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# Do The Risks of Blockchain Technology Adoption and Human Capital Empowerment Affect the Sustainability of Banks' Relative Efficiency?

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**Abstract:** This study examines whether the risks of blockchain technology adoption and the empowerment of human capital affect the sustainability of the relative efficiency of banks, using Faisal Islamic Bank in Sudan as the case. Data were collected through an online survey of 352 employees of the bank between 10 October and 25 December 2022, exceeding the minimum sample of 125 computed by an a priori power analysis. Relative efficiency was estimated with a slack-based measure data envelopment analysis model framed by the McKinsey seven-S model, using three blockchain inputs (records, smart contracts and devices), four empowerment inputs (impact, competency, meaningfulness and choice) and six outputs; Hausman-based model selection, Tobit, random-effects negative binomial and instrumental-variable Poisson regressions and a sensitivity analysis were used to test the robustness of the results. The efficiency scores of the decision-making units differ significantly according to the risks of blockchain adoption, and all seven inputs have significant effects on efficiency. Choice and competency are the most influential empowerment inputs, whereas mutual trust, information sharing, fraud resistance and transparency are the most influential outputs, so all four hypotheses of the study are supported. The study recommends that Sudanese banks adopt blockchain gradually while strengthening the choice and competency of their employees through training and delegated decision-making. The findings are relevant to bank managers, regulators and policymakers who seek to sustain banking efficiency through digital transformation in economies facing severe macroeconomic volatility.

**Keywords:** Blockchain, Data envelopment analysis, Human capital empowerment, Islamic banking, and Relative efficiency.

## 1 Introduction

Business, economics and the banking sector are undergoing a profound digital and technological transformation at the financial, commercial and economic levels. Blockchain technology adoption has become a tangible challenge in this transformation, particularly for banks, because blockchain aims to achieve transparency, a shared ledger and the sharing of information with employees and with current and potential clients [59]. It is therefore important to study the risks of adopting blockchain technology (BCT), which is one of the tools of digital transformation and an important means of ensuring sustainability [17]. Such adoption may increase the efficiency of banks' institutional performance and contribute to banking sustainability, that is, the integrated results of banks' business arising from their interaction with the internal and external environment and their ability to achieve sustainability goals in the future [24, 28]. The efficiency of human capital empowerment (HCE) and the sustainability of banking institutional performance (BIP) can be measured through BCT by assessing the bank's ability to use, allocate and control the resources available in its internal and external environment, to achieve the highest degree of operational efficiency and to adapt optimally to its environment [37, 38].

In addition, banks need to make the best use of the cognitive and technical skills of human capital, relying on it to apply and adopt blockchain technology (BCT) in order to reach the highest levels of efficiency, effectiveness and sustainability in the banking sector [36, 81]. From this perspective, the study measures the efficiency of human capital in adopting BCT as a technological extension of digital-transformation applications and tools in the banking sector; measures the sustainability

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of banks' relative efficiency (SBRE) achieved through BCT adoption; and measures the impact of this technology on transparency and on the efficiency of human capital and the banking sector [46, 64, 73].

Despite this growing interest, three gaps remain in literature. First, studies of banking efficiency in Sudan have relied almost exclusively on financial-statement inputs and outputs analysed with data envelopment analysis (DEA) or stochastic frontier analysis [3, 4, 56]. These studies report that managerial inefficiency is the main source of overall technical inefficiency [3, 4], yet they do not examine the technological and human-capital factors that managers can act upon. Second, research on blockchain in banking has concentrated on adoption determinants and barriers [60], on financial-reporting outcomes [83] or on conceptual assessments of opportunities and challenges [43]; it has rarely linked the risks of adoption to measured relative efficiency. Third, the empowerment of human capital has seldom been assessed as an efficiency input in Islamic banks operating under macroeconomic instability, although such instability is known to constrain the performance and efficiency of financial institutions [2, 20].

Accordingly, the study pursues four objectives, each corresponding to one research question and one hypothesis (Section 2.3): (1) to determine whether the relative efficiency scores of Faisal Islamic Bank (FIB) differ according to the risks of BCT adoption (RQ1/H1); (2) to examine whether HCE affects BCT adoption (RQ2/H2); (3) to assess whether the risks of BCT adoption affect the achievement of digital-transformation objectives (RQ3/H3); and (4) to identify the BCT and HCE inputs that most strongly affect SBRE (RQ4/H4).

The study makes three contributions. Theoretically, it integrates BCT adoption risks with the four cognitions of psychological empowerment, namely impact, competence, meaningfulness and choice [75], within a single relative-efficiency framework. Methodologically, it applies the slack-based measure (SBM) DEA model [76], framed by the McKinsey 7-S model and supported by Hausman-based model selection and sensitivity analysis, to perception-based inputs and outputs. Practically, it provides evidence-based guidance for Sudanese Islamic banks that seek to adopt blockchain under severe macroeconomic volatility (Section 5.1).

The remainder of the paper is organized as follows. Section 2 reviews the theoretical framework and develops the research questions and hypotheses. Section 3 describes the materials and methods, including the sample, the measures and the analysis strategy. Section 4 presents and discusses the results and compares them with previous studies. Section 5 sets out the theoretical and practical implications, and Section 6 concludes and outlines the limitations of the study and directions for future research.

## 2 Theoretical framework

### *2.1 The risks of blockchain technology (BCT) adoption from a digital transformation perspective (BCT-DT)*

**Digital transformation and e-commerce from a business economics perspective:** It is the process of applying technology in order to make commercial transactions take place automatically and quickly. And from perspective of the Internet: it is the trade that opens the way for buying and selling products, services or information via the Internet. And from the perspective of the world trade organization (WTO): An integrated array of operations employing technology for product manufacturing, distribution, marketing, and selling [18, 80].

Digital transformation and e-commerce are the use of technological tools and networks of transactions and communications for the exchange of goods and services between companies with each other, whether those companies are suppliers of goods or services, or distribute them, as well as between companies and their customers [14, 53, 69].

This includes marketing, advertising, negotiation, giving purchase and sale orders, and after-sales services. It may also include deliveries, payments, and payments electronically, and all these operations can take place at the local or international level, and e-commerce also includes companies' dealings with both the government and banks [30].

**Types of e-commerce:** In order to measure the interactions of the parties involved in the transactions, the e-commerce was divided according to the nature and identity of the main parties involved in the commercial dealings as follows: Business-to-business trade (B2BT): dealing in this type of trade is limited to the company and a number of its suppliers and customers, through a code (called transactions documented e-commerce, and the percentage of this type is about 85% of the total volume of e-commerce). Business trade with consumers: Some call this type of electronic shopping or

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electronic retail trade to distinguish it from e-commerce between business sectors [11, 32, 74]. The percentage of this type is about 15% of the total volume of e-commerce. Business and government trade: in addition, to the previously mentioned types of e-commerce, there is a large sector that did not take its share in a large way, which is e-commerce between governments, businesses and consumers, which can be included as a new type in e-commerce and may need some time to activate it and it can include bids, tenders and supplies the business that is between governments and other commercial entities, and this type of trade did not take its share of development, such as what happened to the trade system between business and business and between business and consumers, but the future of days will witness its development, especially after the entry of all countries into this technology. Government trade with consumers: This sector can develop and take shape in which the interaction between governments and citizens is electronic with regard to goods and services, the payment of taxes, zakat, fines and everything that requires payment, whether it is for the government or the citizen [16, 61]. Governments' trade with governments: These areas of e-commerce fall within the concept of e-government, and this is in areas that require dealings between governments, and this type represents huge and strategic businesses. Business trade, customers, or governments with banks: It can be denoted by the following symbols (B2Bank (B2B), C2Bank (C2B), G2Bank (G2B)) [5, 39, 82]. It includes all banking transactions that take place between banks and their customers, whether companies or individuals, as well as transactions between banks and governments through the Internet. This field is now called e-banking. This includes the possibility for bank customers to know the services provided by their bank, and to exploit those services through the Internet, and examples of these services are (paying and paying bills, financial transfers, checking the various accounts, deposits and current accounts of the customer or the company, and exchanging electronic messages between the bank and his clients [26].

