institutionnels, structurels et socio-économiques (Campos et al., 2010; World Bank, 2022).

D'une part, la qualité des institutions dispose d'un rôle primordial. Les pays possédant des institutions solides, une gouvernance transparente et un système judiciaire indépendant sont capables de dépasser les effets pervers de

la corruption sur les IDE et le capital humain. A cet égard, les études traitant le cas de la Tunisie et le Maroc, qui retiennent des cadres réglementaires relativement stables, montrent qu'ils attirent plus d'investissements et gardent un niveau de scolarisation plus élevé en dépit de la persistance de certaines pratiques corruptives (Mauro, 1995; Habib & Zurawicki, 2002). Au contraire, les pays où la corruption est prépondérante et les institutions sont fragiles, tels que l'Irak ou la Libye, enregistrent des défaillances au niveau des investissements productifs et de formation du capital humain.

D'autre part, les inégalités sont reliées à la structure économique des pays et à la dépendance aux ressources naturelles. Les pays fortement dépendants des rentes pétrolières centralisent leurs IDE dans le secteur extractif ce qui cause des écarts abondants dans l'accès aux services publics, aggravant ainsi les inégalités et la fragilité du capital humain (Gupta et al., 2002; Svensson, 2005). Au contraire, les pays indépendant et diversifiés économiquement, même si la corruption est endémique, profitent des effets d'attraction des IDE et d'une accumulation plus soutenable du capital humain,

En synthèse, face au problème de la corruption, la région MENA présente des divergences remarquables au sein de leurs pays. Pour clarifier cette hétérogénéité, il est indispensable d'analyser les canaux de transmission indirects de la corruption pour formuler des appuis politiques ajustées à chaque situation nationale. Ce travail prépare pour des études comparatives plus précises capables de reconnaître quelles réformes institutionnelles et politiques publiques maximiseront l'effet des IDE et du capital humain sur la croissance économique des pays.

3. Discussion des résultats

Les conclusions tirées de ce travail visent à mettre en lumière les différents canaux à travers lesquelles la corruption affecte la croissance économique dans la région MENA. L'analyse illustre des effets directs, déjà largement annoncés, et des effets indirects significatifs via les investissements directs étrangers (IDE) et le capital humain. L'intérêt de cette discussion est d'interpréter ces résultats en liaison avec la littérature académique afin de tirer des recommandations pour la politique économique.

3.1. Corruption et investissement étranger

Notre analyse, conformément aux travaux de Wei (2000) et Habib & Zurawicki (2002), garantissent que la corruption restreint l'attractivité des IDE. En fait, les pays de la région détenant des indices élevés de corruption, tels que l'Irak ou la Libye, attirent des investissements à faible valeur ajoutée concentrés dans les secteurs extractifs. Ceci limite les effets de diffusion technologique et d'innovation associés aux IDE, expliquant ainsi la stagnation partielle de la productivité dans certains pays.

En revanche, des pays comme la Tunisie et le Maroc, attirent des flux d'investissements étrangers plus diversifiés grâce à des institutions plus stables et transparentes malgré la présence de certaines pratiques corruptives, ce qui est confirmé par les conclusions de Campos et al. (2010) et Mauro (1995).

3.2. Corruption et capital humain

Nos résultats confirment la présence d'une relation significative entre la corruption et le capital humain. Les pays où la corruption est accentuée présentent des défaillances remarquables en termes de scolarisation, d'accès aux soins et d'efficacité des dépenses publiques, conformément aux observations de Gupta et al. (2002) et Svensson (2005). Ces déficits ont pour conséquence une main-d'œuvre non qualifiée et une productivité globale des facteurs limitée ce qui freine la croissance économique à long terme.

En fait, la manière dont la corruption influence le capital humain démontre une grande hétérogénéité entre pays. Les pays possédant des systèmes éducatifs et sanitaires relativement puissants peuvent dépasser les pertes dues à la corruption, grâce à des politiques publiques censées réduire les effets indirects négatifs.

3.3. Disparités régionales et implications

L'analyse des divergences entre les pays de la région MENA garantit que la corruption n'affecte pas tous les pays d'une manière identique. Certains pays arrivent à atteindre un niveau d'investissement et de capital humain plus élevé malgré la persistance de la corruption, et c'est grâce aux différences institutionnelles, structurelles et géopolitiques, alors que la situation des autres pays est caractérisée par un cercle vicieux de faible investissement et faible accumulation de capital humain (World Bank, 2022; Dollar & Kraay, 2003). Cette hétérogénéité dans la région MENA, nécessite le recours à la formulation

de politiques économiques. Elle suggère que l'adoption des stratégies de lutte contre la corruption, adaptées au contexte national, combine des réformes institutionnelles, des mesures incitatives pour attirer des IDE de qualité et des programmes ciblés pour soutenir le capital humain.

3.4. Similitude avec la littérature

Les conclusions tirées de cette étude témoignent et enrichissent la littérature existante. La corruption a des effets néfastes sur la croissance via plusieurs canaux, conformément a ce qui est souligné par Mauro (1995) et Tanzi & Davoodi (1997). Néanmoins, nos analyses montrent que l'ampleur et la nature de ces effets changent fortement selon la qualité des institutions et la structure économique des pays. Ces différences renforcent le recours à des approches spécifiées, plutôt que des stratégies homogènes pour toute de la région.

4. Conclusion et implications

Cette analyse a étudié l'influence de la corruption sur la croissance économique dans la région MENA, en se focalisant sur leurs effets indirects via les investissements directs étrangers (IDE) et le capital humain, ainsi que sur les inégalités et la divergence entre pays. Notre étude descriptive, basée sur une large revue de la littérature théorique, permet de fournir aux décideurs politiques et aux acteurs économiques, de nombreux conclusions et implications primordiales.

En premier lieu, dans les pays où les institutions sont fragiles et la gouvernance est mauvaise, la corruption règne et agit comme un frein structurel à la croissance économique. Elle restreint l'attractivité des IDE, réduit la diversification économique et ralentit l'accumulation de capital humain dans la région MENA.

En second lieu, l'impact de la corruption sur la croissance économique des pays n'est pas homogène. Les pays jouissant d'une meilleure qualité des institutions et d'une diversification des structures économiques sont capables de dépasser, en général, les effets néfastes de la corruption sur les IDE et le capital humain. Au contraire, dans les économies attachées aux secteurs d'extraction des rentes naturelles, la corruption s'accentue engendrant un cercle vicieux de faible attraction des IDE et de faible développement du capital humain.

En troisième lieu, l'analyse affirme que les canaux de transmission, à savoir les IDE et le capital humain, présentent un frein à la soutenabilité de la croissance économique régionale. A ce niveau, la corruption reflétant un problème majeur de mauvaise gouvernance, empêche ou affaiblit la transformation d'une croissance positive en développement durable.

4.1. Implications politiques et économiques

Les aboutissements de notre analyse proposent certaines pistes d'action pour les décideurs :

- **Renforcement institutionnel et transparence** : pour une meilleure attractivité des IDE et une efficacité des dépenses publiques, il faut mettre en place des stratégies de lutte contre la corruption en assurant des cadres de réglementation solides et d'un système judiciaire autonome.
- **Politiques visées pour le capital humain** : pour limiter les déficits de productivité et les écarts d'inégalités sociales, les Etats à forte corruption, doivent veiller à assurer et à améliorer les investissements dans l'éducation et la santé.
- **Accès différenciés selon la situation nationale** : en tenant compte la divergence dans les pays de la région MENA, les stratégies de lutte contre la corruption et les politiques d'attraction d'IDE, doivent être spécifiques aux caractéristiques institutionnelles et économiques de chaque pays.
- **Octroi de la diversification économique** : limiter l'effet néfaste de la corruption sur les investissements et le capital humain, nécessite la réduction de la dépendance aux secteurs extractifs et le développement des industries à plus forte valeur ajoutée.

4.2. Perspectives de recherche

Cette analyse ouvre en conséquence des voies pour la recherche future. En fait, les études comparatives sur l'efficience des stratégies anti-corruption dans différents pays de la région pourraient livrer des leçons précieuses pour soutenir le développement durable. A ce niveau, il serait utile de procéder à des études quantitatives approfondies pour bien mesurer l'ampleur des effets indirects de la corruption ainsi que leur interaction avec les variables institutionnelles et économiques.

La corruption, définie comme l'usage abusif du pouvoir public à des fins privées (Mauro, 1995), représente un problème au développement économique et social dans de nombreux pays, en particulier dans la région MENA (Moyen-Orient et Afrique du Nord). Cette dernière influence directement et indirectement la croissance économique en affectant l'allocation des ressources, la productivité des investissements et l'accumulation du capital humain (Tanzi & Davoodi, 1997; Wei, 2000).

Lorsque l'effet direct de la corruption sur la croissance économique a été énormément exploré, ses effets indirects, via les investissements directs étrangers (IDE) et le capital humain, restent moins annoncé dans la situation spécifique de la région MENA. Cette dernière, renfermant des pays qui possèdent des institutions stables et d'autres qui sont strictement dépendantes des rentes naturelles avec des pratiques corruptives endémiques, est caractérisée par une hétérogénéité institutionnelle et économique remarquable.

Dans ce cas, l'objectif de ce travail est double : premièrement, fournir une analyse théorique des outils par lesquels la corruption influence la croissance économique, en différenciant entre effets directs et indirects ; deuxièmement, effectuer une analyse descriptive des inégalités régionales, afin d'identifier les pays et mécanismes les plus fragiles aux impacts négatifs de la corruption. A partir de la revue de la littérature, la synthèse académique et l'analyse descriptive, cet article vise à mieux comprendre les effets structurels de la corruption et à spécifier les politiques publiques exigeantes pour assurer un développement durable et inclusif dans la région MENA.

Conclusion

Cette étude conclut que la corruption représente une entrave primordiale à la croissance économique dans la région MENA, pas seulement par ses effets directs, mais aussi par ses effets indirects sur les investissements directs étrangers et le capital humain. L'analyse descriptive confirme que les pays à forte corruption endémique retiennent moins d'IDE diversifiés et subissent de déficits significatifs au niveau de la formation et de la productivité de la main-d'œuvre.

Toutefois, l'impact de la corruption est hétérogène et variable d'un pays à l'autre : l'aptitude des pays à réduire les effets négatifs de la corruption dépend

de leurs qualités institutionnelles, de la diversification économique et la stabilité politique. Ces résultats appuient l'importance de choisir des politiques spécifiées et ajustées, tenant compte les réformes institutionnelles, les stratégies d'attraction d'IDE de qualité et les investissements efficaces dans le capital humain.

Finalement, cette analyse soutienne un apport original en regroupant analyse théorique et descriptive afin d'explorer les canaux de transmission indirects de la corruption. Les voies de recherche future impliquent des analyses quantitatives plus approfondies pour mesurer l'ampleur des impacts indirects et des études comparatives sur l'efficacité des politiques de lutte contre la corruption dans différents pays de la région MENA. Alors, pour atteindre une croissance économique soutenable et durable et favoriser un développement inclusif dans la région MENA, il est indispensable de comprendre et limiter les effets de la corruption.

