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The impact of anti-money laundering measures on remittance costs: moderating role of frontier technology

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Central banks are increasingly experimenting with frontier technologies, such as Central Bank Digital Currencies (CBDC) and Distributed Ledger Technology (DLT) platforms, alongside advancements in traditional systems like the SWIFT network. While prior research has largely examined technology readiness and regulatory frameworks in isolation, their interactive effects on remittance costs remain underexplored. This study investigates how the Frontier Technology Readiness Index (FTRI) moderates the relationship between remittance costs and the Anti-Money Laundering (AML) Index. The lack of integration of these dimensions is a critical research gap that is addressed to help achieve Sustainable Development Goal 10c (SDG-10c) and G20 targets. Panel data regression, followed by fixed and random effects to test robustness, was employed using datasets for remittance-sending and remittance-receiving countries derived from Worldwide Remittance Price data. In remittance-sending countries, enhanced technological readiness combined with a less stringent AML framework is associated with lower remittance costs. On the contrary, despite high technological readiness, in remittance-receiving countries, higher AML stringency tends to increase costs. Technology and AML measures in receiving countries and the amount of remittance paid in sending countries, in isolation, don't have a significant influence on the cost of remittances. The analysis focuses solely on remittance cost efficiency and proposes incorporating transfer speed and transparency in future studies. Findings imply that the prevalence of informal channels like hawala and current pricing models does not encourage and reward higher remittance volume. Remittance cost reduction policies should focus on anti-money laundering measures and technology readiness in conjunction rather than in isolation. Incorporating national indexes provides a clear direction for improving the defined set of variables that are measurable and thus actionable to policymakers.

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Introduction

Remittances are the funds migrant workers send to their families in their home country. Remittances contribute to poverty alleviation and boost economic development in low and middle-income countries (Seng, 2021; Ahmed et al., 2023; Barkat et al., 2023). Despite holding high importance, the transaction costs incurred by remitters and beneficiaries deprive them of the full value. It undermines the measures towards financial inclusion. The issue is aggravated by regulatory frameworks designed to prevent anti-money laundering and terrorist financing. To bypass the formal systems, remitters move to informal channels of money transfers like hawala (Gupta et al., 2009; Freund & Spatafora, 2008).

According to Remittance Prices Worldwide data (World Bank, 2024b), the global average cost of remittance in Q1 of 2023 is 6.25% for sending USD200 and 4.33% for sending USD500 for the same period. The bilateral costs in the highest bracket for 2023 are between Tanzania and Uganda (51.7%), the UK and Lithuania (34.36%), Sweden and India (29.44%), and Kuwait and Pakistan (30%).

According to a McKinsey report, regulatory pressures inflate the cost of remittances (Denecker et al., 2016). Money laundering measures include KYC—Know Your Customer Verification, CDD—Customer Due Diligence, Enhanced CDD (EDD), FATCA—Foreign Accounts Tax Compliance Act of the United States, FATF—Financial Action Task Force checks (Esoimeme, 2020) and screening money transfer requests against the list of black or gray-listed entities. Accordingly, the regulation mandates financial institutions to freeze the accounts, adhere to trade restrictions, report suspicious transactions, and identify real owners of the companies. Often, bank operators need to seek additional information by contacting customers. For these manual efforts, banks charge fees that add to the remittance cost. Building IT—Information Technology systems to comply with these regulations is a cost overhead (Antwi et al., 2023) and may discourage financial development, leading to reduced remittance flows (Gurira, 2024), via the formal channels.

The Sustainable Development Goal—SDG 10 target is to maintain the remittance cost at a 3% level (Beck et al., 2022; Kpodar & Imam, 2022). The G20 target is to reduce global remittance costs to 5% by 2030. It's an international agenda to reduce transaction costs for payments across borders (Boston Consulting Group, 2018; G20, 2023; Khan et al., 2021). G20 has set a target to increase the speed of payments. It aims to make the funds available in the recipient bank within an hour for 75% of the transactions by 2027. Although lowering remittance costs is the direct emphasis of SDG 10.c, social protection, economic mobility, and financial inclusion all play a part in the more significant relationship between remittances and eliminating inequality. Beyond cost reduction, remittance flows can be optimized to maximize their influence on the livelihood of people through the integration of frontier technologies, supporting SDG 10's objectives.

A key determinant of remittance costs is the regulatory framework governing cross-border transactions. Anti-money laundering (AML) measures, while crucial for preventing illicit financial flows, impose significant compliance burdens on financial institutions. These increased costs are typically passed on to remittance users, potentially offsetting the positive impact of remittance inflows (Ecer & Tompkins, 2013; Beck et al., 2022; Kpodar & Imam, 2022).

Emerging frontier technologies, such as blockchain, offer a promising opportunity to offset the cost of regulatory burden. Ripple is a private blockchain service provider to financial institutions. It offers products to leverage blockchain technology (Guo and Dan, 2023). Blockchain helps reduce the number of intermediary banks, thus minimizing reliance on legacy systems. This model can lower transaction fees and expedite remittance transfers (Christodoulou et al., 2024; Lin et al., 2024; Gurira, 2024). However, about 90 percent of the formal global cross-border transactions are conducted over the SWIFT network (CPMI & SWIFT, 2023). Migrating from SWIFT-connected legacy applications to a blockchain-based application is a long and costly journey for incumbent players due to the uncertainty of cost savings (Denecker et al., 2016). Despite these challenges, Ripple is already implemented in around 40+ countries across six continents. As Habib et al. (2022) quote, blockchain network congestion may result in higher transaction costs for faster processing during peak transaction flows. Therefore, the researchers (Christodoulou et al., 2024) who claim that blockchain will reduce costs need re-validation.

It is evident that existing studies focused on granular variables and overlooked the holistic effect of technology and legal dimensions from the PESTLE framework, which can be measured by using global indexes. Furthermore, the extent to which these technological advances can moderate the adverse cost effects of stringent AML measures remains underexplored. It is evident that existing studies do not consider the distinct dynamics of remittance-sending and remittance-receiving countries. Therefore, our research question is: How do anti-money laundering measures and frontier technology readiness interact with remittance flows to influence remittance costs in both remittance-sending and remittance-receiving countries?