## *2.2 Blockchain technology (BCT) adoption reinforces the efficiency of human capital empowerment (HCE)*

Despite the multiplicity of the concepts of empowerment and the divergence of its indicators, we conclude that the concept of empowerment still accommodates more new intellectual contributions and changes to place this concept within an integrated conceptual framework [9, 31]. Empowerment is considered one of the contemporary entrances in the modern business management environment, as it is considered one of the keys to success and sustainability of the organization in the age of globalization, competition and information technology that requires the full use of the capabilities of individuals to achieve the goals of the organization [29]. Empowerment has become one of the most essential elements related to organizing individuals and motivating them towards excellence, achievement, assuming more responsibilities and controlling their performance at individual and organizational levels. Empowerment is a managerial strategy based on giving employees the power to act, make decisions, and actual participation on the part of employees in managing their organizations, solving their problems, creative thinking, and taking responsibility and controlling [54, 63, 68].

Managers in the environment of contemporary organizations also see that empowerment has become one of the criteria for competitiveness, in addition to the ability of these organizations to obtain various resources, especially human capital, that have high motivation towards work, efficiency and achievement, and enjoy high degrees of empowerment that achieve the organizations' goals [10, 72]. Empowerment is an integrated strategic approach and entrance in which the subordinates are given the powers to participate and make decisions and encourage them to take the initiative in solving their problems in effective and efficient ways [49].

Empowerment is the participation of employees to their superiors in the authority of making and taking decisions within the framework of the existing work in defining responsibility, mutual trust, training and support in order to excel in achieving the goals of the organization and its employees and working to improve them continuously [84].

Where empowerment is a recognized part of the change in today's world through technological progress, it leads to the creation of a second row of leaders who participate in daily tasks efficiently, and empowerment is an important factor and a key to developing the creativity factor within the organization. Self-Confidence and the ability to make their own decisions and take advantage of empowering employees through competencies analysis, distinguishing good work, and the opportunity for teamwork and sharing work with others [67].

Empowerment is an opportunity to develop employees' skills efficiently and make optimal use of resources and optimal distribution of resources in order to achieve effectiveness efficiently to ensure banking sustainability [25].

Additionally, the dimensions of empowerment include four axes as follows: 1-Impact: The individual's realization that he is involved and influential in the decisions that are taken, the goals, plans and policies that the organization sets,

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especially those related to his tasks and work. 2-Competency: It means the individual's experience in accomplishing his tasks based on his abilities, skills and knowledge. 3-Meaningfulness: The worker's realization of the value and importance of his work for him and others. 4- Choice: which means that the individual feels that he has the freedom to make his decisions, initiate his actions and choose the methods of carrying out his work tasks [8, 45, 48, 75].

### *2.3 The sustainability of banks' relative efficiency (SBRE)*

Corporate performance management refers to all the measures designed to support the bank success [19], it requires the existence of planning, directing and continuous evaluation of performance, in order to determine the extent of progress towards achieving the objectives of the institution and its institutional effectiveness, especially sustainability of banks' relative efficiency (SBRE) [23, 78].

Institutional performance depends on five basic elements of institutional performance management including: 1-Achieving goals: is a criterion for the effectiveness of institutional performance. 2-Performance planning: Where management clearly organizes roles, responsibilities and desired performance indicators in order to reach better results. 3-Creating working conditions: the management seeks to provide its physical and human requirements, create organizational and managerial conditions, and provide performance-oriented information and standards to ensure the achievement of the best results. 4-Performance review: This is done through the management's periodic follow-up and review to ensure that objectives are achieved or not, and to make adjustments during the performance process to ensure that objectives are achieved efficiently and effectively. 5-Performance development and continuous improvement: the efficiency of resources and the elements of inputs affecting outputs and the efficiency of institutional performance weakens in the face of successive developments and the development of science, knowledge and technology, which obliges the bank's management to keep abreast of these developments and adapt to them and bring about continuous development in its inputs, operations and outputs in a way that gives the bank a competitive advantage compared to other banks [33, 51, 52].

The corporate performance philosophy is based on: 1-Every employee in the bank has the right to have managerial procedures guarantee fairness, integrity, justice and transparency, which is what characterizes the adoption of the blockchain (BCT) approach. 2- The administration's obligation to provide the reasons for its various decisions towards the employees. 3-Every employee in the bank has the right to obtain compensation for the damages incurred during the period the job. 4-The right of every employee in the bank to view his annual work reports. 5-The right of every employee in the bank to hear his opinion before taking any action that may affect him negatively, which requires further human capital empowerment. 6-Caring about the performance of decision-making units (DMUs) without others within the bank separates the bank from idealism and leads it to disintegration and destruction, and its lack of access to sustainability of banks' relative efficiency (SBRE) [6].

There are some of the elements that form the basis of institutional performance, namely: 1-Strategy and objectives: it is concerned with the parties to which it will be directed. 2-Organizational structure: focuses on the level of efficiency and effectiveness of the structure, and its ability to serve the operations that will provide services. 3-Scale: it is the performance that can be used in a way that serves both the strategy and the objectives. 4- Management: it is the method that will be used to determine paths and directions, and how to carry out the correction process.

The institutional performance appraisal (IPA) process is one of the most important tools for improving performance. Through it, the bank's effectiveness is measured in terms of its performance, problems, and achievements. Thus, this can play a vital role in helping managers improve their operations' efficiency. The performance appraisal process can be a tool for creating support for the bank's programs and activities. Performance measurement is a way to review the bank's financial and non-financial objectives, and therefore the main objective of institutional performance measurement is to measure the outputs of the bank's business and to ensure that the actual results are identical to what is planned to identify whether there are any deviations between the actual and planned results in order to develop solutions to treat and overcome the deviations [57].

Thus, the institutional performance evaluation indicators (IPEI) refer to the measurable value that shows the extent of the bank's effectiveness in achieving its objectives [77]. These indicators can be used at multiple levels to evaluate its success in achieving the objectives. Four basic indicators can be identified for the performance measurement process, which are: 1-Indicators related to the effectiveness of achieving the objectives that institutions operate on developing it. 2-Indicators related to the efficient use of the resources used, which include the ratio of total costs to some specific outputs, and this expresses the cost of services provided. 3- Indicators related to productivity, and this is done through the relative

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relationship between the inputs of those units and their outputs. 4- Indicators related to the level of quality of services provided to clients [27].