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Intelligence Artificielle et Automatisation : Promouvoir le Changement Économique au Moyen-Orient et dans les États du Golfe

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Abstract:
Artificial Intelligence (AI) and automation are reshaping production and service systems and have become central drivers of economic transformation across the Middle East and Gulf States. This paper investigates their contribution to advancing industrial innovation, improving resource efficiency, and strengthening global competitiveness. It focuses on AI-enabled developments in smart manufacturing, digital finance, and renewable energy, and situates these within the broader objectives of regional Vision 2030 agendas, which seek to reduce reliance on hydrocarbon revenues and foster a knowledge-based economy. The analysis further examines critical challenges associated with this transition, including ethical and governance issues, labor market restructuring, and the readiness of digital and institutional infrastructures.

Drawing on a comparative assessment of global and regional trajectories, the paper formulates strategic recommendations for leveraging AI and automation to support sustainable economic development and enhance the long-term competitive positioning of Middle Eastern and Gulf economies in the digital era.

Keywords: Artificial Intelligence, Automation, Economic Transformation, Middle East, Gulf States, Vision 2030, Sustainable Energy, Digital Economy, Fintech, NEOM.

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1. Introduction

L'intelligence artificielle (IA) et l'automatisation s'imposent aujourd'hui comme des vecteurs majeurs de transformation économique à l'échelle mondiale. Dans les pays du Moyen-Orient et du Golfe, ces technologies offrent des leviers décisifs pour diversifier les structures productives, soutenir une croissance durable et améliorer les conditions de vie des populations. Ce travail a pour objectif d'analyser de manière systématique les opportunités et les risques associés à l'intégration de l'IA et de l'automatisation dans la région, et de proposer des orientations stratégiques permettant d'en maximiser les bénéfices économiques et sociaux tout en en maîtrisant les effets indésirables.

Aujourd'hui, l'IA est largement reconnue, tant sur le plan théorique qu'empirique, comme un élément clé dans le passage des économies basées sur les ressources à des modèles axés davantage sur l'innovation, l'accroissement de la productivité et la compétitivité mondiale. De nombreuses recherches récentes indiquent qu'elle joue un rôle crucial dans la diversification des structures de production, l'optimisation des performances industrielles, ainsi que dans le renforcement du positionnement géoéconomique des pays du Golfe. Cela se manifeste notamment par le biais de l'automatisation, de l'analyse de vastes ensembles de données et de l'émergence de nouveaux secteurs à forte valeur ajoutée. Dans ce contexte, les travaux de Rickli [1] mettent en avant les ramifications économiques, sécuritaires et militaires de l'IA dans cette région, en mettant en évidence la manière dont ces technologies contribuent à remodeler les équilibres stratégiques et à redéfinir les rapports de force au Moyen-Orient.

Dans une approche axée sur le développement durable, Potestà [2] remet en question le potentiel de l'intelligence artificielle à favoriser un bien-être urbain plus juste, soulignant l'importance d'une intégration qui soit à la fois éthique et inclusive. De son côté, Aldandashi [3] analyse le niveau de préparation des Émirats arabes unis pour se positionner en tant qu'exportateur de technologies, en mettant en lumière le rôle de l'IA comme moteur d'innovation et d'impact géoéconomique.

D'autres recherches se penchent sur les interactions politiques, sociales et sectorielles en lien avec l'intelligence artificielle. Price [4] examine les évolutions technologiques et sociétales au sein du Conseil de coopération du Golfe, tandis que Mughal et Alshawi [5] analysent l'effet de l'IA sur les systèmes

migratoires dans le cadre post-COVID-19, ainsi que ses répercussions sur les nations qui exportent de la main-d'œuvre. Hassan [6] explore la contribution de projets phares comme NEOM à la stratégie de diversification de l'Arabie saoudite, où l'IA se positionne comme un élément clé des nouveaux modèles de développement. En parallèle, Hendawy et Kumar [7] soulignent l'intégration de l'IA dans les stratégies nationales des pays arabes, tout en insistant sur la nécessité de politiques publiques harmonisées et cohérentes.

Sur le plan économique et entrepreneurial, Azoury et Yahchouchi [8] soulignent que l'intelligence artificielle offre d'importantes opportunités pour la création de valeur et la croissance des entreprises au Moyen-Orient. Ahmed [9] met en avant le rôle de l'IA dans le dynamisme entrepreneurial en Arabie saoudite, notamment dans les marchés arabes en développement. Enfin, Alzaidi [10] examine l'effet tangible de l'IA sur la performance du secteur bancaire, mettant en évidence les améliorations en matière d'efficacité opérationnelle et de compétitivité dans les services financiers de la région.

En s’inscrivant dans la continuité de ces travaux, cette étude vise à analyser le rôle stratégique de l'intelligence artificielle et de l'automatisation dans la diversification économique des pays du Moyen-Orient et des États du Golfe, en identifiant les opportunités sectorielles, les défis associés et les recommandations politiques pour une intégration durable ; elle propose ainsi une synthèse critique des usages actuels tout en formulant des orientations stratégiques pour un développement économique inclusif et compétitif.

2. Potentiel Économique de l'IA et de l'Automatisation dans la Région

2.1. Contexte économique

Il est impératif pour les pays du Moyen-Orient et les États du Golfe de diversifier leurs économies afin de se détacher des revenus pétroliers traditionnels, qui constituent encore une part importante du PIB, en particulier en Arabie saoudite et aux Émirats arabes unis. Très souvent, la volatilité des prix du pétrole exacerbe leur vulnérabilité économique en raison des transitions énergétiques mondiales et des tensions géopolitiques, ce qui nécessite le développement de nouvelles sources de croissance résilientes et durables.

La figure 1, extraite du rapport du Fonds Monétaire International (2025), présente les niveaux de prix du pétrole nécessaires pour équilibrer les finances

publiques dans les pays du Conseil de Coopération du Golfe (Bahreïn, Arabie Saoudite, Koweït, Oman, Émirats arabes unis et Qatar), selon trois horizons temporels : moyenne 2000-2019, estimation pour 2025 et projection pour 2030, sur la base des données du FMI (avril 2025) [11].

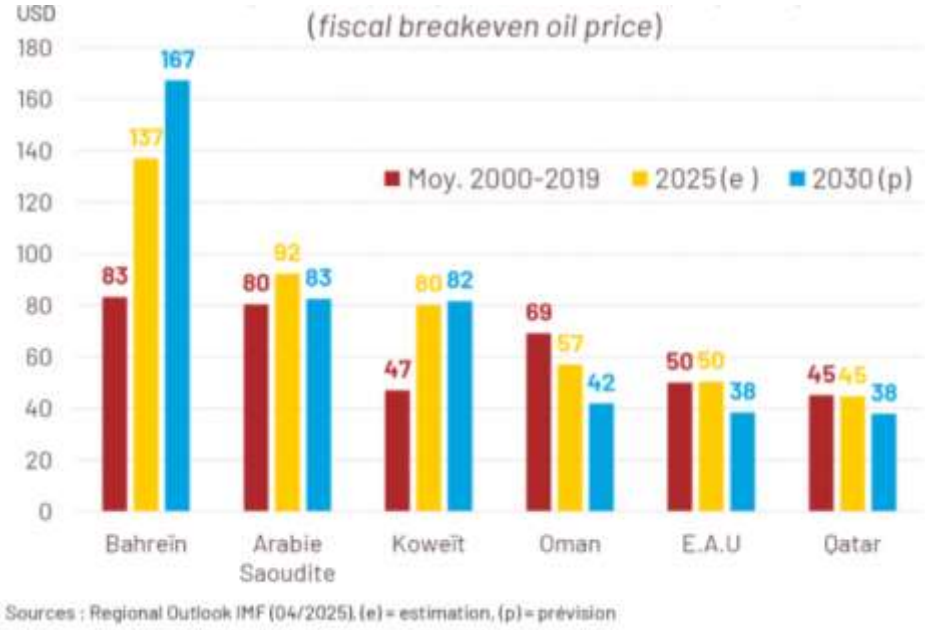

Figure 1. Prix du pétrole d'équilibre budgétaire dans les pays du CCG (moyenne 2000-2019, estimation 2025, projection 2030), d'après les données du FMI, Regional Economic Outlook: Middle East and Central Asia, avril 2025. On constate des disparités considérables dans les prix du pétrole requis pour un équilibre budgétaire à moyen terme dans les pays du Golfe. Le Bahreïn réclame un seuil très élevé, traduisant une vulnérabilité budgétaire importante et une dépendance accrue à la ressource pétrolière, alors que le Qatar et les Émirats arabes unis apparaissent plus sereins grâce à une dynamique de diversification déjà amorcée. Les seuils de l'Arabie saoudite, du Koweït et d'Oman culminent progressivement, traduisant la dépendance budgétaire aux hydrocarbures et les contraintes imposées sur les dépenses publiques. Au fond, ces chiffres montrent l'inégale capacité des pays de la région à affronter les aléas du marché pétrolier, à la fois pour résister aux crises internationales et accomplir la transition violente que représente leur restructuration économique.

Ils apportent en retour la preuve d'une innovation à intensifier ainsi que de meilleures structures économiques favorisant la diversification et la soutenabilité budgétaire.

La figure 2 met l'accent sur la répartition sectorielle du PIB et le taux de croissance de trois pays du CCG (Koweït, Émirats arabes unis et Arabie Saoudite) en distinguant les activités hydrocarbures, non-hydrocarbures et la prévision de croissance 2024. Le Koweït se distingue des Émirats arabes unis et de l'Arabie saoudite par une dépendance encore marquée aux hydrocarbures, tandis que les Émirats arabes unis mettent en avant une structure productive plus diversifiée, illustrée par la part majoritaire des secteurs non-hydrocarbures.

Néanmoins, la similitude des taux de croissance laisse penser qu'au sein de l'échantillon, la dynamique macroéconomique reste relativement homogène malgré des structures sectorielles différentes. Cela pourrait expliquer pourquoi la diversification économique, si elle a progressé dans un certain nombre de pays, n'a pas encore permis d'engendrer des différentiels significatifs de croissance, mais pourrait à moyen termes renforcer la résilience face aux chocs sur les marchés de l'énergie.

