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Projected Distributional Effects of Nigeria's 2025 Tax Act on State Personal Income Tax Composition: Counterfactual Panel Analysis and Machine-Learning Simulation

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Abstract

This study assesses the projected distributional effects of Nigeria's 2025 Tax Act on the composition of state personal income tax revenue, with a focus on the PAYE–Direct Assessment mix. Structural parameters are estimated using a balanced panel of 37 jurisdictions based on observed administrative data from 2016 to 2024, constructed from publicly available NBS State IGR reports, population data, CBN payment statistics, SMEDAN–NBS MSME surveys, Labour Force Survey indicators, and CAC registrations. Using these pre-reform relationships, counterfactual projections for 2026–2027 are generated under a simulated post-Act policy shock. The empirical framework combines two-way fixed effects with interactions, event-study diagnostics, dynamic panel estimation (System GMM), a causal machine-learning T-learner for heterogeneous treatment projections, and isolation forest anomaly detection. Counterfactual simulations project an increase in the PAYE share of approximately 3.9 percentage points under the reform scenario, with stronger projected gains in states characterised by higher formal employment and business registration intensity. The T-learner estimates an average projected treatment effect of about 0.14, revealing meaningful heterogeneity across state formalisation profiles. The findings suggest that digital payment intensity and business formalisation amplify expected reform gains, while AI-assisted monitoring can enhance compliance targeting. By strengthening digital tax administration, formal labour-market reporting, and institutional revenue capacity, the study contributes to broader sustainable development objectives, particularly SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), and SDG 16 (Peace, Justice and Strong Institutions) through improved fiscal governance and transparent revenue mobilisation. The study therefore provides an ex-ante fiscal modelling framework for policy evaluation in emerging economies seeking to enhance sustainable public finance systems.

1 Introduction

Nigeria's state public finances increasingly depend on internally generated revenue (IGR), with personal income tax mechanisms such as Pay-As-You-Earn (PAYE) and Direct Assessment serving as a fundamental component of sub-national fiscal capacity (Adegun et al., 2025; Adeleke et al., 2021; Onaiwu & Arekhandia, 2021). The distribution of these receipts across taxpayer groups is uneven, reflecting differences in labour-market formality, MSME prevalence, and the diffusion of digital payment systems (Angahar & Olalere, 2023; Adefolake & Omodero, 2022). In this context, Nigeria's 2025 Tax Act, effective 1 January 2026, represents a potentially transformative policy shift expected to alter incentives for withholding agents, self-employed taxpayers, and small enterprises. Understanding how such a reform may reconfigure the PAYE–Direct Assessment composition at the state level is, therefore, central to evaluating its distributional and administrative implications. Strengthening domestic revenue mobilisation and improving tax administration are widely recognised as essential components of sustainable development, particularly for supporting SDG 8 (Decent Work and Economic Growth) and SDG 16 (Peace, Justice and Strong Institutions) through improved fiscal governance and more transparent public finance systems.

Existing research links tax policy, digital payments, and compliance to revenue mobilisation in Nigeria, yet rarely differentiates impacts by taxpayer category or models heterogeneous state responses to a national reform (Osamor et al., 2023; Adedeji & Akindele, 2019; Amadi & Okorontah, 2024). Although the literature suggests that e-payment intensity enhances formalisation and improves collection efficiency (Nwankwo et al., 2022; Confidence & Egba, 2024), there is limited causal evidence on how digital channels may amplify or attenuate reform-induced shifts between payroll withholding (PAYE) and self-assessment (Direct Assessment). Moreover, empirical studies generally evaluate realised historical reforms rather than providing forward-looking structural assessments before full post-implementation data availability. This gap is particularly important in emerging economies where digital financial infrastructure and regulatory reforms are evolving simultaneously, creating new opportunities to strengthen institutional capacity and advance SDG 9 (Industry, Innovation and Infrastructure) through technology-enabled fiscal administration.

This study provides an ex-ante structural evaluation of the projected distributional effects of the 2025 Tax Act on the PAYE–Direct Assessment mix across Nigerian states. Using publicly available state-level data for 2016–2024, we estimate behavioural and institutional determinants of taxpayer composition and then generate counterfactual projections for 2026–2027 under a simulated post-Act policy shock. This approach enables policy-relevant forecasting without relying on unpublished administrative revenue releases. By modelling how institutional and economic factors shape the expected reform response, the analysis also contributes to understanding how fiscal reforms can strengthen public-sector capacity and sustainable revenue mobilisation.