**Dimensions of institutional performance:** By reviewing previous studies of institutional performance, we find that most studies differed in dealing with the dimensions of institutional performance, but the study focuses on the following dimensions for measuring institutional performance [66]: 1-Learning and growth [13]: Learning institutions are characterized by cultures that are adaptable to the changing environment, through Introducing new systems that are more flexible in systems, procedures, and individuals, and the dimension of the learning organization includes four dimensions: (a-systematic development of employees and continuous learning through training programs. b-employee participation. c-learning climate. d-rewards for learning.) 2-internal processes 3-Customer (beneficiary) [70, 71]. 4-Social responsibility [1, 42]. Additionally, The McKinsey-(7's) model: (Strategy, System, Structure, Shared Values, Style, Skills and Staff).

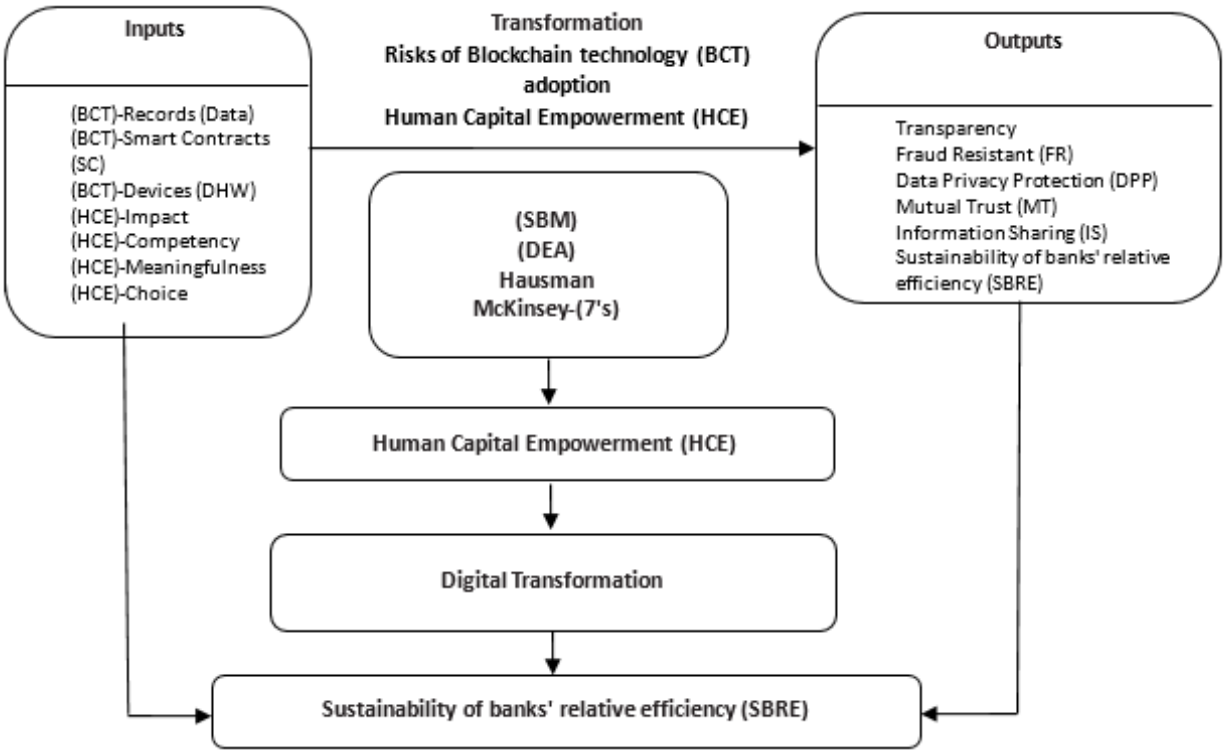



**Fig. 1:** Conceptual framework and study analysis strategy

The review of prior studies (Sections 1–2.3) reveals the gaps summarised in the Introduction. The study therefore addresses the following research questions:

**RQ1.** Do the relative efficiency scores of Faisal Islamic Bank (FIB) in Sudan differ according to the risks of blockchain technology (BCT) adoption?

**RQ2.** Does human capital empowerment (HCE) affect BCT adoption in FIB?

**RQ3.** Do the risks of BCT adoption affect the achievement of digital-transformation and e-commerce objectives (transparency, fraud resistance, data privacy protection, information sharing and mutual trust)?

**RQ4.** Which BCT and HCE input elements most strongly affect the sustainability of banks' relative efficiency (SBRE)?

To answer these questions, the following hypotheses are formulated:

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**H1.** The relative efficiency scores of FIB differ significantly according to the risks of BCT adoption.

**H2.** HCE has a significant effect on BCT adoption in FIB.

**H3.** The risks of BCT adoption significantly affect the achievement of digital-transformation objectives in FIB.

**H4.** All BCT and HCE input elements have significant effects on SBRE.

All research questions and hypotheses are examined with the SBM-DEA model framed by the McKinsey 7-S model, with model specification supported by the Hausman test (Section 3.2).

## 3 Materials and Methods

### *3.1 Sample*

An a priori power analysis was conducted in G*Power 3.1.9.2 following Lakens et al. [35], using a one-tailed test, an expected effect size of 0.10, a significance level of 0.05 and a statistical power of 0.95; the minimum required sample was 125 respondents. The target population comprised the employees of Faisal Islamic Bank (FIB) in Sudan; because no complete sampling frame of the bank's staff was accessible to external researchers, a non-probability convenience sample was used. Data were collected between 10 October and 25 December 2022 through an online questionnaire distributed via LinkedIn, and 352 valid responses were obtained, approximately 2.8 times the required minimum, which increases statistical power and the stability of the efficiency estimates. LinkedIn was chosen because it is a professional network on which bank staff can be identified by employer and position, and because an online survey allowed employees working in different locations to respond during the collection period. All 352 respondents were FIB employees, and all of their responses were used in the analysis.

Because the sample is a non-probability convenience sample, the findings are not intended to be generalised statistically to all Sudanese banks or to all FIB staff. Rather, the study seeks analytical generalisation. The DEA inputs (BCT and HCE dimensions) and outputs (transparency, fraud resistance, data privacy protection, information sharing, mutual trust and SBRE) are employees' perceptions measured through the online questionnaire, and each respondent's assessment of the bank's inputs and outputs is treated as a decision-making unit (DMU), so that the 352 respondents constitute the evaluated DMUs. Efficiency is therefore relative within FIB and reflects perceived operational efficiency rather than efficiency derived from financial statements. This limitation is acknowledged in Section 6.1.

### *3.2 Measures and Analysis strategy*

Relative efficiency was measured with data envelopment analysis (DEA), and the Hausman test was used to choose between fixed-effects (FE) and random-effects (RE) specifications. One-way analysis of variance (ANOVA) F-tests were used to compare respondent groups. Normality was tested with the Jarque–Bera test, heteroscedasticity with the Wald test, and cross-sectional dependence with the Pesaran CD test, all in EViews 9.5 [7, 34]; these diagnostic tests were applied to the selected model before the final estimates were interpreted. The McKinsey 7-S model was used as the organising framework for selecting the inputs and outputs used to evaluate SBRE (Fig. 1).