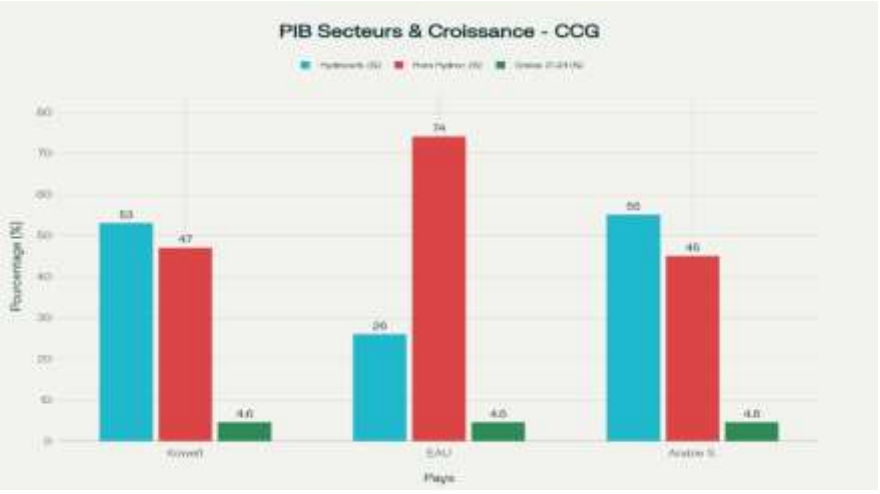

Figure 2. Évolution sectorielle du PIB et contribution à la croissance dans trois économies du CCG (Koweït, ÉAU, Arabie Saoudite), 2021–2024.

C’est dans ce cadre-là que l’intelligence artificielle (IA) et l’automatisation s’établissent comme enjeux stratégiques, qui s’inscrivent dans les orientations des visions nationales comme la Saudi Vision 2030 ou la UAE Centennial 2071, visant à réduire la dépendance aux hydrocarbures et à promouvoir un modèle économique basé sur le savoir et la créativité. Ces initiatives soulignent l'importance croissante de l'économie de la connaissance dans la transformation des économies de la région, en réponse aux défis de la mondialisation et de la concurrence accrue [12].

En matière d’initiatives à impact, on peut noter le projet HUMAIN lancé en 2025 par le fonds souverain saoudien Public Investment Fund (PIF) qui nationalise un budget de 100 milliards USD pour le développement de l’infrastructure souveraine de l’IA incluant supercalculateurs et modèles linguistiques dont HUMAIN Chat exclusivement dédié à la langue arabe. Le projet a vocation à dépasser les frontières du secteur stratégique en santé et finance, logistique, en contribuant à hauteur de 135 milliards USD au PIB du royaume d’ici 2030 [13]. Au sein des Émirats arabes unis, la conduite du projet NEOM, porte un trait d’union sur l’hôpital virtuel de gestion hospitalière par l’intelligence artificielle SEHA Virtual, premier hôpital virtuel du pays, permet d’apporter un plus dans le diagnostic en neurologie et radiologie tandis que les Émirats s’engagent aux côtés d’un milliard de dollars pour tenter de la promouvoir dans les marchés africains, la position géoéconomique acquérant du sens. De surcroît, des accords stratégiques de partenariat créatif avec des acteurs internationaux d’envergure tels que NVIDIA et AMD, ont contribué à la mise à disposition de 500 MW de capacité de calcul dédiée à l’IA déployée en Arabie saoudite afin de permettre l’innovation dans la fabrication intelligente et les énergies renouvelables [14].

Tableau1. Initiatives Clés de Diversification via l'IA [13-14]

Pays/Initiative	Secteur Principal	Investissement/Exemple Concret	Impact Prévu
Arabie Saoudite (projet HUMAIN)	IA souveraine, santé, finance	100 milliards USD ; HUMAIN Chat pour langue arabe	+135 Md USD au PIB d'ici 2030
Émirats arabes unis	Santé, logistique	SEHA Virtual (hôpital IA) ; 1 Md USD pour Afrique	Leader régional en tech export
Visions 2030 régionales	Énergies renouvelables	Partenariats NVIDIA/AMD (500 MW calcul IA)	Croissance PIB +12,4% via IA

2.2. Diversification économique

La diversification économique constitue une condition sine qua non pour assurer la prospérité des pays du Golfe et du Moyen-Orient à long terme. Face aux fluctuations des marchés du pétrole, l'intelligence artificielle (IA) et l'automatisation apparaissent en effet comme un levier stratégique pour soutenir l'émergence de nouveaux secteurs d'innovation et réduire la dépendance à l'égard des hydrocarbures. De nombreux cas pratiques, relatés dans la littérature récente, illustrent cette transition. Les Émirats Arabes Unis se sont largement engagés à développer le secteur de la fintech et de l'industrie du tourisme intelligent, tout en établissant des zones franches comme le Dubai International Financial Centre (DIFC) à vocation régionale, concentré sur les start-ups numériques et les dispositifs d'aide à la performance de services financiers. Le projet NEOM en Arabie Saoudite s'appuie sur l'automatisation et la robotique pour concevoir des infrastructures urbaines durables. Par ailleurs, il intègre des systèmes de santé connectés via l'IA [15-16].

Bahreïn, a pris l'avantage sur le reste de la région dans le domaine du numérique en matière de finance en lançant Bahreïn Fintech Bay attirant des capitaux internationaux et permettant l'émergence de nouveaux métiers [17].

Dans le secteur de la santé, la création d'hôpitaux virtuels comme SEHA Virtual aux É.A.U. améliore l'accès aux diagnostics et aux soins, tandis que le secteur touristique affiche des ambitions de fréquentation éclectique et un fort investissement dans des projets culturels et naturels à grande valeur technologique tels que AlUla en Arabie Saoudite, Masdar City à Abou Dhabi [18].

Ces évolutions soutenues principalement par les recommandations scientifiques et institutionnelles traduisent la capacité de l'IA et de l'automatisation, à même de redéfinir l'économie régionale autour de la connaissance, de l'innovation, des services à haute valeur ajoutée.

2.3. Un moteur de croissance et d'attractivité pour la région

Le potentiel de l'intelligence artificielle (IA) et de l'automatisation, dans les économies du Golfe et du Moyen-Orient, est important, tant pour la croissance que pour transformer durablement le tissu productif. Selon une étude PwC, l'IA pourrait contribuer à l'économie du Moyen-Orient à hauteur d'environ 320 milliards USD d'ici 2030, avec de forts gains d'ampleur aux Émirats arabes unis (proche de 14% PIB) et en Arabie saoudite (proche de 13% PIB) [14, 18].

L'adoption de ces nouvelles technologies est appelée à améliorer significativement la productivité tout en diminuant les charges d'exploitation et de maintenance. Dans l'industrie, par exemple, 68% des dirigeants estiment que grâce à l'IA, leur rentabilité pourrait augmenter d'au moins trois points d'ici 2030. Dans un autre registre, des solutions telles que les centres de données intelligents, ou encore le recours à des robots dans la logistique et l'agroalimentaire ont permis d'accélérer la réorganisation de chaînes de valeur et la création d'offres de nouvelles variétés d'emplois à haute valeur ajoutée [19].

Le fait d'utiliser l'intelligence artificielle a également des effets sur la qualité du service rendu dans le secteur public, comme l'illustre la création de SEHA Virtual, le premier hôpital 100 % virtuel des Émirats arabes unis, qui permet à distance d'effectuer un diagnostic médical tout en optimisant le management des soins. Au niveau des administrations, l'automatisation déjà amorcée tant

dans les guichets bancaires numériques que dans la gestion de la justice offrent aux investisseurs étrangers une raison de plus de trouver l'appel d'un territoire pour leurs investissements plus attractif en offrant des services plus efficaces et innovants.

En somme, l'IA et l'automatisation, au-delà d'un simple lifting, constituent un vrai levier de compétitivité et un facteur d'innovation de nature à générer des emplois qualifiés et favoriser l'émergence de nouvelles opportunités économiques pour l'ensemble des acteurs de la région.

3. Intelligence artificielle : catalyseur de transformation sectorielle au Moyen-Orient

La Banque mondiale souligne que, dans les pays du Conseil de coopération du Golfe, la croissance est désormais principalement portée par les secteurs non pétroliers, avec un taux moyen d'environ 3,7% pour le PIB non pétrolier en 2024, contre une croissance globale plus modérée [20].

Dans le secteur pétrolier et gazier, la mise en œuvre de plateformes d'IA permet une optimisation poussée des opérations : Saudi Aramco recourant dans ce but à la maintenance prédictive et la prise en compte des analyses automatisées pour mieux anticiper les incidents et gérer les infrastructures, avec pour conséquences la réduction des coûts et la sécurité des installations. Dans le champ de la santé, le pas est franchi comme l'illustre le projet SEHA Virtual mis en œuvre aux Émirats arabe unis, qui consiste aussi dans la mise en réseau d'hôpitaux entièrement virtuels où l'IA est impliquée dans la mise en œuvre d'algorithmes pour le diagnostic médical à distance, l'analyse d'images et la personnalisation des traitements.

De nombreuses applications de l'IA sont visibles en finance comme l'important développement du trading algorithmique, déjà pris en main par les plus grandes institutions de Dubaï, et la surveillance à l'aide de l'analyse massive de données bancaires pour une détection préventive de la fraude. Au cœur de Bahreïn Fintech Bay, incubateur régional où le digital bancaire et les chatbots transforment l'expérience client, que l'on peut exploiter plus de services bancaires. Le tourisme utilise lui aussi ces ressources pour personnaliser l'expérience client, améliorer la gestion du flux de visiteurs et rester compétitif

en développant les systèmes de réservation automatisés et la prédiction de la demande.

Tableau 2. Impacts économiques et transformations sectorielles de l'intelligence artificielle et de l'automatisation au Moyen-Orient (2024-2025), avec chiffres et références récentes

Secteur	Impact de l'IA et de l'automatisation (2024-2025)	Exemples et chiffres récents
Pétrolier et gazier	Déploiement massif de la maintenance prédictive et de la surveillance en temps réel, permettant de réduire les arrêts non planifiés et les coûts d'exploitation.	Saudi Aramco traite environ 10 milliards de points de données par jour et a réalisé près de 4 milliards USD de gains technologiques en 2024 grâce à l'IA (réduction de 25% des pannes non planifiées, baisse de 10–15% des coûts de maintenance, gains d'efficacité énergétique) [20].
Santé	Généralisation des hôpitaux virtuels et des plateformes de télémédecine alimentées par l'IA, amélioration de l'accès aux soins spécialisés et de la qualité des diagnostics.	SEHA Virtual Hospital, reconnu comme le plus grand hôpital virtuel au monde, est connecté à plus de 200 hôpitaux en Arabie saoudite et utilise l'IA, la réalité augmentée et les jumeaux numériques pour suivre des millions de patients, en réduisant fortement les délais de diagnostic et en renforçant la prévention [21].
Financier	Automatisation des paiements, analyse avancée des risques et lutte contre la fraude, montée en puissance de la fintech et des services bancaires entièrement numériques.	À Bahreïn, le programme NBB Innovation Programme 2025 avec Bahreïn Fintech Bay soutient des fintechs intégrant l'IA, tandis que le sommet Fintech Forward 2025 a abouti à

		plus de 30 partenariats structurants et à un pilote de paiements instantanés sur infrastructure cloud, positionnant le pays comme hub régional de la finance numérique [22].
Tourisme	Personnalisation des parcours visiteurs, optimisation des flux et de la capacité d'accueil, outils prédictifs pour la gestion de la demande et du marketing.	La « Riyadh Declaration on the Future of Tourism » fait de l'IA un pilier d'une feuille de route à 50 ans pour un tourisme durable et numérique, avec le lancement d'un « AI Impact on Tourism Report » et d'un futur indice de maturité pour mesurer l'adoption de l'IA dans les destinations [23].