This study addresses the critical gap by investigating how AML measures impact remittance costs and examining the moderating role of frontier technology. We employed a novel approach by incorporating global indexes as variables and studied the bi-directional flow. The AML Index to gauge regulatory stringency and the Frontier Technology Readiness Index (FTRI) to assess technological adoption. It's coupled with bi-directional data (Shastri, 2022) on remittance flows (both paid and received) to develop separate models for remittance-sending and remittance-receiving countries.

For managers of the remittance service providers, our research contributes to the ongoing debate on how best to balance regulatory rigor with technological innovation to enhance the efficiency of cross-border payments. The findings promise valuable insights for policymakers and managers of financial institutions striving to optimize remittance flows by considering the interaction effect of technology and regulation as against individual dimensions recommended for policymakers by the existing studies. The results impact the livelihoods of over 170 million migrant workers and their families worldwide, which is the motivation behind this study. This is one of the few empirical studies using panel data analysis on remittance costs that splits the data for remittance-sending countries and remittance-receiving countries (Shastri, 2022; Lim et al., 2023) and investigates the impact of the relationship between technology and compliance frameworks on remittance costs.

The subsequent sections detail the literature review, outline the conceptual model, describe the data methodology, and discuss the empirical results that underpin our analysis.

Review of literature

The literature reveals that technological innovations and regulatory frameworks shape the cost of remittance transactions. On one hand, emerging frontier technologies promise to reduce costs and enhance financial inclusion; on the other, stringent anti-money laundering (AML) and sanctions measures tend to drive up transaction expenses. This review critically examines these

dimensions and their influence on remittance value and volume, setting the stage for investigating how technological improvements can moderate the cost burdens imposed by regulatory compliance.

Remittance paid and received. In 2022, Global remittance volume was 630 billion (World Bank, 2024a). Financial institutions charge either a flat fee or a percentage of the remittance value. In the first charging mechanism, a higher remittance amount may lower costs. The increase in cross-border payment volume contributes to faster and cheaper payments (Stark, Lafave, 2024). According to Kpodar & Imam (2022), a four-year study from 2013–2017 by the Bank of Mexico showed that workers remitted less if the cost of transactions was higher. Their study also states that income per capita increases remittance levels only up to a certain threshold, which aligns with the results of (Barkat et al., 2023) in the study of 109 countries for the period of 2000–2019. A study in Pakistan by Khan et al. (2021) highlights that the determinants of remittances from Saudi Arabia and the UAE to Pakistan are unskilled workers' experience and income level.

The total transaction costs may be lower as the bank's transaction volume increases over the SWIFT network. However, the level of network fees charged by SWIFT to banks is opaque. Kpodar & Imam (2022) have listed a number of studies on cross-country, country-specific, such as Russia, the Netherlands, and Tonga, that conclude that remittance costs are detrimental to the remittance paid or received. At an individual level, the number of remittance transactions is eight to ten per annum, which may not provide economies of scale to institutions to offer a better rate. With the rising fintech, the financial inclusion rate may improve, resulting in the growth of transaction volumes and lowering the cost. The unaccounted remittances over informal channels and remittances in cash may become part of the mainstream financial system, as in Sub-Saharan Africa and the Middle-East, as per Gupta et al. (2009) and in Pakistan, as per Mughal et al. (2023). Therefore, this study considers remittance paid and received to account for the effects of variables apart from AML and FTRI.

Due to varying levels of technology adoption, sanctions restrictions, and various other factors, the cost varies by country/region. SWIFT has different charging structures for regions/countries, Perez-Saiz & Zhang (2023). According to World Bank (2024b), from 2017 to 2022, the cost of sending remittances from Africa was always higher than receiving remittances in Africa from other regions. For Europe and Central Asia, while the cost of receiving remittances is almost constant, the cost of sending from Europe and Central Asia is constantly rising. Therefore, this divides the dataset into receiving and sending countries and studies the effect separately from the perspectives of both. Thus, our first and second hypotheses become:

The first hypothesis,

H_{01} = In Remittance-Sending Country, Remittance paid does not reduce Remittance-Sending Cost.

H_{a1} = In the Remittance-Sending Country, the Remittance paid reduces the Remittance-Sending Cost.

The second hypothesis,

H_{02} = In Remittance-Receiving Country, Remittance Received does not reduce Remittance-Receiving Cost.

H_{a2} = In Remittance-Receiving Country, Remittance Received reduces the Remittance-Receiving Cost

Frontier technology. According to a United Nations report (Unctad, 2021) on Technology and Innovation, blockchain is listed as a part of a group of new technologies called frontier technologies. FTRI—Frontier Technology Readiness Index is a composite index consisting of ICT—Information Communication Technology deployment, skills, research and development, industry activity, and finance, which assesses the extent of ICT usage, evaluates the skill levels of the workforce and the education levels of the end users, measures the investment and its output, the capacity to produce technology and export digital services, and the availability of financial resources supporting technological innovation respectively (UNCTDstat, 2023).

Existing literature touches on speed (Lin et al., 2024), transparency (Gurira, 2024), and cost of transactions (Ecer & Tompkins, 2013; Beck et al., 2022; Kpodar & Imam, 2022; Christodoulou et al., 2024) using blockchain. However, regulators and banks worldwide also do not favor involving private parties owning the blockchain infrastructure, as it could be used as a vehicle for illegal financing (Feinstein & Werbach, 2021). Bitcoin is used to siphon off over USD 75 billion (Foley et al., 2019). It gives evidence of vulnerability that can be exploited for illegal activities using blockchain. Reputational damage for a bank is the biggest loss, as it stands on the foundation of trust. Central banks worldwide are experimenting with their own digital currencies called CBDC, Central Bank Digital Currency, to address this issue and benefit from the technology. The CBDC aims to minimize the reliance on cash and aims to improve financial inclusion, speed of money transfer, and transparency in financial transactions. India's Jan Dhan Account scheme helped bring 550 million unbanked citizens into the financial system in 10 years and contributed to financial inclusion without migrating from legacy platforms. Hence, political will may be a significant contributor in addition to the technology adoption.