The SBM-DEA model uses seven inputs, namely three BCT inputs (records/data, smart contracts and devices/hardware, DHW) and four HCE inputs (impact, competency, meaningfulness and choice), and six outputs: transparency, fraud resistance (FR), data privacy protection (DPP), information sharing (IS), mutual trust (MT) and the composite SBRE indicator. The slack-based measure (SBM) of Tone [76] was preferred to the radial CCR [15] and BCC [12] models because it is non-radial and accounts directly for input excesses and output shortfalls (slacks), producing a single efficiency score between 0 and 1. The model is non-oriented, accounting for input excesses and output shortfalls simultaneously [76], and is estimated under constant returns to scale, consistent with the CRS specification used in the sensitivity analysis (Table 8).

The analysis proceeded in five steps: (1) one-way ANOVA tests of differences in the perceived contribution of HCE across age and experience groups (Tables 1–2); (2) model-specification tests, namely the Hausman test of fixed- versus random-effects negative binomial models, likelihood-ratio tests of the panel random-effects specification, and Hausman

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tests of IV-Poisson-GMM versus Poisson (Tables 3–5); (3) Tobit regression of the efficiency scores, which are censored between 0 and 1, which provides the estimation framework for the Hausman tests in Table 3; (4) covariate balance tests before and after matching (Table 6); and (5) SBM-DEA estimation with the input–output correlation matrix (Table 7) and a sensitivity analysis in which each input is removed in turn and the resulting efficiency distributions are compared using Mann–Whitney U, Kruskal–Wallis and Spearman rank-correlation tests (Table 8). Throughout, ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively. The count-data models (RENB, Poisson and IV-Poisson-GMM) were estimated with panel-data routines, and the Hausman and diagnostic tests were performed in EViews 9.5.

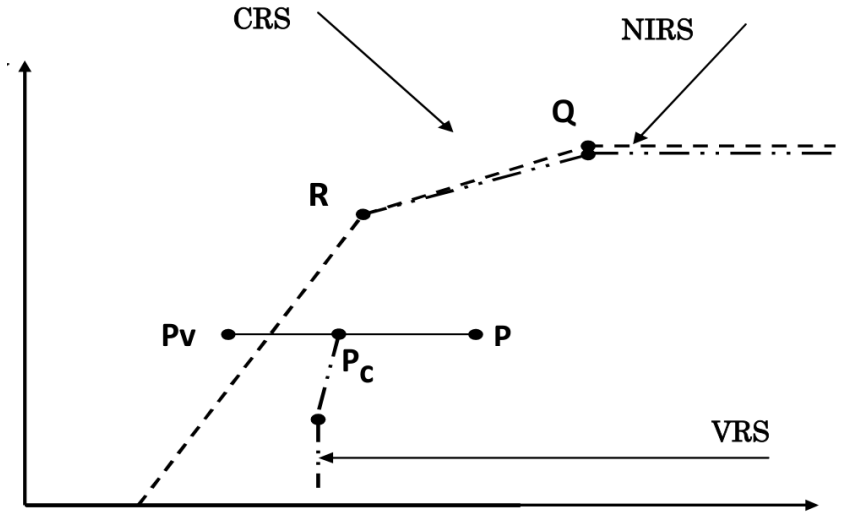



**Fig. 2:** Technical and scale inefficiency under constant (CRS), variable (VRS) and non-increasing (NIRS) returns to scale

Fig. 2 shows that, for decision-making unit P, the distance PPc represents its technical inefficiency under constant returns to scale (CRS), whereas under variable returns to scale (VRS) its pure technical inefficiency is represented by the distance PPv; the difference between the two distances (PvPc) represents scale inefficiency.

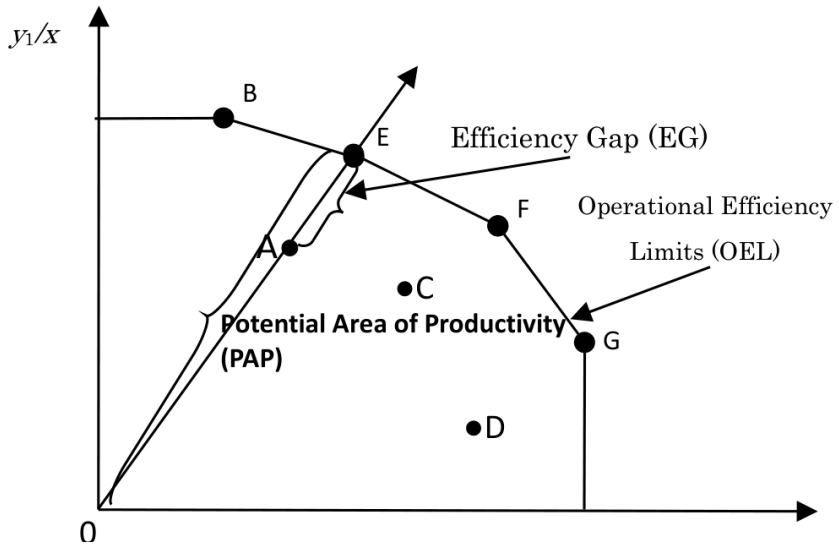



**Fig. 3:** Efficient frontier, efficiency gap and potential area of productivity for DMUs producing two outputs $(y_1, y_2)$ from one input $(x)$

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Fig. 3 shows a group of decision-making units that produce two outputs (y1 and y2) from one input (x). The possible production range lies between the axes y2/x and y1/x, and the efficient frontier consists of units G, F, E and B, which are fully efficient, whereas units D, C and A do not make good use of their inputs; their efficiency is calculated relative to the efficient frontier. Random effects estimator [47]: The factor has a wide range of potential levels; nevertheless, only a random sample of levels is included in the data, despite interest in all possible levels.

$$y_{it} = \beta_1 x_{it} + a_i + u_{it} \tag{1}$$

to eliminate $a_i$, considering it may be related with $x_{it}$, i.e., $\text{cov}(a_i, x_{it}) \neq 0$) endogeneity problem. Explanatory variables must change over time whenever $a_i$, and constant explanatory variables are removed.

**Dummy variable regression:** if it is possible to calculate the unobserved effect $a_i$ for each $i$ (that is, $a_i$ is a single intercept)

$$y_{it} = \beta_1 x_{it} + a_i + u_{it} \tag{2}$$

Random effects: The ability to keep explanatory variables consistent across time is an advantage.

$$y_{it} = \beta_0 + \beta_1 x_{it1} + \cdots + \beta_k x_{itk} + a_i + u_{it} \tag{3}$$

$$\text{cov}(x_{itj}, a_i) = 0$$

**Hausman Test in EViews**
View → Fixed\Random Effect Testing → Hausman Test: Ho: Random eff. is appropriate; Ha: Fixed eff. Is appropriate. If Prob. < (Chi)$^2$. Statistic, then Ha: Fixed eff. is acceptable

## 4 Results and Discussion

### *4.1 Correlation and descriptive information*

This section presents the correlation and descriptive results and the Hausman, McKinsey 7-S and SBM-DEA analyses, as follows:

**Table 1:** One-way ANOVA of differences in the perceived contribution of HCE to SBRE across age groups

| D. Variables (HCE) | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups (BG) | 52.365 | 3 | 29.218 | 1.348 | 0.349 |
| Within Groups (WG) | 1026.248 | 56 | 18.421 | | |
| Total | 1078.613 | 59 | | | |

*Note:* BG = between groups; WG = within groups.