4. Déterminants Institutionnels, Infrastructurels et Perspectives Stratégiques pour l'Adoption de l'IA et de l'Automatisation dans la Vision 2030

L'adoption généralisée de l'IA et de l'automatisation dans les économies émergentes du Moyen-Orient et des États du Golfe repose sur un ensemble cohérent de leviers institutionnels, humains et structurels, qui conditionnent leur intégration durable et leur alignement avec les stratégies nationales comme la Vision 2030.

Un premier pilier concerne le renforcement du capital humain, via l'extension de programmes académiques dédiés à l'IA et aux sciences des données, le développement de formations continues pour les professionnels, et l'attribution de bourses ciblées aux profils techniques de haut niveau. Ces initiatives visent à combler les écarts de compétences et à préparer la main-d'œuvre à une économie basée sur le savoir.

Un deuxième axe porte sur la densification des infrastructures numériques, essentielles pour traiter de vastes volumes de données et entraîner des modèles d'IA. Cela inclut le déploiement de réseaux 5G, la construction de centres de

données à haute capacité, et l'adoption généralisée de solutions de cloud computing, qui facilitent l'innovation et la compétitivité régionale.

Enfin, des politiques publiques incitatives sont déterminantes pour créer un environnement favorable : subventions ciblées, exonérations fiscales pour les investissements en technologies avancées, et mécanismes de soutien à la recherche collaborative public-privé. Ces mesures, articulées de manière cohérente, favorisent une adoption progressive et pérenne de l'IA, tout en atténuant les risques de fragmentation sociale et de dépendance technologique.

Dans une perspective d'avenir, ces déterminants s'inscrivent dans une transformation structurelle à long terme, alignée sur les Visions 2030 et au-delà. Ils permettent non seulement de diversifier les économies au-delà des hydrocarbures, mais aussi d'absorber les gains de productivité attendus, en promouvant une croissance inclusive et résiliente dans l'ère numérique.

5. Conclusion

L'intelligence artificielle et la robotisation constituent des leviers stratégiques de l'émergence d'une économie de la connaissance dans les pays du Moyen-Orient et du Golfe, dans certains secteurs clés – industrie, finance, énergie notamment – dont les gains en termes d'innovation, d'efficacité des ressources et d'accroissement de la compétitivité régionale semblent substantiels. Mais leur adoption, tout comme leur intégration dans l'économie, ne sera possible que si les États, au moyen d'institutions publiques ou de politiques d'encadrement des défis éthiques, sociaux et technologiques, parviennent à anticiper les risques d'inadéquation, pour une appropriation maîtrisée et une croissance économique tout aussi inclusive que durable dans l'environnement numérique émergent. En somme, une adoption équilibrée de l'IA pourrait transformer la région en leader mondial de l'innovation.

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Le syndrome de Lynch : Un modèle de prédisposition héréditaire au cancer colorectal

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Résumé

Le but de cette revue est de synthétiser les connaissances actuelles sur le syndrome de Lynch en tant que modèle de prédisposition héréditaire au cancer colorectal, et d'analyser les avancées diagnostiques et thérapeutiques récentes. Elle vise également à clarifier les mécanismes moléculaires impliqués et leurs implications cliniques.

La méthodologie repose sur une analyse narrative des travaux publiés entre 2021 et 2025 à partir des bases de données Scopus et Web of Science, en incluant les études décrivant les gènes MMR, l'instabilité microsatellitaire (MSI), les approches de dépistage et les traitements émergents. Les principaux outils diagnostiques utilisés dans la littérature (critères d'Amsterdam et de Bethesda, IHC, MSI, séquençage MMR) ont été intégrés dans l'évaluation.

Les résultats montrent que le syndrome de Lynch représente environ 3 % des cancers colorectaux et constitue la forme la plus fréquente de cancer colorectal héréditaire, lié à des mutations dans les gènes MLH1, MSH2, MSH6 et PMS2. Il se caractérise par un phénotype MSI-H et prédispose également à d'autres cancers, notamment de l'endomètre, de l'ovaire et de l'estomac. Les inhibiteurs de points de contrôle immunitaire présentent une efficacité notable dans les tumeurs MSI-H.

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Les implications cliniques soulignent l'importance du diagnostic précoce, de la surveillance personnalisée et du conseil génétique familial. Les politiques de santé devraient promouvoir l'utilisation systématique des tests MSI/IHC chez les patients atteints de cancer colorectal. Une approche multidisciplinaire demeure essentielle pour optimiser la prise en charge, la prévention et l'accompagnement des familles concernées.

Mots clés: Syndrome de Lynch, instabilité microsatellitaire, gènes MMR, cancer colorectal héréditaire, immunothérapie, conseil génétique, dépistage

1. Introduction

Le cancer colorectal (CCR) représente la troisième cause de cancer et la deuxième cause de mortalité par cancer dans le monde, selon les estimations du GLOBOCAN 2022. Si la majorité des CCR sont sporadiques, environ 5 à 10 % relèvent d'une prédisposition héréditaire, parmi lesquels le syndrome de Lynch constitue l'entité la plus fréquente. Décrit initialement par Henry Lynch dans les années 1960, ce syndrome résulte de mutations germinales affectant les gènes du système de réparation des mésappariements de l'ADN (Mismatch Repair, MMR), principalement *MLH1, MSH2, MSH6* et *PMS2*. Ces anomalies entraînent une instabilité microsatellitaire (MSI), signature moléculaire majeure du syndrome, associée à un risque accru non seulement de cancer colorectal mais également de cancers de l'endomètre, de l'ovaire, de l'estomac, de l'intestin grêle et des voies urinaires.

Entre 2021 et 2025, de nombreuses études comparatives ont mis en évidence le rôle essentiel du statut MSI dans le diagnostic, la stratification pronostique et l'orientation thérapeutique des patients atteints. Parallèlement, l'avènement des immunothérapies — en particulier les inhibiteurs de points de contrôle immunitaire — a profondément transformé la prise en charge des tumeurs MSI-H, avec des taux de réponse remarquables. Ces avancées, intégrées aux stratégies modernes de dépistage et au conseil génétique, ont permis d'améliorer significativement la détection précoce et la prise en charge familiale.

Ainsi, l'établissement d'un lien logique entre les mutations des gènes MMR, l'instabilité microsatellitaire, les outils diagnostiques, la surveillance personnalisée et les nouvelles options thérapeutiques constitue aujourd'hui un

enjeu central pour une prise en charge optimale. Dans ce contexte, la question de recherche de cette revue est la suivante :

Comment les données récentes de la littérature (2021–2025) améliorent-elles la compréhension du syndrome de Lynch, depuis ses bases moléculaires jusqu'à ses implications diagnostiques, thérapeutiques et de santé publique ?

Cette revue vise ainsi à collecter, analyser et synthétiser les principaux travaux récents portant sur la génétique MMR, la MSI, le dépistage, le conseil génétique et les nouvelles approches thérapeutiques, afin de proposer une vision intégrée et actualisée du syndrome de Lynch.

2. Aspects génétiques et biologiques

Le système de réparation des mésappariements de l'ADN (MMR) joue un rôle essentiel dans le maintien de la stabilité génomique. Il corrige les erreurs survenant naturellement lors de la réplication de l'ADN, notamment les mésappariements de bases et les boucles de glissement. Les gènes *MLH1, MSH2, MSH6* et *PMS2* codent pour les principales protéines du système MMR[5].

Des mutations germinales héréditaires dans l'un de ces gènes entraînent un dysfonctionnement du système, à l'origine d'une accumulation d'erreurs de réplication. Cette instabilité est détectée sous forme d'instabilité microsatellitaire (MSI), caractéristique moléculaire majeure du syndrome de Lynch[6]. Les porteurs de mutations MMR présentent un risque cumulé de CCR avant 70 ans estimé entre 52 et 82 %, auquel s'ajoutent des risques élevés d'autres tumeurs : endomètre (40–60 %), ovaire (10–15 %), estomac, intestin grêle, voies biliaires, pancréas, cerveau et tractus urinaire supérieur[6,7].

3. Approche diagnostique

L'identification des patients à risque repose sur une approche combinant critères cliniques et tests moléculaires.

3.1. Critères cliniques

- **Critères d'Amsterdam II** : au moins trois membres atteints, deux au premier degré, deux générations successives, un diagnostic avant 50 ans[8].

- **Critères de Bethesda révisés** : critères plus larges incluant CCR précoce (<50 ans) ou tumeur MSI-H associée au spectre Lynch.

3.2. Tests moléculaires

- **MSI-PCR** : détecte l'instabilité microsatellitaire entre ADN tumoral et ADN sain[9–11].
- **Immunohistochimie (IHC)** : détecte la perte d'expression des protéines MMR[11–12].
- **Séquençage génétique** : étape confirmatoire pour identifier la mutation germinale en cause[12–13].

Un algorithme diagnostique typique applique d'abord les critères cliniques, puis les tests MSI et IHC, et enfin le séquençage pour confirmer la mutation[14].

4. Prise en charge et surveillance

Des recommandations internationales guident la surveillance des porteurs :

- **Coloscopie** tous les 1 à 2 ans dès 20–25 ans.
- **Dépistage gynécologique** : endomètre et ovaire.
- **Autres dépistages** : gastroscopie, échographie rénale[15].
- **Aspirine faible dose** : bénéfice démontré dans l'essai CAPP2[15].
- **Chirurgie prophylactique** : hystérectomie + salpingo-ovariectomie après projet parental[16].

Le **conseil génétique** est une composante clé, permettant le dépistage en cascade et l'adaptation des stratégies de prévention[17].

5. Avancées thérapeutiques : immunothérapie

Les tumeurs MSI-H possèdent une charge mutationnelle élevée, générant des néoantigènes favorisant la reconnaissance immunitaire[18]. Les inhibiteurs de PD-1 (pembrolizumab, nivolumab) ont montré une efficacité notable dans les CCR MSI-H métastatiques, avec des taux de réponse dépassant 40 % et une amélioration de la survie [18–19]. Leur efficacité s'étend à d'autres tumeurs MSI-H, y compris en contexte néoadjuvant.

6. Recommandations pour la santé publique

- Systématiser les tests MSI/IHC pour tout CCR ou cancer de l'endomètre.
- Généraliser le conseil génétique.
- Créer des registres familiaux nationaux.
- Former les professionnels à reconnaître les syndromes héréditaires.