Dong et al. (2024) used ICT—Information Communication Technology and Industry, the components within the Frontier Technology Readiness Index, to assess the availability and adoption of frontier technology, respectively. It adopted a panel regression methodology. In a study by Sarabdeen et al. (2024), FTRI is incorporated as a proxy for digital adaptation and as a moderator of income inequality. Xie et al. (2024) considered Frontier technology in the study of economic growth. Despite these advances, the direct application of frontier technology to remittance cost reduction remains an underexplored area—a gap this study aims to address.

With this, our third and fourth hypotheses become as below:

Third hypothesis,

H_{03} = In Remittance-Sending Country, FTRI does not moderate the relationship between Remittance Paid and Remittance-Sending Cost.

H_{a3} = In the Remittance-Sending Country, FTRI moderates the relationship between Remittance Paid and Remittance-Sending Cost.

The fourth hypothesis,

H_{04} = In the Remittance-receiving country, FTRI does not moderate the relationship between the Remittance Received and the Remittance-Receiving Cost.

H_{a4} = In the Remittance-receiving country, FTRI moderates the relationship between the Remittance Received and the Remittance-Receiving Cost.

Anti-money laundering and sanctions. The anti-money laundering—AML Index is a composite index comprising the quality of the AML/CTF framework, corruption risk, financial transparency and standards, public transparency and accountability, and political and legal risks. It is used to gauge the level of risks of using countries' banks and financial institutions for money laundering and terrorist financing, the prevalence of corruption within the country, transparency of financial institutions'

compliance to global standards, openness and accountability of public institutions, and examines the stability and integrity of the political and legal systems (Basel Institute on Governance, 2023). However, according to Gurira (2024), political stability does not influence remittance in emerging markets; rather, cost transparency does.

Research by Beck et al. (2022) explores and employs AML indicators in the research. While technology adoption aims toward financial inclusion, the AML regulations may prove counterproductive to these efforts. Esoimeme (2020) proved it in his study of the UK and Nigeria. According to the Bank for International Settlements, more than 20% of banks terminated their correspondent banking relationships due to AML regulations. The number of correspondent banks has constantly been declining from the year 2017 due to the challenges in doing remittance business (World Bank & International Monetary Fund, 2022; CPMI & SWIFT, 2023). It would make remittance services inaccessible and costly. Furthermore, it would indirectly encourage the adoption of informal channels for transfers. Fintechs and Money Transfer Operators (MTOs) have to abide by less stringent AML/CTF regulations compared to banks. It's to promote financial inclusion. As a result, the remittance cost is the highest for banks and lowest for MTOs (World Bank and International Monetary Fund, 2022).

Sanctions will force the financial ecosystem to advance (Antwi et al., 2023) technologically, including adopting CBDCs. However, higher upfront investment costs may delay the break-even point, so immediate cost reductions may not be visible. Feinstein and Werbach (2021) are proponents of limiting the regulations on cryptos. However, a paper by the World Bank and BIS—Bank for International Settlements (Ardic et al., 2022) clarifies that only low-risk customers are recommended to be ignored during screening as per FATF guidelines. Due to the risk of reputational damage, banks prefer not to classify any customer as low-risk and continue screening everyone with equal rigor. Furthermore, political stand by countries to not cooperate with global sanctions and financial crime pose challenges. This is where employing the index that gauges a country's position on AML and sanctions compliance level, considering legal and political aspects, can be useful in the research. Our study contributes to this effort.

With this, our fifth and sixth hypotheses become as below:

The fifth hypothesis,

H_{05} = In the Remittance-Sending Country, FTRI does not moderate the relationship between the AML Index and Remittance-Sending Cost.

H_{a5} = In the Remittance-Sending Country, FTRI moderates the relationship between AML Index and Remittance-Sending Cost.

The sixth hypothesis,

H_{06} = In the Remittance-receiving country, FTRI does not moderate the relationship between the AML Index and Remittance-Receiving Cost.

H_{a6} = In the Remittance-receiving country, FTRI moderates the relationship between the AML Index and the Remittance-Receiving Cost.

By testing these hypotheses, this study aims to provide empirical evidence on how regulatory and technological factors interact to influence remittance costs, ultimately informing policies that support lower transaction fees and broader financial inclusion.

Theoretical background and conceptual framework. This study takes support from several tightly coupled theories that explain the interplay between the regulatory framework, technological advancement, and economic outcome in the remittance market. The Regulatory Theory and Institutional Theory (Bae et al., 2024; Hsiao et al., 2024) explain how the regulatory and legal environment affects remittance flow. The costs incurred by banks in complying with regulations are ultimately passed on to the customers, making remittances costly.

The Transaction Cost Theory focuses on how technology impacts the efficiency of remittances and overall financial operations. Adoption of innovative technologies will reduce operational burdens associated with AML compliance. Countries with higher technological adoption and acceptance will be able to comply with the evolving regulations and still manage to keep the associated costs lower. Frontier Technology Readiness Index (FTRI) considers not only technology advancement but also adoption, penetration, and the level of Research and Development in the country. From the existing literature, the study by Kpodar & Imam (2022) considers ICT—Information Communication Technology as a determinant. However, with a cost adaptation policy in place, this determinant does not significantly impact the transaction costs.

Remittance flow is the antecedent of the remittance cost. A number of theories, such as the insurance theory and the altruism theory, support this relationship. The purpose of remittances sent from the US, the UK, and Germany to Ghana or Nigeria is consistent with the Altruism Theory (Ecer & Tompkin, 2013). It implies that migrants will send higher remittances to meet their family needs and less for investment purposes, which may ensure them once they return to their home countries.

This research contributes to the existing theory by adopting a combination of these theories that focus on AML, Remittance flows and FTRI (Li et al., 2024). Figure 1—The conceptual model captures the logical model. The study integrates regulatory framework and technological and economic theories to investigate how improvements in AML and FTRI index work together to reduce remittance costs. This model remains the same for both the Remittance-Sending and Remittance-Receiving Countries.