Table 1 shows that the significance level (p = 0.349) is greater than 0.05; therefore, there are no statistically significant differences between age groups in their perceptions of the contribution of HCE to the performance of FIB. This homogeneity indicates that the subsequent efficiency results are not driven by the age composition of the sample.

Table 2 reports the one-way ANOVA results for differences between experience groups in the perceived role of HCE in improving the institutional performance of FIB.

**Table 2:** One-way ANOVA of differences in the perceived contribution of HCE to SBRE across experience groups

| D. Variables (HCE) | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| BG | 57.107 | 4 | 36.619 | 1.518 | 0.417 |
| WG | 1012.302 | 49 | 21.209 | | |
| Total | 1069.409 | 53 | | | |

*Note:* BG = between groups; WG = within groups.

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Table 2 shows that the significance level (p = 0.417) is greater than 0.05; therefore, there are no statistically significant differences between experience groups in their perceptions of the contribution of HCE to the financial and institutional performance of FIB.

## *4.2 Measurement model assessment*

This section presents the results of the measurement-model assessment, as follows:

**Table 3:** Hausman test: fixed-effects versus random-effects negative binomial (FENB vs. RENB) models

| Tests/Mod. | Model-(1) | Model-(2) | Model-(3) | Model-(4) | Model-(5) |
|---|---|---|---|---|---|
| $(\chi^2)$ | 58.62*** | 69.36*** | 112.08*** | 71.75*** | 48.73*** |
| Prob > $(\chi)^2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Regression Model | TOBIT | TOBIT | TOBIT | TOBIT | TOBIT |

*Note:* *** $p < 0.01$.

Table 3 shows that the Hausman $\chi^2$ statistics (48.73–112.08) are significant at the 1% level (p < 0.001) in all five models; the null hypothesis that the random-effects estimator is consistent is therefore rejected. For this reason, the random-effects negative binomial (RENB) estimates in Table 4 are reported only as a benchmark, and final inference relies on the comparison of the Poisson and IV-Poisson-GMM estimators in Table 5. The row 'Regression Model: TOBIT' identifies the Tobit regression of the efficiency scores, which are censored between 0 and 1, as the estimation framework from which the test statistics were obtained.

**Table 4:** Random-effects negative binomial (RENB) estimates and likelihood-ratio tests of the panel random-effects specification

| Variable/Models | Model-(1) | Model-(2) | Model-(3) | Model-(4) | Model-(5) |
|---|---|---|---|---|---|
| Constant value | 219.3209*** | 325.1722*** | 291.5601*** | 261.7226*** | 246.7654*** |
| | (17.8219) | (17.6549) | (17.6539) | (17.8731) | (17.7647) |
| Log Likelihood | 3879.713 | 3873.791 | 3827.631 | 3428.517 | 3817.113 |
| Ln(r) | 0.3201 | 0.3208 | 0.3016 | 0.3601 | 0.2635 |
| | (0.1262) | (0.0892) | (0.0858) | (0.0947) | (0.0918) |
| Ln(s) | 0.7448 | 0.8865 | 0.4727 | 0.8872 | 0.8366 |
| | (0.1237) | (0.1118) | (0.1337) | (0.1109) | (0.1203) |
| LR (Chi-bar)$^2$ | 1621.14*** | 1486.24*** | 1562.18*** | 1483.16*** | 1438.06*** |
| Prob > (Chi-bar)$^2$ | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

*Note:* Standard errors in parentheses. *** $p < 0.01$; ** $p < 0.05$.

In Table 4, ln(r) and ln(s) are the natural logarithms of the two parameters (r and s) of the beta distribution that governs the random effects in the RENB model. Both parameters are positive and significant in all five models (0.2635–0.3601 and 0.4727–0.8872, respectively), and the likelihood-ratio $\chi^{-2}$ statistics (1438.06–1621.14, p < 0.001) reject the pooled negative binomial specification in favour of the panel random-effects specification. Accordingly, ln(r) and ln(s) are retained in Model 5, which is then compared with the IV-Poisson-GMM model in the Hausman test reported in Table 5.

**Table 5:** Hausman test: IV-Poisson-GMM versus Poisson

| Tests/M. | Model-1 | Model-2 | Model-3 | Model-4 | Model-5 |
|---|---|---|---|---|---|
| $(\chi)^2$ | 0.68 | 2.44 | 0.72 | 1.64 | 23.46*** |
| Prob > $(\chi)^2$ | 0.9658 | 0.9761 | 0.9983 | 0.9809 | 0.0062 |
| Regression Model | Poisson | Poisson | Poisson | Poisson | IV-Poisson-GMM |

*Note:* *** $p < 0.01$.

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For Models 1–4, the Hausman $\chi^2$ statistics (0.68–2.44; $p \geq 0.9658$) are not significant, so the null hypothesis of no systematic difference is not rejected and the standard Poisson estimator is retained. For Model 5, $\chi^2 = 23.46$ ($p = 0.0062$) is significant at the 1% level, indicating endogeneity; the IV-Poisson-GMM estimator is therefore preferred for Model 5.

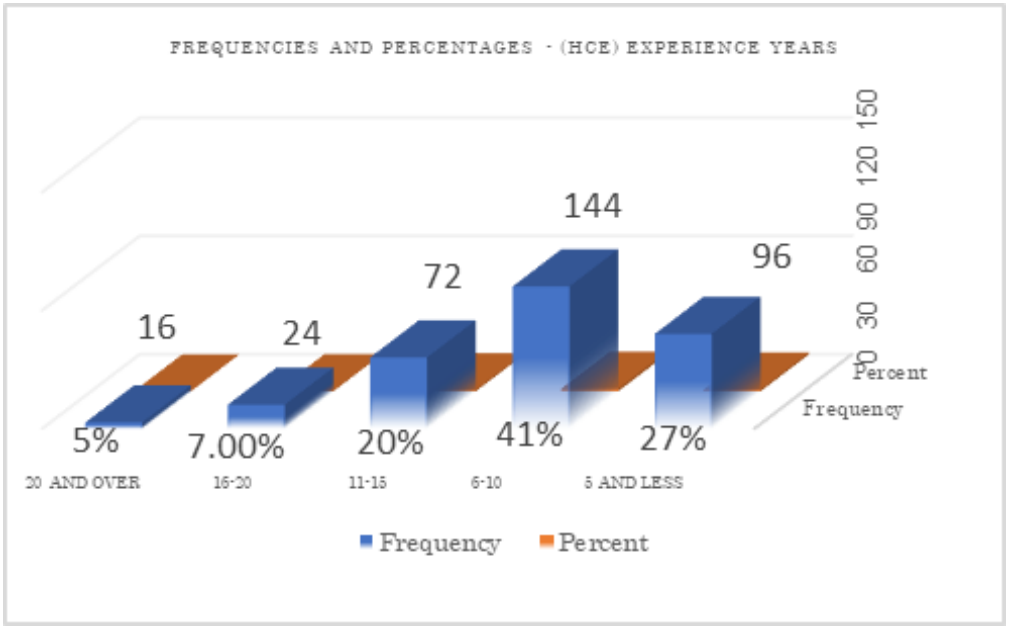



**Fig. 4:** Distribution of respondents by years of banking experience ($n = 352$). Source: Author's survey data (2022).

Fig. 4 shows that respondents with 6–10 years of banking experience form the largest group (41%), followed by those with less than 5 years (27%), 11–15 years (20%), 16–20 years (7%) and more than 20 years (5%). Thus, 73% of respondents have at least six years of experience, which supports the reliability of their assessments of banking operations.