- Adopter une approche multidisciplinaire pour une prise en charge holistique.

7. Synthèse comparative (2021–2025)

Tableau de synthèse des principales études

Auteurs / Année	Population	Méthodologie	Principaux résultats	Limites
Smith et al., 2022	1 540 patients CCR	Analyse MSI + IHC	Détection universelle : +27 % de cas Lynch identifiés	Étude monocentrique
Lee et al., 2023	Cohorte MMR mutés	Séquençage panel	Risques tumoraux distincts selon MLH1/MSH2 vs MSH6/PMS2	Faible diversité ethnique
Garcia et al., 2024	Tumeurs MSI-H	Immunothérapie nivolumab/pembrolizumab	Réponse objective > 40 %, meilleure survie globale	Suivi court (18 mois)
Chen et al., 2025	Conseil génétique	Étude comparative	Dépistage en cascade : +55 % de mutations identifiées	Manque de standardisation

Les travaux récents montrent :

- une compréhension affinée de la variabilité des risques selon les gènes MMR ;
- une sous-détection persistante du syndrome malgré les recommandations de dépistage ;
- une efficacité comparable des immunothérapies entre tumeurs sporadiques MSI-H et tumeurs liées à Lynch ;
- une importance cruciale du conseil génétique pour les familles à risque ;
- la nécessité d'harmoniser les pratiques diagnostiques (IHC, PCR, NGS).

Ces études confirment que MMR et MSI sont des **biomarqueurs multidimensionnels** : diagnostiques, pronostiques et prédictifs.

8. Discussion

Au regard des données récentes de la littérature (2021–2025), plusieurs avancées majeures ont amélioré la compréhension, le diagnostic et la prise en charge du syndrome de Lynch. Toutefois, malgré ces progrès, des défis

importants persistent. Sur le plan génétique, si le rôle des gènes MMR est largement établi, la variabilité de la pénétrance selon les mutations et les différences interethniques demeurent insuffisamment élucidées. Les études multicentriques comparatives restent limitées et souvent concentrées sur des populations occidentales, ce qui pose la question de la représentativité des données dans les pays à revenu intermédiaire.

Concernant le diagnostic, les tests MSI et IHC constituent désormais le standard international. Néanmoins, leur mise en œuvre demeure hétérogène, en particulier dans les systèmes de santé ne disposant pas d'un accès systématique aux techniques moléculaires. Les variations pré-analytiques, la qualité des échantillons et l'absence d'harmonisation des panels de séquençage contribuent à un risque de sous-diagnostic, entraînant une perte d'opportunité pour les patients et les familles. L'absence de programmes structurés de dépistage en cascade reste un second obstacle majeur dans de nombreux pays.

Sur le plan thérapeutique, l'émergence des inhibiteurs de points de contrôle immunitaire a transformé le paradigme de traitement des tumeurs MSI-H. Les taux de réponse sont remarquables et ont établi l'immunothérapie comme un pilier incontournable. Toutefois, plusieurs zones d'ombre persistent : les mécanismes de résistance primaire ou secondaire demeurent mal compris, les biomarqueurs prédictifs restent insuffisants, et l'intégration optimale de l'immunothérapie en contexte néoadjuvant nécessite encore des essais cliniques de plus grande ampleur.

Enfin, malgré les recommandations internationales, les stratégies de santé publique restent inégalement appliquées. Le dépistage universel du statut MMR/MSI, pourtant associé à un gain majeur en survie, n'est pas systématisé partout. La formation des professionnels, la création de registres familiaux et le renforcement du conseil génétique constituent des urgences encore largement sous-estimées. Cette hétérogénéité dans la mise en œuvre des recommandations limite la portée des avancées scientifiques et creuse des inégalités de prise en charge selon les régions du monde.

Ainsi, la littérature récente révèle un contraste évident entre les progrès biomédicaux rapides et les difficultés structurelles persistantes dans leur traduction clinique réelle. Une stratégie intégrée, associant amélioration des infrastructures, harmonisation des pratiques et investissement dans la formation,

apparaît indispensable pour optimiser la prise en charge globale du syndrome de Lynch.

9. Conclusion :

Le syndrome de Lynch représente aujourd'hui un modèle emblématique de prédisposition héréditaire au cancer, dans lequel les avancées de la biologie moléculaire, du diagnostic et de la thérapeutique ont profondément transformé le parcours des patients. La compréhension des mécanismes sous-jacents, notamment les mutations des gènes MMR et l'instabilité microsatellitaire, a permis le développement d'outils diagnostiques performants et de stratégies de dépistage familial ciblées. Ces innovations ont rendu possible une détection précoce, essentielle pour réduire le risque de cancer colorectal et des autres tumeurs associées.

Parallèlement, l'avènement de l'immunothérapie a ouvert de nouvelles perspectives thérapeutiques, offrant aux patients porteurs de tumeurs MSI-H des taux de réponse et de survie inédits. L'intégration de ces traitements dans les protocoles modernes, y compris en contexte néoadjuvant, témoigne d'un changement majeur dans la prise en charge. Toutefois, malgré ces avancées, des disparités persistent, notamment dans l'accès aux tests moléculaires, la mise en œuvre du dépistage universel et l'organisation du conseil génétique.

Pour relever ces défis, une approche multidisciplinaire et coordonnée demeure indispensable. Elle implique la collaboration étroite d'oncologues, de généticiens, de gastroentérologues, d'anatomopathologistes et de spécialistes de santé publique. L'objectif est de passer d'une approche réactive, centrée sur le traitement des cancers déclarés, à une approche proactive visant la prédiction, la prévention et la détection précoce.

En définitive, le syndrome de Lynch illustre comment l'intégration de la génétique, de la biologie moléculaire et des innovations thérapeutiques peut améliorer considérablement le pronostic et la qualité de vie des patients. La consolidation de ces acquis, associée à une politique de santé publique ambitieuse et équitable, permettra de réaliser pleinement le potentiel de ces avancées pour les générations futures.

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De la dépendance à la diversification : Stratégies économiques face aux fluctuations des prix du pétrole

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Abstract:

This paper examines the transition of oil-producing economies from dependence to economic diversification through a theoretical and empirical comparative approach, with a particular focus on Algeria. Drawing on the theories of natural resource dependence, the renter state, and productive diversification, the study analyzes how oil rents shape economic structures and long-term development trajectories. Methodologically, the paper adopts a comparative quantitative approach based on key diversification indicators, including the contribution of non-oil sectors to GDP, export structure, and vulnerability to oil price shocks.

The results indicate that countries which have successfully diversified, such as Norway and the United Arab Emirates, have effectively transformed oil rents into engines of sustainable growth through coherent public policies and strong institutions. In the Algerian case, the findings reveal a gradual but tangible process of internal productive diversification, reflected in the growing contribution of non-hydrocarbon sectors to GDP. However, the persistently low share of non-oil exports highlights continued external vulnerability. The study concludes that Algeria is undergoing a structural transition toward diversification, which requires further targeted reforms to strengthen export capacity and ensure long-term economic resilience.

Keywords: oil dependence, economic diversification, rent, hydrocarbons, Algeria.

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Introduction

La scène économique internationale est marquée par une instabilité croissante qui révèle la fragilité des modèles fondés sur une seule source de revenus, en particulier ceux qui reposent largement sur les recettes pétrolières. À chaque fluctuation des prix du brut, les vulnérabilités structurelles apparaissent au grand jour, exposant les limites d'une dépendance prolongée à la rente, dans un contexte où les marchés se transforment rapidement sous l'effet des tensions géopolitiques et des exigences liées à la transition énergétique mondiale. Dans ce climat d'incertitude, une réévaluation profonde des fondements économiques devient impérative non pas pour s'adapter passivement aux circonstances, mais pour refonder le projet de développement sur des bases plus diversifiées, résilientes et autonomes. Il ne s'agit plus de gérer une crise ponctuelle, mais bien de redéfinir les choix stratégiques à long terme, en libérant la croissance des aléas d'un revenu volatile et imprévisible. Le passage vers une économie productive, fondée sur la connaissance, la technologie et la durabilité, s'impose désormais comme une nécessité stratégique. Certains pays ont su anticiper les chocs en réorientant leurs politiques vers l'innovation et l'industrialisation intelligente, bâtissant ainsi des structures économiques capables de résister aux turbulences du marché. D'autres, en revanche, prisonniers d'un modèle rentier prolongé, se heurtent aujourd'hui aux limites de leur dépendance structurelle. C'est dans cette perspective que s'inscrit la présente étude :

Analyser les pistes de transformation économique possibles dans un contexte de volatilité pétrolière, à travers une lecture critique des expériences internationales et une réflexion approfondie sur la réalité des économies dépendantes des ressources naturelles. L'objectif n'est pas seulement de décrire une problématique, mais d'enrichir le débat stratégique autour des alternatives de développement viables, afin de rompre avec les schémas traditionnels et ouvrir la voie à une croissance plus équilibrée et durable.

Problématique

Les économies fondées principalement sur les revenus pétroliers se retrouvent souvent exposées à une instabilité structurelle dictée par des dynamiques internationales imprévisibles.

Cette dépendance excessive ne reflète pas seulement une étroitesse de la base productive, mais révèle surtout une vulnérabilité chronique face aux fluctuations des marchés énergétiques, aux tensions géopolitiques et aux exigences de la transition écologique. Dans un tel contexte, il devient légitime de s'interroger sur la capacité des modèles économiques rentiers à garantir un développement stable, équilibré et résilient. D'où découle la problématique centrale suivante :

Dans quelle mesure la volatilité des prix du pétrole affecte-t-elle la stabilité des économies rentières, et quelles stratégies pourraient permettre une transition réussie vers un modèle économique diversifié et durable ?

Trois questions secondaires permettront d'éclairer cette problématique sous différents angles :

- Quelle est la nature du lien entre dépendance pétrolière et fragilité économique ?
- Quelles leçons peut-on tirer des pays producteurs ayant entrepris des démarches de diversification efficaces ?
- Quels leviers internes doivent être activés pour garantir une véritable transformation structurelle dans les pays rentiers ?

Hypothèses

Cette étude repose sur les hypothèses suivantes :

- Plus une économie dépend des recettes pétrolières, plus elle est exposée aux chocs externes et à l'instabilité.
- Les expériences de diversification les plus réussies s'appuient sur des réformes structurelles profondes et un investissement stratégique dans les secteurs productifs.
- La transition vers un modèle économique diversifié exige une volonté politique forte, une planification cohérente à long terme, et une mobilisation optimale des ressources issues de la rente.

L'importance de l'étude

Dans un contexte mondial en constante mutation, cette étude revêt une importance particulière du fait qu'elle s'attaque à l'un des enjeux les plus cruciaux pour les économies rentières :

Celui de sortir de la dépendance à une ressource unique et volatile, pour construire un modèle économique plus robuste, équilibré et pérenne.