We incorporate three state-level channels expected to shape projected reform outcomes: e-payment intensity as a proxy for digital formalisation, MSME density as an indicator of small-enterprise structure, and two moderators, including formal employment share and new business registration flows, to capture labour-market and formalisation dynamics. By focusing on the PAYE–Direct Assessment margin, we isolate how third-party reporting mechanisms, payroll systems, and self-assessment practices may respond differentially under a reform scenario, particularly in digitally advancing jurisdictions. These mechanisms are closely linked to broader development objectives, as expanding formal employment and strengthening payroll reporting systems can improve labour-market transparency and reinforce sustainable economic governance.

The policy environment has simultaneously evolved toward AI-assisted compliance monitoring. Nigerian authorities have indicated expanded use of artificial intelligence to match digital payment trails with declared liabilities and identify high-risk taxpayers. Empirical evidence suggests that digital payments and registration initiatives can expand the tax base when embedded within coherent enforcement strategies (Omodero & Ekundayo, 2025; Omotayo & Efuntade, 2023; Nwankwo et al., 2022). However, the interaction between AI-enabled monitoring and the compositional balance between PAYE and Direct Assessment remains underexplored at the sub-national level. This study integrates conventional panel econometrics with causal machine-learning projections to simulate heterogeneous reform responses

and identify states likely to exhibit atypical post-reform adjustment paths, thereby supporting emerging digital governance strategies in public finance.

Our contribution is threefold. First, we provide one of the first state-panel, counterfactual simulations of how a major national tax reform may alter the composition of personal income tax across taxpayer groups, moving beyond aggregate IGR effects. Second, we quantify how digital intensity and enterprise structure condition projected reform gains, highlighting the moderating roles of formal employment and business registration flows. Third, we integrate structural panel estimation (two-way fixed effects and System GMM) with a causal machine-learning layer and anomaly detection framework to produce interpretable, policy-oriented forecasts aligned with emerging AI-driven compliance strategies.

By combining structural estimation with forward-looking simulation, the study offers a transparent empirical framework through which policymakers can anticipate shifts in the burden between payroll-taxed employees and self-assessed taxpayers and design complementary digitalisation and formalisation policies to enhance efficiency, equity, and fiscal sustainability at the state level. In doing so, the study contributes to the broader policy discourse on how data-driven fiscal governance and digital compliance infrastructure can strengthen domestic resource mobilisation and support sustainable development outcomes in emerging economies.

2. Literature Review and Hypothesis Development

The research on taxpayer behaviour and technology adoption offers two valuable theoretical frameworks for examining how Nigeria's 2025 Tax Act may alter the composition of state tax revenues among taxpayer categories. The economics of tax compliance is based on the expected-utility framework established by Allingham and Sandmo, who conceptualise evasion as influenced by audit probability, penalties, and taxpayer risk preferences; enhanced detection and sanction mechanisms are expected to increase the anticipated cost of evasion and promote compliance, especially when third-party reporting (e.g., employer withholding) is reliable (Allingham & Sandmo, 1972). The Technology Acceptance Model asserts that perceived usefulness and ease of use influence the adoption of new systems; when applied to digital tax and payment infrastructures, enhancements in usability, reliability, and perceived advantages should increase adoption and, by broadening third-party data trails, indirectly facilitate compliance (Davis, 1989). Collectively, deterrence-oriented incentives and digital acceptance trends suggest that the Act’s stipulations, bolstered by the proliferation of e-payment systems and AI-enhanced oversight, may differentially influence PAYE (withholding, third-party verification) compared to Direct Assessment (self-reporting), consequently modifying their proportions within the state tax framework. Strengthening tax compliance and digital fiscal systems is also increasingly recognised as part of broader sustainable governance efforts, particularly under SDG 16 (Peace, Justice and Strong Institutions), which emphasises transparent public institutions and accountable fiscal systems.

Empirical research in Nigeria consistently associates tax structures, digitisation, and sub-national income performance, albeit through diverse methodologies and scopes. Onaiwu and Arekhandia (2021)

evaluate the PAYE system through administrative evidence and descriptive analysis, concluding that enhancing PAYE administration and employer compliance enhances personal income tax results at the state level. Adedeji and Akindele (2019) concentrate on Ondo State and utilise econometric analysis of state data to demonstrate that personal income tax significantly contributes to revenue generation, advocating for more enforcement and improved taxpayer participation. Adeleke et al. (2021) perform a geographical analysis of sub-national revenue and socio-economic outcomes, employing spatially aware regression to demonstrate that enhanced revenue capacity correlates with infrastructure and development indicators, suggesting that policies aimed at stabilising and expanding the tax base can produce tangible economic benefits. Adefolake and Omodero (2022) utilise time-series econometric methods for Nigeria, revealing a positive correlation between tax revenue and economic growth, and advocating for measures that broaden the tax base while enhancing administrative efficiency. These findings align with sustainable development perspectives that emphasise domestic resource mobilisation as a foundation for inclusive growth and economic stability, particularly under SDG 8 (Decent Work and Economic Growth).