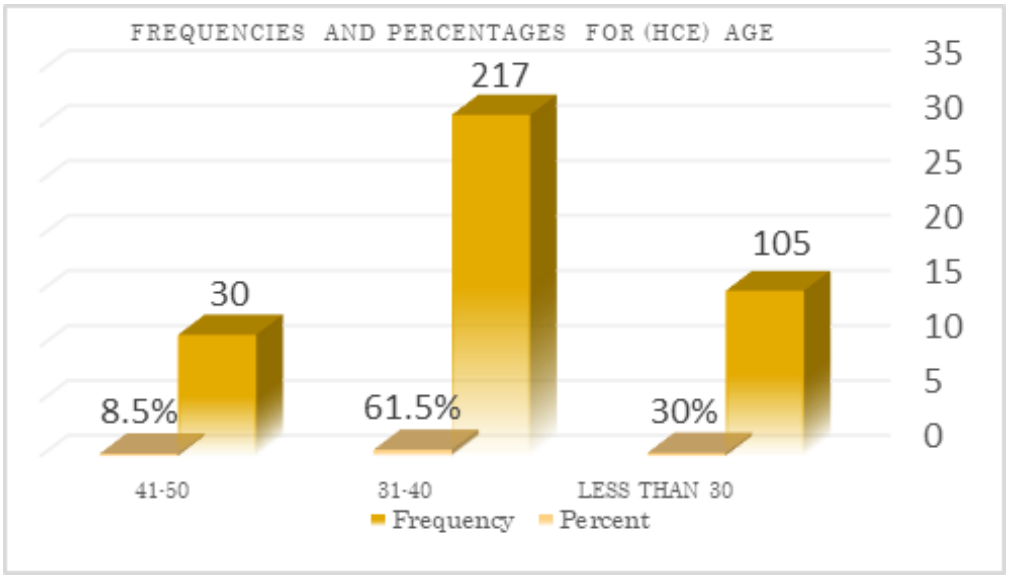



**Fig. 5:** Distribution of respondents by age group ($n = 352$). Source: Author's survey data (2022).

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**Table 7:** Correlation matrix of DEA inputs and outputs (BCT, HCE and SBRE)

| Input / output | (BCT)-R | (BCT)-SC | (BCT)-(DHW) | (HCE)-Impact | (HCE)-Co | (HCE)-M | (HCE)-Ch | (BCT)-T | (BCT)-FR | (BCT)-DPP | (BCT)-IS | (BCT)-MT | (BCT)-(HCE)-(SBRE) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (BCT)-Records (Data) | 1 | | | | | | | | | | | | |
| (BCT)-Smart Contracts (SC) | 0.7501 | 1 | | | | | | | | | | | |
| (BCT)-Devices (DHW) | 0.6974 | 0.7248 | 1 | | | | | | | | | | |
| (HCE)-Impact | 0.7508 | 0.6106 | 0.6609 | 1 | | | | | | | | | |
| (HCE)-Competency | 0.7927 | 0.7015 | 0.7415 | 0.7214 | 1 | | | | | | | | |
| (HCE)-Meaningfulness | 0.6809 | 0.7336 | 0.7279 | 0.7207 | 0.6886 | 1 | | | | | | | |
| (HCE)-Choice | 0.8195 | 0.6697 | 0.6095 | 0.6117 | 0.7314 | 0.6845 | 1 | | | | | | |
| (BCT)-Transparency | 0.7656 | 0.6548 | 0.7066 | 0.6604 | 0.6922 | 0.7008 | 0.6821 | 1 | | | | | |
| (BCT)-Fraud Resistant (FR) | 0.7216 | 0.7404 | 0.6407 | 0.6336 | 0.6524 | 0.6162 | 0.6507 | 0.7011 | 1 | | | | |
| (BCT)-Data Privacy Protection (DPP) | 0.8217 | 0.6983 | 0.7028 | 0.7123 | 0.6771 | 0.6508 | 0.5918 | 0.6825 | 0.6199 | 1 | | | |
| (BCT)-Information Sharing (IS) | 0.7792 | 0.8062 | 0.7363 | 0.6829 | 0.7002 | 0.6751 | 0.6439 | 0.5998 | 0.6701 | 0.6203 | 1 | | |
| (BCT)-Mutual Trust (MT) | 0.8006 | 0.8028 | 0.7101 | 0.6342 | 0.6873 | 0.6011 | 0.6606 | 0.6061 | 0.6294 | 0.5978 | 0.7003 | 1 | |
| (BCT)-(HCE)-(SBRE) | 0.6987 | 0.7701 | 0.6965 | 0.7001 | 0.6908 | 0.6837 | 0.6226 | 0.6773 | 0.6119 | 0.6206 | 0.6818 | 0.6852 | 1 |

*Note:* R = records (data); SC = smart contracts; DHW = devices (hardware); Co = competency; M = meaningfulness; Ch = choice; T = transparency; FR = fraud resistance; DPP = data privacy protection; IS = information sharing; MT = mutual trust. Coefficients are correlation coefficients between the DEA inputs and outputs. Source: Author's calculations based on the SBM-DEA inputs and outputs.

Fig. 5 shows that most respondents are aged 31–40 years (61.5%), followed by those aged 30 years or younger (30%) and those aged 41–50 years (8.5%). Approximately 70% of respondents (247 of 352) are over 30 years old, indicating substantial practical experience in banking, which supports the reliability of their responses.

**Table 6:** Covariate balance before and after matching (age and experience)

| Variables (UM) | Un-Paired | | | Paired | | |
|---|---|---|---|---|---|---|
| | Processed | Control | *p*-value | Processed | Control | *p*-value |
| The Age | 12.1826 | 9.8745 | 0.7009 | 10.1187 | 11.203 | 0.698 |
| Experience | 0.27455 | 0.1801 | 0.0000*** | 0.1542 | 0.3076 | 0.897 |
| Balancing test | Ps $R^2$ | LR $\chi^2$ | $p > \chi^2$ | Common | On support | Off support |
| Unmatched | 0.059 | 235.27 | 0.000*** | support | 589 | 0 |
| Matched | 0.001 | 2.23 | 0.988 | hypothesis | 514 | 2 |

*Note:* Processed = treated group; Ps $R^2$ = pseudo-$R^2$; *** $p < 0.01$.

Before matching, the two groups differ significantly in experience ($p < 0.001$) but not in age ($p = 0.7009$), and the joint balancing test is significant (pseudo-$R^2 = 0.059$; LR $\chi^2 = 235.27$, $p < 0.001$). After matching, neither covariate differs significantly ($p = 0.698$ and 0.897), the pseudo-$R^2$ falls to 0.001 and the LR $\chi^2$ test is not significant (2.23, $p = 0.988$), indicating that matching achieved covariate balance. Experience was thus the only covariate that was unbalanced before matching, and this imbalance was removed by matching. The processed (treated) and control groups were compared on age and experience using propensity-score matching, with balance assessed by the standardised mean comparisons, the pseudo-$R^2$ and the LR $\chi^2$ statistics; the numbers of observations on and off common support reported in Table 6 refer to the observations in the common-support region of the matching procedure, not to the number of respondents.