Data and research methodology

Data. The Remittance Prices Worldwide data is divided into two groups—Remittance Cost at the Sending Countries and Remittance Cost at the Receiving Countries. For each group, there are two dependent variables. FTRI data is available for 147 countries over a 14-year period. Remittance Paid and Received is available for 200 countries spanning 63 years. AML data is available for a minimum of 110 countries in certain years, up to 162 countries, and for a maximum period of 11 years. Names of the countries in different databases or within a database over different years may be captured differently due to geopolitical reasons. Clean-up of such names is done to identify the observation uniquely. For example, Republic of Korea is treated as South Korea, Russian Federation or Soviet Union is treated as Russia, Ivory Coast is treated as Côte d'Ivoire, Czcheia is treated as Zchec Republic, Siam is treated as Thailand, the United States of America is treated as the United States and Türkiye is treated as Turkey. Remittance prices data is treated as the base. The data file is split into two datasets by using the 'Sending Country' and 'Receiving Country' columns, along with their respective remittance cost percentage value columns. For each data file, the observations where the "Transparent" value is 'No" are omitted. The data is organized in a panel format in ascending years and sorted alphabetically by country as a second-level sorting. The observations are numbered, and a unique key is created by concatenating the year and the serial number. A secondary key is created by concatenating "Year" and "_Country Name". In the Remittance Paid, Remittance Received, FTRI and AML Index data files, a key similar to 'Secondary key' is created by

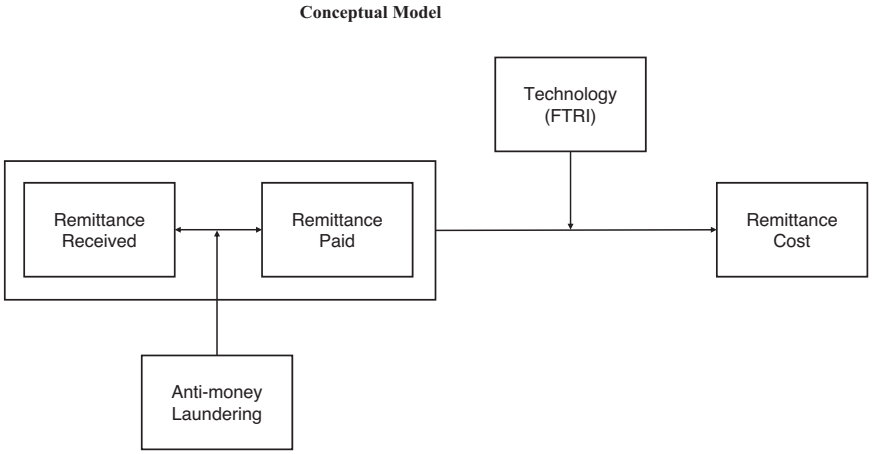

Fig. 1 Conceptual model: The figure depicts the conceptual model with the interplay across all the variables used for empirical analysis.

concatenating "Year" and "_Country Name". Using the common key, the data is joined in each 'Sending Country' and 'Receiving Country' data files. The combined data available for the study is from 2011 to 2023. Missing values are not imputed in the panel data.

The key theoretical constructs include remittance cost (dependent variable), the Anti-Money Laundering (AML) Index, and the Frontier Technology Readiness Index (FTRI), which are grounded in the conceptual framework linking financial regulation, technological readiness, and transaction efficiency. The constructs are operationalized using data sources like the World Bank (2024b), Remittance Prices Worldwide, Basel AML Index, and UNCTDstat. FTRI is chosen as a mediator (Sarabdeen et al., 2024). Table 1 lists all the variables. Control variables include remittance paid and received values to account for volume-based effects.

Sub-elements constitute the AML Index and Frontier Technology Readiness Index, which are investigated by various studies. However, their holistic impact is rarely measured. Our study fills this gap by using the 'Indexes' of all such constituents of AML and FTRI as variables. The effect of all determinants of these dimensions is summarized in a single Index value. The holistic effect of all determinants of remittance is ultimately reflected in the remittance paid and remittance received variables. The choice of variables aligns with the study's objective.

Research methodology. The sample selection of countries is based on the data captured by primary sources. Data clean-up by removing missing value observations further reduced the sample size. Statistical analysis is performed using Stata v15 software. We adopted panel data analysis to capture the effects of cross-section (country—in our model) across different time periods. Model selection was guided by the Hausman test, which indicated the appropriateness of Fixed or Random Effects. If fixed effects drive the model, it implies that unobserved, time-invariant factors are correlated with the explanatory variables. Conversely, if random effects drive the model, unobserved effects are assumed to be uncorrelated with the regressors. A number of studies adopted this methodology in their experiments of a similar nature (Beck et al., 2022; Barkat et al., 2023; Dong et al., 2024). Additionally, the presence of potential endogeneity is validated by Sargan and Arellano-Bond diagnostic tests.

Research is on two base models and two interaction models. Among base models, one is for the sending country and another for the receiving country. The FTRI is used as an interaction term on the base model to develop two interaction models. In the equations, the error term is Uit.

Model 1: Receiving Country Remittance Cost Base Model:

$$Yo = \alpha + \beta 1 \cdot remrcvd + \beta 2 \cdot ftri + \beta 3 \cdot rcvaml + Uit \quad (1)$$

This model measures the impact of remittances received, the FTRI, and the Anti-Money Laundering (AML) index on the remittance cost in receiving countries.

Model 2: Receiving Country Remittance Cost Interaction Model:

$$Yo = \alpha + \beta 1 \cdot remrcvd + \beta 2 \cdot ftri + \beta 3 \cdot rcvaml + \beta 4 \cdot remrcvdftri + \beta 5 \cdot rcvamlftri + Uit \quad (2)$$

In this model, FTRI moderates the relationship between remittances received, AML, and remittance costs in receiving countries through interaction terms.

Model 3: Sending Country Remittance Cost Base Model:

$$Yo = \alpha + \beta 1 \cdot rempd + \beta 2 \cdot snd\_ftri + \beta 3 \cdot sndaml + Uit \quad (3)$$

This model captures the effect of remittances paid, the FTRI, and the AML index on remittance cost in sending countries.