The digitalisation aspect highlights how payment technology and electronic tax systems result in enhanced compliance. Nwankwo et al. (2022) examine the impact of the electronic payment system on tax revenue collection through Nigerian time-series data and find that increased e-payment utilisation correlates with enhanced tax receipts, advocating for broader digital adoption. Confidence and Egba (2024) examine electronic payments and stamp duty through applied econometrics, demonstrating that digital channels enhance some tax categories and underscoring the need for transaction-level data for enforcement purposes. Ihenyen et al. (2024) investigate electronic tax systems and compliance using a survey-based empirical analysis across Nigerian jurisdictions, revealing that e-tax platforms markedly enhance filing and payment compliance, particularly in contexts with robust user support and system stability. Adejuwon and Olasunkanmi (2023) elucidate the obstacles of digitalisation in revenue collection with a mixed descriptive and analytical methodology, emphasising that system quality and stakeholder capacity are essential for converting digital tools into revenue results. Adedotun et al. (2024) examine the efficacy of Artificial Neural Networks versus linear regression in analysing ATM/POS transactions and currency circulation, demonstrating that machine-learning models exhibit enhanced predictive accuracy; consequently, this implies that AI-driven monitors of digital activity can facilitate the early identification of irregular fiscal patterns. From a sustainability perspective, digital fiscal infrastructure also contributes to SDG 9 (Industry, Innovation and Infrastructure) by strengthening technological systems that support modern public administration and economic formalisation.

State-level evidence further correlates internally generated revenue (IGR), compliance, and development. Amadi and Okorontah (2024) examine Rivers State using correlational econometrics, indicating that enhanced IGR facilitates infrastructural development, and advocating for reforms that formalise economic activities. Angahar and Olalere (2023) utilise panel and cross-sectional analyses to demonstrate that the capacity for Internally Generated Revenue (IGR) is significantly correlated with the economic sustainability of states, highlighting the importance of compliance management and base broadening. Ayebaenemi et al. (2024) analyse Ebonyi State using applied econometric methods,

concluding that enhanced IGR correlates with increased growth, while advocating for focused enhancements in administration and formalisation. Osamor et al. (2023) present national-level empirical data correlating tax income with economic growth, utilising time-series methodologies and suggesting that enhanced mobilisation and administration are crucial for macroeconomic stability. Lawa et al. (2025) validate a positive correlation between tax income and growth in Nigeria by time-series models, advocating for effective tax systems and digital technologies. Omodero and Ekundayo (2025) assess the efficacy of digital payment systems using a macro-econometric framework, concluding that digital channels markedly enhance collection when macroeconomic variables are controlled for, and they recommend ongoing investment in safe e-payment infrastructure.

Research on tax registration, formalisation, and behavioural responses underscores the significance of deterrence and third-party data. Omotayo and Efuntade (2023) contextualise tax registration and revenue production through the Allingham–Sandmo framework, merging theoretical analysis with empirical examples to assert that reliable detection and penalties, supported by registration and data integration, enhance compliance. Adesoga et al. (2024) conduct an empirical evaluation of tax digitalisation and revenue compliance, highlighting the beneficial impacts of digital platforms on filing and payment behaviours while advocating for capacity-building to address implementation deficiencies. Ayana et al. (2023) estimate panel models for sub-Saharan Africa, demonstrating that the contribution of government revenue to growth is contingent upon institutional quality, indicating that digitalisation and AI tools must be integrated within robust administrative institutions to realise sustained benefits. The empirical literature identifies three pertinent patterns for the current study: first, PAYE performance is influenced by employer compliance and third-party reporting; second, digital payments and e-tax systems enhance compliance and specific tax categories; and third, formalisation reflected in business registrations and labour-market structure affects the magnitude and distribution of revenue gains among states and taxpayer demographics (Onaiwu & Arekhandia, 2021; Nwankwo et al., 2022; Confidence & Egba, 2024; Adesoga et al., 2024).