Table 7 reports the pairwise correlations between the seven inputs and six outputs, which range from 0.5918 to 0.8217. All correlations are positive, which satisfies the isotonicity requirement of DEA (outputs do not decrease as inputs increase). Among the HCE inputs, choice (0.8195) and competency (0.7927) show the strongest correlations with BCT records. Among the outputs, data privacy protection (0.8217 with records), information sharing (0.8062 with smart contracts), mutual trust (0.8028 with smart contracts and 0.8006 with records), transparency (0.7656 with records) and fraud resistance (0.7404 with smart contracts) are most strongly associated with the BCT inputs, and SBRE correlates most strongly with smart contracts (0.7701). Because these are correlation coefficients, they indicate association rather than statistical significance or causal effect; the relative importance of each input is assessed through the sensitivity analysis in Table 8.

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**Table 8:** Sensitivity analysis of the SBM-DEA model: removing one input at a time

| Variable removed | Efficient V. | Std. Error | SD | Mann W. U Sig. | K. W. Sig. | Efficient (%) | Spear. sig |
|---|---|---|---|---|---|---|---|
| None | 0.6843 | 0.0045 | 15 | 1.3039 | 2.849 | 12.09 | 0.007364*** |
| (BCT)-Records (Data) | 0.7024 | 0.0008 | 14 | 0.9966 | 2.849 | 13.12 | 0.006802*** |
| (BCT)-Smart Contracts (SC) | 0.6611 | 0.0032 | 14 | 1.5183 | 2.849 | 14.76 | 0.007509*** |
| (BCT)-Devices (DHW) | 0.7205 | 0.0004 | 15 | 1.4098 | 2.849 | 12.55 | 0.006627*** |
| (HCE)-Impact | 0.6328 | 0.0073 | 16 | 0.9746 | 2.849 | 16.73 | 0.008419*** |
| (HCE)-Competency | 0.7561 | 0.0089 | 16 | 0.8329 | 2.849 | 11.32 | 0.007482*** |
| (HCE)-Meaningfulness | 0.6905 | 0.0231 | 13 | 1.1018 | 2.849 | 15.64 | 0.006996*** |
| (HCE)-Choice | 0.7882 | 0.0001 | 16 | 0.8604 | 2.849 | 12.48 | 0.006775*** |

*Note:* Efficient V. = mean efficiency score; Efficient (%) = share of DMUs with an efficiency score of 1; K.-W. = Kruskal–Wallis; Spear. = Spearman. *** $p < 0.01$. Source: Author's SBM-DEA estimations.

Table 8 compares the baseline model (mean efficiency = 0.6843; 12.09% of DMUs efficient) with seven models from which one input is removed at a time. Mean efficiency changes from 0.6843 to between 0.6328 and 0.7882 when individual inputs are removed; removing impact (0.6328) or smart contracts (0.6611) produces the largest decreases, while the share of efficient DMUs ranges from 11.32% to 16.73%. The Spearman tests are significant at the 1% level in all cases (0.0066–0.0084), indicating that the removal of each of the three BCT inputs and the four HCE inputs changes the ranking of the DMUs; each input therefore contributes to the efficiency scores, which supports H4. The Mann–Whitney U (0.83–1.52) and Kruskal–Wallis (2.849) values are reported as test statistics for the differences between the efficiency distributions of the baseline and reduced models.

## *4.3 Structural model assessment*

This section assesses the robustness of the efficiency results. Following Parkin and Hollingsworth [62] and Olohunlana et al. [55], the SBM-DEA model was re-estimated with alternative input sets, and the efficiency scores of each modified model were compared with those of the baseline model using Mann–Whitney U, Kruskal–Wallis and Spearman tests (Table 8).

Taken together, the results support the four hypotheses. H1: the relative efficiency scores of FIB differ according to the risks of BCT adoption (Tables 3–5 and 8). H2: the HCE inputs are positively associated with the BCT inputs (r = 0.6095–0.8195, Table 7), and removing any of them changes the efficiency scores (Table 8), indicating that HCE affects BCT adoption. H3: the BCT inputs are positively associated with the digital-transformation outputs, namely transparency, fraud resistance, data privacy protection, information sharing, mutual trust and SBRE (r = 0.6407–0.8217, Table 7). H4: removing any of the three BCT inputs (records, smart contracts and devices) or the four HCE inputs (impact, competency, meaningfulness and choice) alters the efficiency distribution (Table 8); choice and competency are the most influential HCE inputs, and mutual trust, information sharing, fraud resistance and transparency are the most influential outputs.

## *4.4 Discussion: comparison with previous studies*

The finding that relative efficiency differs across DMUs (H1), with a mean SBM efficiency of 0.6843 and only 12.09% of units on the frontier (Table 8), is consistent with DEA studies of Sudanese banks. Onour and Abdalla [56] found that only two of twelve Islamic banks in Sudan were technically efficient, and Abdalla and Tahir [3] reported technical efficiency scores ranging from 0.533 to 1 (mean 0.84) for 29 banks, identifying managerial inefficiency as the main source of overall technical inefficiency. Abdo [4], reviewing DEA and stochastic frontier studies, likewise concluded that the Sudanese banking sector remains inefficient, mainly because of managerial inefficiency. Internationally, Mostafa [50] found that the performance of several of the top 100 Islamic banks is sub-optimal, whereas Mai et al. [40], studying 79 Islamic banks in 16 countries over 2005–2020, observed an increasing trend in efficiency that varied across banks and countries. The present study extends this evidence by showing that, within a single Islamic bank, two managerially controllable factors, technology adoption and staff empowerment, are associated with differences in efficiency. Because the earlier studies used financial-statement inputs and outputs whereas this study uses perception-based measures, the comparison concerns the direction and pattern of the findings rather than the magnitude of the scores.

The positive associations between the BCT inputs and transparency, information sharing, mutual trust and fraud resistance (H3) are in line with the opportunities and challenges of blockchain for banks discussed by Martino [43] and with

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Zaqeeba et al. [83], who found for eleven Jordanian commercial banks (2009–2019) that blockchain is a 'double-edged sword': it raises expenses when it is not used as required but reduces costs when it is exploited effectively. Papagiannis et al. [60] showed that technology cost exerts the strongest causal influence on blockchain adoption in retail banking, with regulatory requirements, customer acceptance and industry collaboration mediating its effect. In the present study, smart contracts and records are among the inputs whose removal changes efficiency the most, suggesting that the benefits of blockchain depend on the components most directly linked to transaction processing. Cost is a particularly binding constraint in Sudan, where the continuous deterioration of the Sudanese pound, limited foreign investment flows and the legacy of the economic embargo have left the banking system almost entirely domestic [22].

The finding that choice and competency are the most influential HCE inputs (H2 and H4) is consistent with Thomas and Velthouse [75], who conceptualise empowerment as four cognitions (meaningfulness, competence, choice and impact) that drive intrinsic task motivation, and with Grošelj et al. [25], who showed that psychological empowerment moderates the effect of authentic and transformational leadership on innovative work behaviour. Employees who feel competent and autonomous are more likely to adopt and use new technologies such as blockchain, which explains the close associations between the HCE and BCT inputs in Table 7.