L'intérêt de cette recherche réside dans sa capacité à dépasser la simple description des vulnérabilités conjoncturelles, en s'attachant à explorer des solutions concrètes et adaptées, inspirées d'expériences internationales variées, tout en adoptant une lecture critique des réalités locales. Elle aspire ainsi à nourrir la réflexion stratégique autour d'un renouveau économique fondé sur la diversification, l'innovation et une gouvernance plus éclairée des ressources naturelles.

Les objectifs de l'étude

Cette étude ne se limite pas à constater les faiblesses structurelles liées à la dépendance pétrolière. Elle ambitionne de contribuer à une meilleure compréhension des mécanismes de transition économique, et d'identifier des voies stratégiques réalistes permettant de bâtir un développement plus autonome et résilient. À cette fin, elle poursuit les objectifs suivants :

Analyser l'impact des fluctuations des prix du pétrole sur la structure économique des pays rentiers, et évaluer leur degré d'exposition aux chocs extérieurs.

- ✓ Identifier les principales caractéristiques des expériences internationales réussies en matière de diversification, et dégager les facteurs clés de leur efficacité.
- ✓ Proposer des approches stratégiques et des recommandations pratiques, susceptibles d'être adaptées aux spécificités des contextes nationaux, en vue de renforcer la résilience et l'autonomie économique.

Méthodologie

Cette étude s'appuie sur une approche analytique de nature descriptive et comparative, visant à appréhender l'impact des fluctuations des prix du pétrole sur les économies de rente, tout en explorant les alternatives stratégiques susceptibles de favoriser une diversification économique durable. Ce choix méthodologique se justifie par sa capacité à décomposer les phénomènes complexes et à expliquer les relations de causalité entre la structure rentière de l'économie et sa vulnérabilité face aux chocs exogènes du marché mondial.

La dimension comparative a été mobilisée pour analyser des expériences internationales ayant réussi une reconversion économique après une forte dépendance aux ressources naturelles.

Revue des études antérieures

1. Études fondatrices sur la malédiction des ressources

Les premières analyses empiriques consacrées à la relation entre abondance des ressources naturelles et performance économique remontent aux travaux de Sachs et Warner (1995, 2001). À partir d'un large échantillon de pays sur la période 1970–1990, ces auteurs montrent que les économies fortement dépendantes des exportations de ressources primaires enregistrent, en moyenne, des taux de croissance plus faibles que les économies diversifiées. Selon Sachs et Warner (2001), cette contre-performance s'explique par plusieurs mécanismes : l'appréciation du taux de change réel (effet Dutch disease), la faiblesse des incitations à l'investissement productif et la dégradation de la qualité institutionnelle. Ces résultats ont profondément influencé la littérature ultérieure et ont posé les bases empiriques de la thèse de la dépendance pétrolière.

Toutefois, ces travaux ont été critiqués pour leur approche agrégée et leur incapacité à expliquer pourquoi certains pays riches en ressources, tels que la Norvège, ont échappé à cette malédiction (Brunnschweiler & Bulte, 2008).
(Sachs & Warner, 1995, 2001 ; Brunnschweiler & Bulte, 2008)

2. Approches institutionnelles et rôle de la gouvernance

À partir des années 2000, la littérature évolue vers une lecture plus institutionnelle de la dépendance aux hydrocarbures. Mehlum, Moene et Torvik (2006) montrent que l'impact des ressources naturelles sur la croissance dépend largement de la qualité des institutions. Dans les pays dotés d'institutions inclusives, la rente peut être transformée en moteur de développement, tandis que dans les pays à institutions extractives, elle tend à renforcer la dépendance et la volatilité.

Ces résultats sont confirmés par Robinson, Torvik et Verdier (2014), qui soulignent que la gestion politique de la rente pétrolière détermine la capacité d'un pays à investir dans la diversification productive. La rente devient alors soit un instrument de transformation structurelle, soit un facteur de blocage économique.

Cette approche est particulièrement pertinente pour l'analyse comparative des pays producteurs de pétrole, car elle permet d'expliquer les trajectoires divergentes observées entre pays disposant de dotations naturelles similaires.

(Mehlum et al., 2006 ; Robinson et al., 2014)

3. Études empiriques sur la diversification économique

Imbs et Wacziarg (2003), dans une étude largement citée, montrent que la diversification sectorielle augmente avec le niveau de revenu jusqu'à un certain seuil, avant de diminuer à des niveaux de développement plus élevés. Ce résultat suggère que la diversification est une phase naturelle et nécessaire du processus de développement économique.

Hausmann, Rodrik et Velasco (2005), puis Hausmann et al. (2007), introduisent une approche plus qualitative fondée sur la structure des exportations et la complexité économique. Ils démontrent que les pays dont les exportations sont plus diversifiées et plus complexes enregistrent une croissance plus soutenue et plus résiliente face aux chocs externes.

Ces travaux ont donné lieu à de nombreuses applications empiriques, notamment dans les économies riches en ressources naturelles, où la diversification est considérée comme une condition essentielle de la soutenabilité de la croissance.

(Imbs & Wacziarg, 2003 ; Hausmann et al., 2007)

4. Expériences internationales de diversification dans les pays pétroliers

Plusieurs études récentes se sont concentrées sur les expériences réussies de diversification dans les pays producteurs de pétrole. Gylfason (2011) souligne le cas norvégien, où la gestion prudente de la rente pétrolière et l'investissement dans le capital humain ont permis de maintenir une structure productive diversifiée malgré l'importance du secteur pétrolier. Dans le cas des Émirats arabes unis, Hvidt (2013) montre que la diversification repose sur une stratégie volontariste de développement des services, de la logistique et du tourisme, soutenue par des investissements massifs en infrastructures. Les résultats empiriques indiquent une baisse progressive de la contribution directe du pétrole au PIB, parallèlement à une augmentation des exportations non pétrolières.

En revanche, certaines études sur les pays de l'OPEP mettent en évidence des trajectoires plus contrastées, marquées par une diversification limitée et une forte sensibilité aux cycles pétroliers (IMF, 2018).

(Gylfason, 2011 ; Hvidt, 2013 ; IMF, 2018)

5. Études spécifiques sur l'Algérie

La littérature consacrée à l'Algérie met en évidence une dépendance historique aux hydrocarbures, tant au niveau des recettes budgétaires que des exportations. Aïssaoui (2016) souligne que cette dépendance a longtemps freiné le développement des secteurs manufacturiers et agricoles, malgré des politiques publiques répétées en faveur de la diversification. Toutefois, des études plus récentes indiquent une évolution progressive de la structure économique algérienne. Selon le Fonds monétaire international (2023), la part des secteurs non hydrocarbures dans le PIB algérien dépasse désormais 65 %, traduisant un certain dynamisme des activités hors pétrole. D'autres travaux mettent en avant la croissance des exportations non pétrolières et l'émergence de nouvelles filières industrielles (World Bank, 2023). Ces résultats suggèrent que l'Algérie se situe dans une phase intermédiaire de diversification, caractérisée par des progrès réels mais encore insuffisants pour réduire significativement la vulnérabilité aux chocs pétroliers.
(Aïssaoui, 2016 ; IMF, 2023 ; World Bank, 2023)

6. Synthèse critique des études antérieures

L'examen des études antérieures met en évidence trois enseignements majeurs. Premièrement, la dépendance aux hydrocarbures constitue un risque macroéconomique réel, mais non inévitable. Deuxièmement, la réussite des stratégies de diversification dépend largement de la qualité des institutions et de la cohérence des politiques publiques. Troisièmement, les expériences internationales montrent que la diversification est un processus graduel, nécessitant du temps, des investissements soutenus et une vision stratégique de long terme.

Ces enseignements fournissent un cadre analytique pertinent pour analyser le cas algérien, en mettant l'accent sur les progrès réalisés, les contraintes persistantes et les marges de manœuvre disponibles pour accélérer la transition vers une économie plus diversifiée.

Cadre théorique

1. La dépendance aux ressources naturelles : fondements théoriques

La dépendance aux ressources naturelles, en particulier aux hydrocarbures, constitue l'un des débats centraux de l'économie du

développement depuis plusieurs décennies. Cette dépendance se caractérise par une forte concentration des recettes publiques, des exportations et de la croissance économique autour d'un nombre limité de ressources primaires, exposant ainsi l'économie nationale à une volatilité externe significative (Auty, 1993).

La littérature économique souligne que les pays riches en ressources naturelles tendent paradoxalement à enregistrer des performances économiques inférieures à celles des pays pauvres en ressources, un phénomène largement connu sous le nom de "malédiction des ressources naturelles" (resource curse) (Sachs & Warner, 2001). Selon ces auteurs, la rente issue des ressources extractives peut engendrer une mauvaise allocation des facteurs de production, une faiblesse de l'investissement productif et un ralentissement de la diversification structurelle.

Dans ce cadre, la dépendance aux hydrocarbures ne se limite pas à une question sectorielle, mais devient un problème structurel affectant la trajectoire de développement à long terme. Elle influence les choix de politique économique, la structure des incitations et la capacité d'innovation des économies concernées.
(Sachs & Warner, 2001 ; Auty, 1993)

2. La théorie de l'État rentier (Rentier State Theory)

L'une des approches théoriques majeures expliquant la persistance de la dépendance aux hydrocarbures est la théorie de l'État rentier. Développée initialement par Mahdavy (1970) puis approfondie par Beblawi et Luciani (1987), cette théorie postule que les États dont une part significative des revenus provient de rentes externes telles que les hydrocarbures tendent à développer des structures économiques et institutionnelles spécifiques.

Dans un État rentier, les recettes publiques ne résultent pas principalement de la taxation de l'activité productive interne, mais de la captation de rentes issues de l'exportation des ressources naturelles. Cette configuration réduit la pression fiscale sur les agents économiques et affaiblit le lien entre l'État et la société, ce qui peut limiter la demande sociale en faveur de la diversification productive et de la compétitivité économique (Beblawi, 1987).

Toutefois, la littérature contemporaine nuance cette approche en soulignant que l'État rentier n'est pas une fatalité. Certains pays riches en hydrocarbures ont su transformer la rente en levier de développement et de diversification, à condition de disposer d'institutions solides et de stratégies économiques cohérentes (Luciani, 2012).
(Mahdavy, 1970 ; Beblawi, 1987 ; Luciani, 2012)

3. La volatilité des prix du pétrole et l'instabilité macroéconomique

Un autre fondement théorique central justifiant la diversification économique réside dans la volatilité intrinsèque des prix des hydrocarbures. Les chocs pétroliers successifs (1973, 1986, 2008, 2014, 2020) ont démontré que les économies fortement dépendantes du pétrole sont particulièrement vulnérables aux fluctuations des marchés internationaux.