Model 4: Sending Country Remittance Cost Interaction Model:

$$Yo = \alpha + \beta 1 \cdot rempd + \beta 2 \cdot snd\_ftri + \beta 3 \cdot sndaml + \beta 4 \cdot rempdftri + \beta 5 \cdot sndamlftri + Uit \quad (4)$$

Here, FTRI moderates the effect of remittances paid and AML on remittance costs in sending countries, and the error term is Uit. Our analysis employs a fixed effects panel regression that controls for unobserved time-invariant heterogeneity to address endogeneity, thereby reducing endogeneity concerns.

Empirical results

This section presents the descriptive statistics, correlation matrices, regression results, and diagnostic test outputs. Each analysis captures the key patterns observed from the data across remittance-sending and receiving countries.

Descriptive statistics. Table 2 captures the descriptive statistics for both the data groups. It captures the Mean, Standard deviation, number of observations available, and the minimum and maximum value for each observation. The panel is imbalanced. The mean for FTRI shows that technology readiness is higher in sending countries (0.64) than receiving countries (0.37). The mean for cost shows that sending countries has higher costs (6.5) compared to receiving countries (7.1). However, outliers exist in sending countries (max cost 51.76 USD) as against 29.8 USD in receiving countries.

Table 1 List of variables.

Interaction model for	Variables	Code	Type	Definition	Citations
Remittance-Receiving Countries	Cost Percentage	rcv_tcost1	DV	The average percentage cost of sending USD200.	World Bank (2024b)
	Remittance Received (Rrcvd)	remrcvd	IV	Personal remittances comprise personal transfers and compensation of employees. Available in USD.	World Bank (2024b), United Nations (2023)
	Frontier Technology Readiness Index (FTRI)	rcv_ftri	MV	The composite index of Financial Inclusion, Research and Development, Technology Adoption etc. It's used as the proxy for technology.	UNCTDstat (2023), Kpodar & Imam (2022).
	Anti-Money Laundering Index (AML)	rcvaml	IV	The composite index of 18 indicators related to AML, Counter Terrorist Financing, Sanctions, Transparency etc.	Basel Institute on Governance (2023), (da Silva Filho, 2021)
	Interaction term —(FTRI.AML)	rcvamlftri	IV	The product of FTRI and AML Index.	
	Interaction Term (FTRI.Rrcvd)	remrcvdftri	IV	The product of FTRI and remittance received.	
Remittance-Sending Countries	Cost Percentage	snd_tcost1	DV	The average percentage cost of sending USD200.	World Bank (2024b), United Nations, 2023)
	Remittance Paid (rpaid)	rempd	IV	Personal remittances comprise personal transfers and compensation of employees. Available in USD.	World Bank (2024b), United Nations, (2023)
	Frontier Technology Readiness Index (FTRI)	snd_ftri	MV	Composite index of Financial Inclusion, Research and Development, Technology Adoption etc. It's used as the proxy for technology.	UNCTDstat (2023), Kpodar & Imam (2022).
	Anti-Money Laundering Index (AML)	Sndaml	IV	The composite index of 18 indicators related to AML, Counter Terrorist Financing, Sanctions, Transparency etc.	Basel Institute on Governance (2023), (da Silva Filho, 2021)
	Interaction term —(FTRI.AML)	sndamlftri	IV	The product of FTRI and AML Index.	
	Interaction Term (FTRI.Rpaid)	rempdftri	IV	The product of FTRI and remittance paid.	

Table 2 Descriptive statistics.

	Variable	Obs	Mean	Std. dev.	Min	Max
Sending country	snd_tcost1	538	6.550056	6.445056	0.26	51.76
	rempd	2654	1.45E + 10	4.65E + 10	2563928	4.63E + 11
	snd_ftri	495	0.642353	0.270017	0.0203	1
	sndaml	453	5.20E + 00	1.03E + 00	2.360348	8.49E + 00
	rempdftri	495	5.90E + 09	1.04E + 10	0	7.27E + 10
	sndamlftri	366	3.29E + 00	1.18E + 00	0.116767	5.80E + 00
Receiving country	rcv_tcost1	1417	7.129549	4.61952	0.99	29.88571
	remrcvd	2884	2.65E + 10	7.75E + 10	204751	7.59E + 11
	rcv_ftri	943	0.3797	0.216789	0.0046	0.9901
	rcvaml	796	5.94E + 00	1.14E + 00	2.68	8.55E + 00
	rcvtcost1ftrii	932	2.55576	1.947623	0	18.88911
	remrcvdftri	943	2.52E + 09	5.94E + 09	0	5.91E + 10
	rcvamlftri	606	2.233546	0.991995	0	5.626314

Source: STATA output.

Correlation matrix. The correlation matrix is captured for both the sending and receiving countries in Tables 3 and 4, respectively. Correlation matrices are used to explore the relationships between the independent and dependent variables for both sending and receiving countries. For remittance-sending countries, some key correlations are: Rempd (Remittances Paid) and snd_ftri (FTRI for Sending Countries) show a positive correlation (0.4037). Snd_ftri and sndaml (AML for Sending Countries) have a negative relationship (−0.6741), indicating that as technological readiness increases, AML scores tend to decrease. A strong positive correlation (0.8974) exists between sndaml and sndamlftri, which points to multicollinearity issues.

For remittance-receiving countries, some significant correlations are—Remrcvd (Remittances Received) and rcv_ftri (FTRI for Receiving Countries) show a positive correlation (0.2606). Rcvaml (AML for Receiving Countries) and rcv_ftri exhibit a negative correlation (−0.6740), indicating that higher technological readiness is associated with lower AML scores. Similar to sending countries, a strong positive correlation (0.9057) between rcvaml and rcvamlftri indicates potential multicollinearity.

High correlation values between the FTRI and AML interaction terms point to potential multicollinearity, particularly for the interaction terms in both sending and receiving country models.

Table 3 Correlation sending country.