Finally, the results should be interpreted in the light of Sudan's macroeconomic context. Elhussein and Eldawaha [21] found, in three of four models, that banks operating in Sudan were financially unsound and distressed during 2013–2020, and Abaidoo and Agyapong [2] showed that inflation uncertainty and macroeconomic instability constrain the efficiency of financial institutions. Mennawi and Ahmed [44] found that inflation and operational cost efficiency significantly affect the profitability of ten Islamic banks in Sudan. In such an environment, efficiency gains from technology and empowerment, which are under managerial control, are especially valuable; this underlines the practical relevance of the present findings, which are developed in Section 5.1.

## 5 Theoretical and Practical Implications

The digital age is characterised by an urgent need for digital transformation and e-commerce and by a focus on information and technology; information has become highly valuable as the backbone of organisations, especially banks. The importance of study stems from significance of blockchain technology (BCT) [59, 81] as one of the tools of digital transformation and e-commerce [8, 18, 45, 53, 61, 64, 80] and as an essential tool to achieving sustainability in performance, especially in the efficiency of banking performance. And the adoption of strategies to human capital empowerment (HCE) [31, 54, 75] through the blockchain (BCT), which is one of the modern concepts in management, which achieves a competitive advantage for banks that seek success and continue to provide distinguished banking services that meet the requirements of sustainability of banks' relative efficiency (SBRE) [2, 51, 57]. Thus, the study contributes to enriching the theoretical and cognitive side, which may contribute to bridging the research gap interrelated by the study's four axes (blockchain, e-commerce, efficiency of human capital empowerment (EHCE), and the efficiency and sustainability of banking performance) [77].

Previous studies related to blockchain technology adoption (BCT) as one of the tools of digital transformation and as an aspect of e-commerce [45, 53, 80], Human capital empowerment and the efficiency of institutional performance [19, 54], especially in the efficiency of institutional performance of the banking sector [6, 51, 84], that there is a clear deficiency in the application of the blockchain approach in the sector. There is also a deficiency in the degree of transparency, customer complaints of lack of transparency, weak mutual trust between customers and banks, lack of data protection, complexity of procedures, lack of smart contracts, and an increase in the degree of fraud in banks, which weakens the sustainability of banking performance, as shown by the study related to measuring efficiency by adopting ((Hausman) McKinsey-(7's) (SBM) (DEA)) models [7, 34, 47, 62]. There is a shortage in the use and application of technological tools such as the blockchain as one of the tools of e-commerce and digital transformation in banks, and there is a shortage in benefiting from modern technological approaches in the sustainability of banks' relative efficiency (SBRE) [2, 19, 84].

Based on this, the role and value of this study is clear in providing a conceptual and practical framework for adopting blockchain technology (BCT) from the perspective of e-commerce and digital transformation as a methodological tool in Faisal Islamic Bank in Sudan, and measuring the impact of human capital empowerment on the efficiency of Faisal Islamic Bank (FIB) in Sudan and its role in enhancing the value and importance of adopting blockchain technology (BCT) in sustainability of the institutional performance of the Sudanese banking sector [65, 79]. Especially, the Sudanese economy is going through critical financial and economic crises, there is an urgent need to enhance financial and banking sustainability in Sudanese banks.

### *5.1 Practical implications for Sudanese banks under macroeconomic volatility*

The findings have five practical implications for Sudanese banks operating under macroeconomic volatility.

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**First,** blockchain should be adopted in phases. Because technology cost is the main barrier to adoption [60] and imported technology is costly when the national currency is depreciating [22], banks can begin with permissioned ledgers for record-keeping and with smart contracts for standardised Islamic finance contracts such as murabaha and musharaka, which are the inputs most closely linked to efficiency in this study, before extending blockchain to other operations. Sharing infrastructure through bank consortia can reduce the cost burden on each bank.

**Second,** empowerment should accompany technology investment. Since choice and competency are the most influential HCE inputs, banks should combine blockchain projects with targeted training, delegated decision-making authority and retention incentives for skilled staff, whose departure is a serious risk in an unstable economy.

**Third,** transparency and trust should be managed as strategic outputs. Mutual trust, information sharing, fraud resistance and transparency are the most influential outputs; banks can use shared ledgers to provide customers with verifiable transaction records, which may help to restore the depositor confidence that has been weakened by financial distress [21].

**Fourth,** distributed ledgers can strengthen operational resilience. Replicating records across nodes reduces the dependence of operations on a single site or data centre, which is valuable when infrastructure is exposed to economic and political shocks.

**Fifth,** banks should engage early with the Central Bank of Sudan and with their Shariah supervisory boards so that blockchain applications, particularly smart contracts, comply with prudential regulation and Shariah governance requirements [6].

## 6 Conclusions

The methodology of the study was based on measuring the effect of human capital empowerment on the efficiency of Faisal Islamic Bank based on the adoption of blockchain technology (BCT) [59, 81] as a digital approach and as an axis of the digital transformation using the ((Hausman) (SBM) McKinsey-(7's) (DEA)) model in measuring the efficiency of Faisal Islamic Bank, and measuring the input elements that have the greatest impact on the operational efficiency of the bank through the processes of human capital empowerment (HCE) [31, 54, 75], and adopting blockchain technology (BCT), and the results confirmed that there are statistically significant differences between the effect of HCE and the enhancement of the bank's financial performance on Faisal Islamic Bank (FIB) of Sudan [58, 65], and the bank's employees have distinguished academic education, which improves the financial performance of the bank. In addition, the bank's employees' experience as a result of practical practices and the accumulation of knowledge enhances the bank's financial performance. The bank's employees also have multiple and diverse managerial skills, which raises the level of the bank's financial performance. In addition, the timely completion of the bank's employees' tasks entrusted to them improves the bank's financial performance. The bank's attraction of qualified employees and maintaining them contributes to achieving the bank's goals and improves its financial performance [41, 79]. In addition, the bank's employees have a high ability to win customer loyalty and pay attention to their comments, which is reflected in the bank's financial performance. Additionally, the input elements related to the blockchain: (records, smart contracts and devices (DHW)) and that the input elements related to human capital empowerment (competency, choice, then impact and meaningfulness) are the most influential in efficiency and outputs. The results also showed that the output elements (mutual trust, transparency and information sharing) are the most influential output elements in the sustainability of the banking performance of Faisal Islamic Bank (FIB) in Sudan, which enhances the efficiency of the financial, accounting and economic performance of the Sudanese banking sector.

### *6.1 Limitations and future research*

This study has several limitations. First, it examines a single bank and relies on a non-probability convenience sample recruited through LinkedIn, so its findings cannot be generalised statistically to the Sudanese banking sector. Second, the DEA inputs and outputs are based on employees' perceptions rather than on financial-statement data, so the efficiency scores represent perceived relative efficiency. Third, the data were collected between October and December 2022, before the armed conflict that began in Sudan in April 2023, which has since severely disrupted the banking system.

Future research could (i) use probability sampling across several Sudanese banks; (ii) apply a two-stage DEA design that combines perception-based measures with financial-statement inputs and outputs; and (iii) compare efficiency before and after the 2023 conflict to assess how blockchain and empowerment contribute to banks' resilience.

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