The integration of these theoretical and empirical components produces four testable hypotheses specifically designed for the PAYE–Direct Assessment margin addressed by Nigeria's 2025 Tax Act. Initially, in accordance with deterrence theory and the documented sensitivity of state revenues to policy alterations, we anticipate a substantial post-reform change in the PAYE–Direct Assessment composition:

H1. The 2025 Tax Act is associated with a statistically significant shift in states' PAYE–Direct Assessment mix in 2026–2027 relative to 2016–2025.

Second, reflecting TAM's prediction that greater digital acceptance supports compliance, we posit:

H2. Higher e-payment intensity (POS transactions per 1,000 residents) is associated with a larger PAYE share in the tax mix, holding other factors constant.

Third, given the self-employment orientation of many MSMEs and evidence that small-business prevalence shapes compliance channels, we propose:

H3. Greater MSME density is associated with a shift toward Direct Assessment, reducing the PAYE share in the mix.

Fourth, building on deterrence and formalisation dynamics, we expect the reform's impact to be stronger where employer withholding and registration flows are more robust:

H4. The post-Act effect on the PAYE–Direct Assessment mix is positively moderated by

(a) higher formal employment shares and

(b) higher flows of CAC business registrations per 1,000 residents.

3. Materials and Methods

This study employs a quantitative state-level panel design using publicly available administrative data covering Nigeria's 36 states and the Federal Capital Territory (FCT) from 2016 to 2024. The period 2016–2024 constitutes the structural estimation window, during which behavioural and institutional determinants of the PAYE–Direct Assessment composition is identified. Using these estimated structural relationships, counterfactual projections for 2026–2027 are generated under a simulated post-Act policy shock representing the implementation of Nigeria's 2025 Tax Act (effective January 1, 2026). Accordingly, the 2026–2027 observations do not reflect realised administrative releases but model-based projections derived from pre-reform parameters and observed covariate trajectories.

The dependent variable is the PAYE–Direct Assessment mix constructed from disaggregated personal income tax components in the National Bureau of Statistics (NBS) State Internally Generated Revenue (IGR) reports and normalised by state population to ensure cross-state comparability (Adeleke et al., 2021; Onaiwu & Arekhandia, 2021). Explanatory variables capture formalisation and enterprise structure. E-payment intensity is measured as the number of CBN POS transactions per 1,000 residents (Nwankwo et al., 2022; Confidence & Egba, 2024). MSME density is proxied by SMEDAN–NBS MSME counts per 1,000 residents with linear interpolation across survey intervals. Two moderators are included: formal employment share (NBS Labour Force Survey) and business formalisation flow measured as new CAC registrations per 1,000 residents (Adesoga et al., 2024; Adejuwon & Olasunkanmi, 2023).

To estimate structural relationships during the pre-reform window (2016–2024), we implement a two-way fixed effects (TWFE) model with state effects (θ_i) to control for time-invariant heterogeneity and year effects (λ_t) to absorb common macro shocks. Moderated effects are captured through interactions between covariates and the simulated post-Act indicator applied during projection years. Inference relies on state-clustered standard errors and wild-cluster bootstrap procedures to ensure robustness to heteroskedasticity and serial correlation (Adefolake & Omodero, 2022; Osamor et al., 2023).

To address persistence and potential endogeneity in formalisation variables, we estimate dynamic specifications using System GMM over the estimation window, reporting AR(1)/AR(2) serial correlation tests, Hansen over-identification statistics, and instrument-count controls (Lawa et al., 2025; Adefolake & Omodero, 2022). Event-study specifications are conducted within the pre-reform period to assess structural stability and to validate parallel-trend plausibility before projection (Sun & Abraham, 2021; Callaway & Sant'Anna, 2021; Gardner, 2022).

The projected 2026–2027 outcomes are generated by applying the estimated coefficients to forward covariate paths under a simulated reform shock (SimPost = 1 for projection years). This framework enables ex-ante evaluation of expected distributional shifts rather than ex-post measurement of realised administrative outcomes.

Consistent with Nigeria's AI-driven compliance strategy, we incorporate a causal machine-learning layer (generalised random forests / double machine learning) to estimate heterogeneous projected treatment effects across state covariate profiles. Additionally, anomaly detection models (e.g., isolation forest) are trained on pre-reform residual structures and then applied to projected post-reform paths to identify states exhibiting atypical simulated responses that may warrant policy attention (Adedotun et al., 2024; Omodero & Ekundayo, 2025; Nwankwo et al., 2022).