	Snd_tcost1	Rempd	Snd_ftri	Sndaml	Rempdftri	Sndamlftri
Snd_tcost1	1.0000					
Rempd	−0.1477*	1.0000				
	0.0017					
Snd_ftri	−0.0734	0.4037*	1.0000			
	0.1320	0.0000				
Sndaml	0.0583	−0.1192*	−0.6741*	1.000		
	0.2462	0.0204	0.0000			
Rempdftri	−0.0530	0.9730*	0.4368*	−0.1276*	1.000	
	0.2768	0.0000	0.0000	0.0146		
Sndamlftri	−0.1880*	0.4636*	0.8974*	−0.3166*	0.4780*	1.000
	0.0008	0.0000	0.0000	0.0000	0.0000	

The * represents the significant correlation coefficient at the significance level of 0.05. Correlation values greater than 0.8 indicate the presence of multicollinearity (e.g., between sndamlftri and snd_ftri).
Source: Author's calculations.

Table 4 Correlation receiving country.

	Rcv_tcost1	Remrcvd	Rcv_ftri	Rcvaml	Remrcv-i	Rcvamlftri
Rcv_tcost1	1.0000					
Remrcvd	−0.1039*	1.000				
	0.0002					
Rcv_ftri	−0.2103*	0.2606*	1.0000			
	0.0000	0.0000				
Rcvaml	0.2091*	−0.0592	−0.6740*	1.0000		
	0.0000	0.1128	0.0000			
Remrcvdftri	−0.0937*	0.9674*	0.3499*	−0.1043*	1.0000	
	0.0042	0.0000	0.0000	0.0102		
rcvamlftri	−0.2262*	0.3216*	0.9057*	−0.3550*	0.4338*	1.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	

The * represents the significant correlation coefficient at the significance level of 0.05. Correlation values greater than 0.8 indicate the presence of multicollinearity (e.g., between rcvamlftri and rcvftri).
Source: Author's calculations.

Results of the regression tests. Regression is run on all four models. Tests for Autocorrelation, Homoscedasticity, and Endogeneity are performed; the null hypothesis tested for both the sending and receiving countries is as below:

H_{07}—Model has homoscedasticity (Durbin-Chi Square Test—Test of heteroscedasticity)

H_{08}—Variables are exogenous (Wu-Hausman Test—Test of Endogeneity)

H_{09}—Model does not have first-order autocorrelation (AR1 Test)

H_{010}—Overidentifying restrictions are valid in the model (Sargan Test)

Table 5 captures the regression results showcasing the coefficient, standard error, and p-value, which state the probability. The Hausman test is run with the results obtained as part of the regression. None of the models has collinearity issues. If the *p*-value of the Hausman test is more than 0.05, the model is considered to be driven by random effects; otherwise by fixed effects. Accordingly, based on the *p*-values of the Hausman test in Table 5, both the base models (#1, #3) have random effects, and both the interaction models (#2, #4) have fixed effects.

Interpretation of results

The results are presented in two sections below, according to the receiving and sending countries.

Remittance-receiving country. From the results in Table 5, the cost of receiving remittances is significantly and negatively correlated with remittances received and the FTRI Index. It's positively correlated with the Anti-Money Laundering Index. The FTRI Index is also negatively and strongly correlated with the AML Index. The remittance received is strongly and positively correlated with the FTRI Index. A unit increase in the FTRI and AML indexes decreases the remittance cost by 19.28 units and 0.94 units, respectively, in the remittance-receiving countries.

The model fitness of the receiving country models is lower than that of the sending country's model. The fitness percentage is 7.83% (Between) for the base model and 8.69% (Between) for the interaction model. Both models have first-order and second-order autocorrelation. The Sargan test shows that overidentifying restrictions are valid in the receiving country's base and interaction models. Similar to the sending country model, here as well, the Durbin Chi-2 and Wu-Hausman test show that the interaction model has endogeneity. However, base model variables are exogenous.

Fixed-effect drives the base model, whereas the random effect drives the interaction model in the remittance-receiving country. The Cost of receiving remittances goes down with the increasing inflow of remittances. The interaction model shows that remittance-receiving cost decreases significantly as the FTRI increases. The AML Index is negatively correlated with the cost of receiving remittances. The AML Index and FTRI combined effect is also negatively correlated with remittance costs.

Model 1 (Base Model for Receiving Countries): Remrcvd (Remittances Received) negatively affects remittance cost, with a statistically significant p-value (0.045). Rcv_ftri and rcvaml are not significant in this base model.

Model 2 (Interaction Model for Receiving Countries): The interaction term rcvamlftri significantly increases remittance cost

Table 5 Regression output.

DV: snd_tcost1	Base Model 3—Sending Country (random effect)			Interaction Model 4—Sending country (fixed-effect)		
	Coeff.	Std. err.	*p*-value	Coeff.	Std. err.	*p*-value
rempd	1.46E-10	1.24E-10	0.242	−3.20E-10	2.40E-10	0.182
snd_ftri	−1.174987	7.58163	0.877	23.26437	11.6687	0.046
sndaml	−2.658105	0.608671	0	1.797925	1.363988	0.187
rempdftri				3.84E-10	2.71E-10	0.157
sndamlftri				−5.688832	1.884242	0.003
Cons.	19.90643	6.350911	0.002	0.8352523	8.908714	0.925
R-square	9.48% (Between)			18.59% (Between)		
Sargan Test	97.54419 (0.0000)			95.45049 (0.0000)*		
AR (1)	−2.2533 (0.0242)*			−2.226 (0.0260)*		
AR (2)	−0.59403 (0.5525)*			−0.8263 (0.4086)		
Durbin Chi-^{2}	2.34329 ($p = 0.1258$)			4.31122 ($p = 0.0379$)*		
Wu-Hausman Test	2.32988 ($p = 0.1280$)			4.28591 ($p = 0.0393$)*		
DV: rcv_tcost1	**Base Model 1—Receiving country (random effect)**			**Interaction Model 2—Receiving country (fixed-effect)**		
remrcvd	−9.58E-11	4.76E-11	0.045	−1.71E-10	1.08E-10	0.114
rcv_ftri	0.263897	2.288445	0.908	−19.28758	5.672769	0.001
rcvaml	−0.015017	0.2209316	0.946	−0.9435929	0.3988685	0.018
remrcvdftri				1.98E-10	1.76E-10	0.261
rcvamlftri				2.631885	0.8683838	0.002
Cons.	7.837577	1.72159	0	15.26631	2.831203	0
R-Sqaure	7.83% (Between, Random Effect)			8.69% (Between)		
Sragan Test	55.0949 (0.1219)			55.13302 (0.1212)		
AR (1)	−1.8782 (0.0604)*			−1.8918 (0.0585)*		
AR (2)	−1.7525 (0.0797)*			−1.7257 (0.0844)		
Durbin Chi-2	2.38967 ($p = 0.1221$)			30.056 ($p = 0.0000$)*		
Wu-Hausman Test	2.38329 ($p = 0.1232$)			31.3113 ($p = 0.0000$)*		

Source: Author's calculations.
Note: The *p*-values are in parentheses and, if significant, are indicated by an asterisk.