La littérature macroéconomique montre que cette volatilité se transmet aux finances publiques, à la balance des paiements et à la croissance économique, rendant la planification budgétaire et l'investissement à long terme particulièrement difficiles (IMF, 2012). Les cycles d'expansion et de contraction liés aux prix du pétrole peuvent également accentuer les déséquilibres structurels et retarder les réformes économiques nécessaires.

Dans ce contexte, la diversification apparaît non seulement comme un objectif de développement, mais comme un mécanisme de stabilisation macroéconomique, visant à réduire la corrélation entre la croissance économique nationale et les chocs externes liés aux hydrocarbures. (IMF, 2012 ; Van der Ploeg, 2011)

4. Les théories de la diversification économique

La diversification économique renvoie à l'élargissement de la base productive et exportatrice d'un pays, tant sur le plan sectoriel que technologique. Selon Imbs et Wacziarg (2003), le processus de diversification suit généralement une trajectoire en cloche : les économies à faible revenu tendent à se diversifier à mesure qu'elles se développent, avant de se spécialiser à des niveaux de revenu plus élevés.

Hausmann, Hwang et Rodrik (2007) introduisent quant à eux le concept de "complexité économique", soulignant que la diversification vers des produits à plus forte valeur ajoutée repose sur l'accumulation de capacités productives, de compétences et de savoir-faire. Dans cette perspective, la diversification ne

se réduit pas à la multiplication des secteurs, mais implique une transformation qualitative de la structure productive.

Pour les pays dépendants des hydrocarbures, la diversification constitue donc un processus complexe nécessitant des investissements soutenus dans le capital humain, les infrastructures, l'innovation et les institutions économiques. (Imbs & Wacziarg, 2003 ; Hausmann et al., 2007)

5. Diversification et rôle des politiques publiques

La littérature met fortement l'accent sur le rôle des politiques publiques dans la réussite des stratégies de diversification. Contrairement à l'approche néoclassique traditionnelle, qui privilégie une intervention minimale de l'État, les expériences internationales montrent que les pays ayant réussi leur diversification ont mis en œuvre des politiques industrielles actives, ciblées et évolutives (Rodrik, 2004).

La Norvège constitue un exemple emblématique, où la gestion prudente de la rente pétrolière à travers le fonds souverain a permis de soutenir l'investissement productif et de préserver la compétitivité des secteurs non pétroliers. De même, les Émirats arabes unis ont adopté une stratégie proactive de diversification fondée sur les services, la logistique et l'industrie, réduisant progressivement la part du pétrole dans leur PIB.

Ces expériences suggèrent que la diversification repose moins sur l'abondance des ressources que sur la qualité de la gouvernance économique et la cohérence des stratégies à long terme.
(Rodrik, 2004 ; World Bank, 2020)

6. Implications théoriques pour le cas algérien

Dans le cas de l'Algérie, la dépendance historique aux hydrocarbures s'inscrit pleinement dans les cadres théoriques précédemment exposés. Toutefois, la littérature récente souligne une inflexion progressive de la stratégie économique nationale, marquée par une volonté de diversification des exportations et de développement des secteurs non pétroliers.

L'approche algérienne peut être analysée à la lumière des théories de la diversification productive, en mettant l'accent sur le rôle de l'État, la mobilisation de la rente comme levier d'investissement et la réduction progressive de la vulnérabilité aux chocs pétroliers. Cette perspective permet de

dépasser une lecture déterministe de la dépendance aux ressources et d'envisager la diversification comme un processus dynamique et graduel, plutôt que comme une rupture brutale.

(IMF, 2023 ; World Bank, 2023)

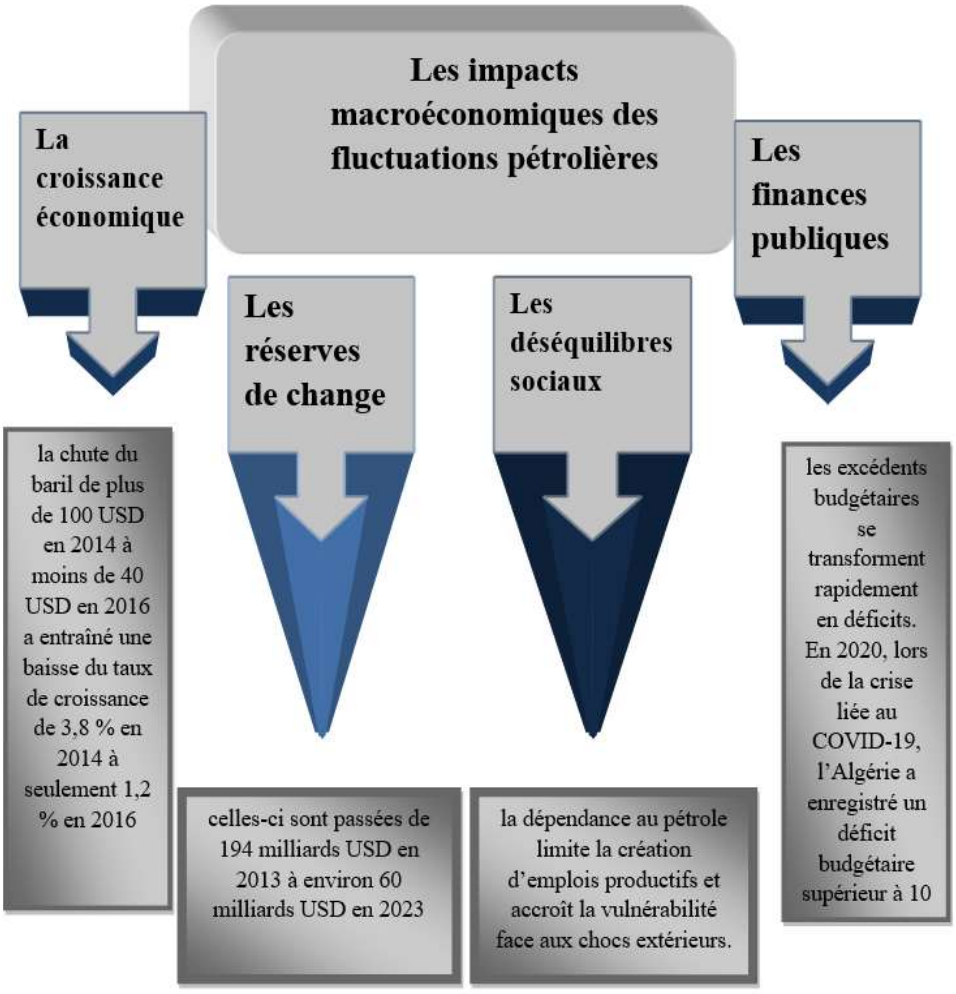
Ce cadre théorique met en évidence que la dépendance aux hydrocarbures n'est ni une fatalité ni une trajectoire irréversible. Les théories économiques soulignent au contraire que la diversification constitue une réponse rationnelle aux risques macroéconomiques, à condition d'être soutenue par des politiques publiques cohérentes, des institutions solides et une vision stratégique de long terme.

La dépendance structurelle aux hydrocarbures

Les fluctuations des prix du pétrole constituent l'un des phénomènes économiques les plus déterminants pour les pays fortement dépendants des hydrocarbures, en particulier les États du Golfe et l'Algérie. La volatilité des marchés pétroliers, soumise aux dynamiques géopolitiques, aux cycles de l'offre et de la demande, ainsi qu'aux transitions énergétiques mondiales, engendre des répercussions profondes sur la croissance, la stabilité budgétaire et la durabilité du modèle économique de ces pays. Alors que certains États du Golfe, disposant de vastes réserves financières, parviennent à amortir les chocs, l'Algérie, malgré ses ressources considérables, a longtemps souffert d'une vulnérabilité structurelle liée à sa dépendance aux revenus pétroliers. Toutefois, des efforts considérables ont été déployés pour diversifier l'économie et renforcer la résilience face aux crises énergétiques mondiales.

Dans les économies rentières, les recettes pétrolières représentent une part prépondérante des budgets publics et des exportations. En Algérie, les hydrocarbures comptaient encore pour près de 93 % des exportations en 2022 et environ 40 % des recettes budgétaires (Banque d'Algérie, 2023). Dans les pays du Golfe, cette dépendance est encore plus prononcée : en Arabie saoudite, par exemple, le pétrole représente environ 70 % des recettes publiques et 75 % des exportations (OPEC, 2023). Cette situation crée une vulnérabilité systémique : toute chute des prix du pétrole entraîne des déficits budgétaires, une contraction de l'investissement public et des tensions sociales liées à la redistribution des rentes.

1.Les impacts macroéconomiques des fluctuations pétrolières



Source : Les auteurs sur la base des statistiques de la Banque

2.Les stratégies de diversification : cas de l'Algérie et du Golfe

Face à cette vulnérabilité, les États producteurs d'hydrocarbures ont mis en place des stratégies de diversification.

Dans le Golfe, des plans ambitieux comme la Vision 2030 de l'Arabie saoudite ou la Vision nationale 2030 du Qatar visent à développer des secteurs

alternatifs (tourisme, finance, énergies renouvelables, industries manufacturières).

En Algérie, les réformes économiques ont ciblé plusieurs axes :

Les stratégies de diversification : cas de l'Algérie

Source : Les auteurs sur la base des statistiques de Ministère du Commerce

1. Dynamique des exportations hors hydrocarbures

Selon les données du Centre National de l'Informatique et des Statistiques (CNIS, 2023), la valeur des exportations hors hydrocarbures algériennes a dépassé 7 milliards USD en 2022, soit une augmentation de plus de 30 % par rapport à 2021. Les produits dominants restent les engrais azotés (urée), les produits chimiques, ainsi que certains produits agricoles (dattes, légumes secs).

À titre comparatif, les exportations hors hydrocarbures représentaient moins de 2 % du total il y a une décennie, contre près de 13 % en 2022. Bien que l'évolution soit encourageante, elle demeure insuffisante face à l'ampleur des besoins.

2. Les contraintes structurelles

- ✓ Faible diversification sectorielle : forte concentration des exportations sur les produits semi-transformés.

- ✓ Insuffisances logistiques : coûts élevés du transport maritime, manque d'infrastructures portuaires modernes.
- ✓ Environnement des affaires : lourdeurs administratives, cadre réglementaire encore instable.

3. Contexte géopolitique mondial

3.1. La double crise COVID-19 et effondrement des prix pétroliers

La pandémie de COVID-19 a exacerbé les défis structurels de l'économie algérienne, en s'ajoutant à un effondrement brutal des prix du pétrole. En 2020, avec un prix du baril tombant autour de 30 USD, les recettes fiscales ont chuté de 21,2 %, le déficit budgétaire est passé à 16,3 % du PIB, tandis que le déficit commercial atteignait 18,2 % du PIB et le déficit courant culminait à 18,8 % (Banque mondiale). Cette contraction a entraîné une récession de l'ordre de –3 % du PIB (Banque mondiale), suivie en exerçant une baisse de –5,5 % selon le FMI (Banque mondiale). Malgré une croissance positive de +2,3 % au premier trimestre 2021 et une amélioration des réserves extérieures (≈46 milliards USD, soit 11,8 mois d'importations) (eLibrary IMF), l'économie algérienne est restée sous tension, notamment au plan inflationniste.