($p = 0.002$), indicating that AML, when moderated by FTRI, significantly impacts remittance costs in receiving countries. Rcv_ftri has a strong negative effect on remittance costs ($p = 0.001$).

Remittance-sending country. From the results in Table 5, the cost of sending remittance varies significantly and negatively with the remittance paid. A similar relationship is observed between the cost and FTRI. The moderation effect of FTRI continues to show similar behavior. However, the direction of the relationship between cost and the Anti-Money Laundering index changes with the moderation of FTRI. Both variables move in the same direction for the base model, albeit the relationship is not statistically significant. The coefficient of FTRI is higher in the interaction model than in the base model. According to the coefficients of the interaction model, a unit increase in the FTRI index and AML index increases the cost by 23.26 units and 1.79 units, respectively, in the remittance-sending countries.

The model fitness is higher (18.59%) in the interaction model compared to the base model (9.48%). These are 'between' values, and the 'overall' and 'within' values are significantly lower. The first-order autocorrelation exists in the sending country's base and interaction model. The Sargan test shows that overidentifying restrictions are invalid in the base and interaction models. The Durbin Chi-2 and Wu-Hausman test shows that the interaction model has endogeneity; however, base model variables are exogenous.

Model 3 (Base Model for Sending Countries): sndaml significantly reduces remittance costs ($p = 0.000$), while rempd (Remittances Paid) is not significant in this model.

Model 4 (Interaction Model for Sending Countries): The interaction term sndamlftri significantly reduces remittance costs ($p = 0.003$), demonstrating the impact of AML when moderated by FTRI. snd_ftri has a positive and significant impact on remittance costs ($p = 0.046$).

Autocorrelation: The AR(1) test for first-order autocorrelation returned significant results in three models ($p < 0.05$), indicating the presence of first-order autocorrelation.

Heteroscedasticity: The Durbin-Chi Square test confirmed heteroscedasticity in the interaction models, particularly for both the receiving ($p = 0.0379$) and sending countries ($p = 0.1258$ for the base model and $p = 0.0393$ for the interaction model).

Endogeneity: The Wu-Hausman test found potential endogeneity in the interaction models for both receiving and sending countries ($p = 0.0393$ and $p = 0.0000$, respectively).

Sargan Test: The Sargan test validated the overidentifying restrictions for all models, indicating no issues with instrument validity.

Summarized interpretation of hypothesis testing results. Both the base and interaction models are driven by fixed effects. The test of robustness shows that the relationship is not by chance. The base model's remittance-sending cost negatively correlates with the AML Index. In the interaction model, the cost of sending remittance is significantly and positively correlated with the FTRI Index. Furthermore, the combined effect of the AML Index and FTRI is positively and significantly related to remittance' cost. To summarize, the results of our hypothesis testing are as in Table 6 below:

Discussion

Our analysis reveals nuanced interactions between regulatory frameworks, technological readiness, and remittance costs in both remittance-sending and remittance-receiving countries. As per the base models, in remittance-sending countries, the remittance paid does not have a significant relationship with the cost of

Table 6 Summary of hypothesis testing results and interpretation.

Hypothesis	Null hypothesis accepted/rejected?	Interpretation of hypothesis testing results
H_{01}	$p = 0.242$ (base model) $p = 0.182$ (interaction model) Accepted	Remittance paid does not have a significant effect on reducing sending costs.
H_{02}	$p = 0.045$ (base model) but $p = 0.114$ (interaction model) Accepted (based on interaction model)	While the base model shows a significant negative effect, in the interaction model, the effect becomes statistically insignificant.
H_{03}	$p = 0.157$, Accepted	There is no significant moderating effect of FTRI on the relationship between remittance paid and sending cost.
H_{04}	$p = 0.002$, Rejected	FTRI significantly moderates the relationship between remittance received and receiving cost.
H_{05}	$p = 0.003$ Rejected	FTRI significantly moderates the relationship between the AML Index and sending cost.
H_{06}	$p = 0.0393$ Rejected	FTRI significantly moderates the relationship between the AML Index and receiving cost.
H_{07}	Sending Countries:- Base Model: $p = 0.1258$; Interaction Model: $p = 0.0379$ Receiving Countries:- Base Model: $p = 0.1221$; Interaction Model: $p = 0.0000$ Base Models-Accepted Interaction Models-Rejected	In the base models, errors appear homoscedastic. However, the interaction models show significant heteroscedasticity, suggesting that variability in errors differs across observations in these specifications.
H_{08}	Sending Countries:- Base Model: $p = 0.1280$; Interaction Model: $p = 0.0393$ Receiving Countries:- Base Model: $p = 0.1232$; Interaction Model: $p = 0.0000$ Base Models-Accepted Interaction Models-Rejected	In the base models, the explanatory variables appear exogenous. However, the significant results in the interaction models indicate that endogeneity may be present when interaction terms are included.
H_{09}	Sending Countries:- Base Model: $p = 0.0242$; Interaction Model: $p = 0.0260$ Receiving Countries:- Base Model: $p = 0.0604$ (marginally significant); Interaction Model: $p = 0.0585$ (marginally significant) Sending Models-Rejected Receiving Models-Rejected	The sending country models show significant first-order autocorrelation. The receiving country models are marginally significant, suggesting that autocorrelation may also be present, though less strongly.
H_{010}	Sending Countries:- Base Model: $p = 0.0000$; Interaction Model: $p = 0.0000$ Receiving Countries:- Base Model: $p = 0.1219$; Interaction Model: $p = 0.1212$ Sending Models-Rejected Receiving Models-Accepted	For sending countries, the significant Sargan Test results suggest that the instruments used might be invalid. In contrast, for receiving countries, the instruments appear valid as the null is not rejected.

sending remittances, implying that the volume of remittances paid does not influence the cost. It could be due to a fixed fee structure, not encouraging the outward flow of remittance by the sending country's regulations, or inefficiencies in the underlying cost structures to be flexible. And, in remittance-receiving countries, FTRI and AML do not have a significant relationship with remittance cost, implying that the frontier technology adoption and anti-money laundering regulation policies, when considered individually, would not help in cost reduction.

Furthermore, in remittance-sending countries, as per the interaction model, the moderation effect of the Frontier Technology Readiness Index (FTRI) on the relationship between remittance paid and remittance-sending cost is not statistically significant ($p = 0.157$). In contrast, the interaction between FTRI and the AML Index for remittance-sending cost is significant ($p = 0.003$), indicating that in sending countries, higher technological readiness combined with a lower AML Index leads to reduced costs.

For remittance-receiving countries, the moderating effect of FTRI on the relationship between remittance received and receiving cost is similarly non-significant ($p = 0.114$). However, the interaction between FTRI and the AML Index is highly significant ($p = 0.0002$), demonstrating that, in these countries, a higher AML Index paired with high technological readiness increases remittance costs. Specifically, a unit increase in FTRI and AML Index raises costs by 23.26 and 1.79 units, respectively, in remittance-sending countries, while in receiving countries, the same unit increases are associated with cost reductions of 19.28 and 0.94 units, respectively. These findings suggest that while enhanced technological capacity can mitigate some cost burdens in sending countries, stricter AML measures in receiving countries may counteract the benefits of technology. The results are based on the robustness check using the fixed effects model. This addresses our research question. If the financial inclusion rate is lower, the remitter may not use formal financial systems, bypassing AML checks entirely. Remittance costs for these informal flows are opaque.

For the receiving countries, the statistical results align with the theoretical understanding that the higher the remittance flows, the lower the remittance cost, which aligns with the economies of scale theory. Higher technological adoption implies higher remittance flows due to deeper penetration and ease of processing. A higher AML Index implies stringent regulations leading to higher costs. All of these relationships are stronger and significant.

Our findings on AML are supported by existing studies like Avgouleas (2015), Esoimeme (2020) and contradict the findings of Kpodar & Imam (2022), who didn't find the role of transparency (a component within the AML index) in remittance costs. According to SWIFT (2023) and Habib et al. (2022), to

reduce remittance costs, technologies like blockchain with CBDC alone can not be the vehicle to ride on, which aligns with the results of this study and contradicts (Christodoulou et al., 2024).

The recommendation for the managers of the remittance service providers in receiving countries is to balance adopting frontier technologies with streamlined AML compliance processes. The recommendation for policymakers is that nations should promote technological innovation to reduce IT infrastructure expenses and streamline compliance processes—such as sanctions screening, KYC, and identity management—through digitalization. Encouraging fintech participation, which generally faces less stringent AML requirements, can further help shift remittance flows into formal channels. Improving compliance with global AML standards can enhance a country's AML Index, attract foreign participation, and ultimately reduce transfer costs through economies of scale. Policies to promote interbank cooperation for the development of interoperable payment systems by adopting ISO20022 Standards at local central banks and participating banks or by using the Internet of Things-IoTs (Lin et al., 2024) or Machine Learning (Mbiva & Correa, 2024) and laying out regulations to avoid redundancy in AML screening within a country or across countries can keep the processes lean and, hence, faster and cheaper (Guo & Dan, 2023). These findings could be generalized and extended for all cross-border transactions other than remittances.

Conclusion

The findings imply that policymakers can not consider increasing remittance volume or improving index scores in isolation. Stricter AML regulations reduce remittance costs when paired with strong technological readiness to reduce inefficiencies in the compliance process, but in receiving countries, they may increase costs by adding compliance burdens despite tech capacity.

This study contributes to the understanding of how anti-money laundering measures and technological readiness interact to influence remittance flows and costs in both sending and receiving countries. The study confirms that an increase in remittance flows leads to a reduction in remittance costs, particularly in countries with advanced digital infrastructures.

Policymakers should foster the adoption of CBDCs and AI-based compliance systems. Additionally, offering tax benefits and interbank cooperation for interoperable payment systems could help achieve the SDG and G20 targets. Countries to improve the AML Index by adhering to global compliance standards. In emerging countries, policymakers to strive to maintain exchange rates and inflation that attracts inward remittances. The key policy challenge is to strike a balance between technological innovation and effective regulatory oversight (Avgouleas, 2015; Ardic et al., 2022; Antwi et al., 2023).

This study's findings are limited by the presence of multicollinearity, particularly between AML and its interaction with FTRI. To address it, future research should explore alternate modeling, such as the ANN—Artificial Neural Network (McNellis, 2005). Our study considers the cost aspect of efficiency; future researchers can study the transparency of fees, exchange rates, and speed. Additionally, deeper investigations into specific AML policies and how they interact with technology in remittance-receiving countries would provide further insights into optimizing cost structures in the remittance market. Future researchers may reduce the weightage of the 'public transparency and accountability' component from the AML index to nullify its effect.

In the study of bilateral country-wide flows, cross-equation error dependencies may occur. Hence, the system of equations, an alternate methodology, can be employed to further validate cross-equation error dependencies. Systems theory (Eustachio et al., 2019) also provides a holistic approach; it can be tested in future research. The future scope of studies is to consider global indicators of other dimensions from the PESTLE framework—Political, Economic, Social, Technology (with indexes other than FTRI), Legal (with indexes other than AML), and Environment as moderating variables.

Data availability

All data generated or analyzed during this study are included in this published article. The data sources for primary data are cited. Consolidated data from multiple sources is made available in a data repository (OpenICPSR) at this link - https://www.openicpsr.org/openicpsr/project/226684/version/V1/view

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Author contributions

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