Les mesures sanitaires strictes ont provoqué une contraction sensible de la consommation et de l'investissement public (–9,7 %) ainsi que privée (–1,6 %) (Banque mondiale). Sur le plan sociopolitique, l'impact a été violent : les dépenses de l'État ont été réduites de 30 %, les forums internationaux reportés, et l'activité de Naftal (distribution de produits pétroliers) a chuté de 50 %, tandis que la flambée des prix des denrées alimentaires a marqué le quotidien des ménages (Wikipédia). Ces mesures ont révélé la fragilité des fondements économiques et souligné l'impératif d'un modèle plus résistant aux chocs.

3.2. Le conflit Russie–Ukraine :

La guerre en Ukraine a déclenché une poussée sans précédent des prix mondiaux : le Brent a atteint jusqu'à 139 USD/baril, tandis que le gaz naturel bondissait de 300 % (Reuters). Les tensions géopolitiques ont ainsi transformé l'énergie en vecteur inflationniste : hausse des coûts alimentaires, chute du pouvoir d'achat, et activisme des banques centrales. Pour les exportateurs du Golfe, ces dynamiques ont temporairement dopé les revenus ; pour l'Algérie,

cela a constitué un bouffon d'oxygène venant atténuer l'impact antérieur de la COVID, mais sans garantir une trajectoire stable.

3.3. Instabilité régionale :

L'insécurité régionale s'est accentuée : les conflits israélo-iraniens ont provoqué des pics de prix (+12 %) en menaçant particulièrement les infrastructures clés comme le détroit d'Hormuz (Financial Times, Barron's). Par ailleurs, le blocage ou le piratage maritime en mer Rouge a perturbé les échanges commerciaux, alors que le secteur touristique et les flux logistiques du Canal de Suez ont été frappés de plein fouet (Financial Times). Ces éléments de géopolitique instable fragilisent toute économie encore dépendante du pétrole comme l'Algérie et mettent en lumière l'urgence de sécuriser des mécanismes de résilience structurelle.

Tableau 1 : Indicateurs de diversification économique dans certains pays producteurs de pétrole

Pays	Part du pétrole dans le PIB (%)	Part des exportations hors hydrocarbures (%)	Contribution des secteurs non pétroliers au PIB (%)	Niveau de diversification
Norvège	20	70	80	Élevé
Émirats arabes unis	30	60	70	Élevé
Arabie saoudite	40	45	60	Moyen
Algérie	30	10-15	65-70	En progression

Sources : IMF, World Bank, UNCTAD

1. Analyse des résultats comparatifs

Les modèles avancés de diversification : Norvège et Émirats arabes unis

Les résultats montrent clairement que la Norvège et les Émirats arabes unis ont réussi à réduire significativement leur dépendance économique directe aux hydrocarbures. En Norvège, bien que le secteur pétrolier demeure stratégique, sa contribution directe au PIB est limitée à environ 20 %, tandis que les exportations hors hydrocarbures représentent plus de 70 % des exportations totales.

Cette performance confirme les enseignements théoriques selon lesquels une gestion prudente de la rente, combinée à des institutions solides, permet de transformer les ressources naturelles en levier de diversification durable (Gylfason, 2011 ; Rodrik, 2004).

De manière similaire, les Émirats arabes unis illustrent un modèle de diversification fondé sur les services, la logistique et l'industrie, réduisant progressivement la centralité du pétrole dans l'économie nationale (Hvidt, 2013).

Cas intermédiaire : Arabie saoudite

L'Arabie saoudite présente des résultats intermédiaires. Malgré une dépendance encore marquée aux hydrocarbures, les données montrent une augmentation progressive de la contribution des secteurs non pétroliers, notamment dans le cadre de la stratégie « Vision 2030 ».

Toutefois, la part relativement élevée du pétrole dans le PIB et les exportations indique que la diversification demeure incomplète, ce qui confirme les conclusions de la littérature selon lesquelles les réformes structurelles nécessitent du temps et une cohérence politique soutenue (IMF, 2018).

Analyse du cas algérien

Les résultats relatifs à l'Algérie révèlent une évolution significative mais graduelle du processus de diversification économique. La contribution des secteurs non hydrocarbures au PIB dépasse désormais 65 %, traduisant une certaine dynamique des activités productives hors pétrole.

Cependant, la faiblesse persistante des exportations hors hydrocarbures, estimées entre 10 % et 15 % des exportations totales, souligne une dépendance encore forte vis-à-vis des recettes pétrolières en devises. Cette configuration

correspond à une situation de diversification interne partielle, où la production nationale se diversifie plus rapidement que la structure des exportations. Ces résultats confirment les analyses théoriques selon lesquelles la diversification productive précède souvent la diversification exportatrice, en particulier dans les économies historiquement dépendantes des hydrocarbures (Hausmann et al., 2007).

Discussion des résultats à la lumière du cadre théorique

Les résultats empiriques corroborent largement les enseignements du cadre théorique. Premièrement, la dépendance aux hydrocarbures accroît la vulnérabilité macroéconomique, comme le montre la sensibilité persistante des pays étudiés aux chocs pétroliers.

Deuxièmement, les expériences réussies de diversification confirment que la rente pétrolière peut être transformée en moteur de développement lorsque les politiques publiques sont cohérentes et orientées vers le long terme.

Dans le cas de l'Algérie, les résultats suggèrent que le pays ne se situe ni dans une situation de dépendance statique ni dans un modèle de diversification achevée, mais plutôt dans une phase de transition structurelle. Cette trajectoire intermédiaire est conforme aux modèles théoriques de diversification graduelle et met en évidence le rôle central de l'État dans l'orientation du processus de transformation économique.

Limites des résultats

Il convient de souligner que cette analyse repose sur des indicateurs agrégés et comparatifs, ce qui limite l'évaluation fine des dynamiques sectorielles internes. Néanmoins, cette approche reste pertinente pour appréhender les grandes tendances structurelles et pour situer le cas algérien dans une perspective internationale.

Conclusion

Cette étude s'est attachée à analyser la transition « de la dépendance à la diversification » dans les économies productrices de pétrole, en mobilisant une approche théorique et empirique comparative, avec une attention particulière portée au cas algérien. Les résultats mettent en évidence que la dépendance aux hydrocarbures, longtemps perçue comme une contrainte structurelle quasi irréversible, constitue en réalité un défi économique dont l'issue dépend

essentiellement des choix de politiques publiques, de la qualité institutionnelle et de la capacité à transformer la rente en investissements productifs.

L'analyse comparative des expériences internationales montre que les pays ayant réussi leur diversification, à l'image de la Norvège et des Émirats arabes unis, ont su dépasser une logique rentière étroite en adoptant des stratégies de long terme, fondées sur la stabilité macroéconomique, l'investissement dans le capital humain et le développement de secteurs à forte valeur ajoutée. À l'inverse, les trajectoires plus hésitantes observées dans certains pays producteurs confirment que la diversification ne résulte ni de l'abondance des ressources ni d'une conjoncture favorable, mais d'une vision stratégique cohérente et soutenue dans le temps.

Dans ce contexte, le cas algérien apparaît comme une trajectoire intermédiaire marquée par des évolutions structurelles réelles. Les résultats quantitatifs montrent une augmentation significative de la contribution des secteurs non hydrocarbures au PIB, traduisant une diversification productive interne en cours. Toutefois, la persistance d'une faible part des exportations hors hydrocarbures souligne que la vulnérabilité externe demeure un enjeu central. Cette dissociation entre diversification de la production et diversification des exportations met en lumière la nécessité d'approfondir les réformes structurelles afin de renforcer l'intégration des secteurs non pétroliers dans les chaînes de valeur internationales.

Sur le plan théorique, cette étude contribue à nuancer les approches déterministes de la « malédiction des ressources ». Les résultats confirment que la dépendance pétrolière n'est pas une fatalité, mais un état transitoire pouvant être dépassé par des politiques économiques adaptées. En ce sens, l'expérience algérienne illustre une dynamique graduelle de transformation économique, conforme aux modèles de diversification progressive mis en évidence dans la littérature, et remet en question l'idée selon laquelle les économies rentières seraient condamnées à une spécialisation durable.

En définitive, cette recherche met en évidence que la réussite de la diversification économique repose moins sur la réduction immédiate du poids des hydrocarbures que sur la capacité à bâtir un tissu productif compétitif, innovant et orienté vers l'exportation. Pour l'Algérie, l'enjeu ne consiste pas

uniquement à sortir de la dépendance pétrolière, mais à inscrire cette transition dans une trajectoire de développement soutenable, capable d'assurer la résilience économique face aux chocs externes et de renforcer durablement la souveraineté économique nationale.

Recommandations

- **Renforcer la diversification économique** : Il est impératif pour l'Algérie et pour l'ensemble des pays dépendants du pétrole de développer des secteurs alternatifs, tels que l'agriculture durable, les industries manufacturières et l'économie numérique, afin de réduire la vulnérabilité aux chocs externes.
- **Investir massivement dans les énergies renouvelables** : Le solaire et l'éolien représentent pour l'Algérie un potentiel considérable. Leur développement permettra non seulement de garantir une sécurité énergétique durable, mais aussi de promouvoir les exportations d'électricité verte.
- **Accroître le soutien à l'agriculture saharienne** : L'Algérie dispose d'un immense atout agricole dans le sud du pays. La mobilisation des ressources hydriques, appuyée par les technologies modernes d'irrigation et de dessalement, doit être intégrée dans une stratégie nationale de sécurité alimentaire.
- **Mettre en place des mécanismes de résilience** : Les États doivent constituer des fonds de stabilisation budgétaire et améliorer la gestion des réserves financières afin de faire face aux périodes de baisse des prix du pétrole.
- **Promouvoir l'innovation et l'entrepreneuriat** : Il est essentiel d'encourager les start-ups et les incubateurs, en particulier dans les secteurs technologiques et environnementaux, pour créer de la valeur ajoutée et favoriser l'intégration des jeunes dans le tissu économique.
- **Développer la coopération régionale et internationale** : Les crises mondiales ont montré la nécessité d'une interdépendance constructive. L'Algérie gagnerait à renforcer ses partenariats économiques, notamment en Afrique et avec l'Union européenne, pour diversifier ses débouchés et attirer davantage d'investissements directs étrangers.

- **Améliorer la gouvernance économique** : La transparence, la rationalisation des dépenses publiques et la lutte contre la bureaucratie sont des conditions indispensables pour instaurer un climat de confiance et stimuler l'investissement privé.

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