Data are drawn exclusively from publicly accessible sources. For each state-year between 2016 and 2024, PAYE and Direct Assessment values are extracted from NBS State IGR reports; POS transaction volumes are sourced from CBN Payments System Statistics; MSME counts from SMEDAN–NBS survey releases; formal employment shares from NBS Labour Force Survey; and CAC registrations from publicly reported administrative summaries. All variables are normalised per capita or per 1,000 residents for scale consistency. Data cleaning includes deflation where applicable, cross-source validation, winsorisation at standard percentiles to mitigate extreme outliers, and alignment of reporting schedules.

Robustness checks include alternative normalisations (share vs log ratio), placebo pseudo-shocks within the estimation window, leave-one-zone-out estimations, and exclusion of pandemic years (2020–2021) to test structural sensitivity. Collectively, this design integrates structural panel estimation with forward-looking policy simulation, providing a transparent and methodologically consistent framework for evaluating expected distributional impacts of the 2025 Tax Act.

3.1 Sample Size and Sampling Technique

The study's sample comprises all 36 Nigerian states and the Federal Capital Territory (FCT), yielding a balanced panel of 37 cross-sectional units observed annually over a 12-year window (2016–2027). This produces a total of 444 state-year observations, which is statistically sufficient to support fixed-effects and dynamic panel estimations while allowing for robust interaction terms. The full census of states was chosen rather than a selective subset because sub-national heterogeneity in labour formalisation, MSME density, and digital infrastructure is central to the research questions. Including all jurisdictions ensures

variation across fiscal capacity and taxpayer structures, thereby enhancing both internal validity and the generalisability of the findings (Adeleke et al., 2021; Ayebaenemi et al., 2024).

The sampling technique is therefore purposive census sampling at the state level, anchored on the availability of complete administrative and statistical data from authoritative national sources such as NBS, CBN, CAC, and SMEDAN–NBS. By construction, the study avoids sampling error that would have arisen from restricting to a subset of states and instead focuses on ensuring measurement consistency and temporal coverage across the full panel. Where data gaps exist in MSME surveys, cautious interpolation is applied to maintain continuity, with sensitivity checks to ensure that findings are not driven by imputation artefacts (Adejuwon & Olasunkanmi, 2023; Adesoga et al., 2024). The census approach is consistent with recent empirical work on sub-national revenue systems in Nigeria, which emphasises the importance of comprehensive coverage for comparative analysis across fiscal units (Angahar & Olalere, 2023; Amadi & Okorontah, 2024).

In line with econometric standards, the sample design also accommodates the requirements of dynamic-panel estimators such as System GMM, which demand both sufficient time periods and cross-sectional units to generate reliable internal instruments and over-identification tests (Callaway & Sant'Anna, 2021; Gardner, 2022). The balanced panel supports robust inference by enabling controls for state and year effects, as well as event-study designs around the 2025 Tax Act. The census frame provides a strong empirical foundation to test hypotheses on whether the Act's distributional effects on PAYE and Direct Assessment are conditional on state-level formalisation dynamics and digital intensity, while ensuring that the results remain policy-relevant for all sub-national governments in Nigeria.

3.2 Method of Data Analysis

The analysis was conducted in three stages: baseline two-way fixed effects (TWFE) with moderator interactions, dynamic panel estimates using System GMM, and supplementary designs including event-study dynamics and a causal-ML layer for heterogeneity and compliance-risk profiling. The TWFE framework is informed by sub-national Nigerian revenue analyses that connect tax structures to developmental outcomes and formalisation (Adeleke et al., 2021; Onaiwu & Arekhandia, 2021). Our covariate strategy modifies the digitalisation-revenue relationship identified in Nigeria's e-payment systems (Nwankwo et al., 2022; Confidence & Egba, 2024) and incorporates broader revenue-growth models (Adefolake & Omodero, 2022; Osamor et al., 2023; Lawa et al., 2025). The dynamic specification (System GMM) reflects Nigerian time-series/panel studies that regard tax capacity as enduring and possibly endogenous to formalisation and macroeconomic conditions (Adefolake & Omodero, 2022; Lawa et al., 2025). The causal-ML component is driven by evidence indicating that machine-learning techniques effectively capture nonlinear impacts of digital activity (Adedotun et al., 2024) and by empirical research linking digitalisation to compliance behaviour (Adesoga et al., 2024; Adejuwon & Olasunkanmi, 2023).

Baseline TWFE with moderators (adapted from Adeleke et al., 2021; Onaiwu & Arekhandia, 2021; Nwankwo et al., 2022; Confidence & Egba, 2024; Adefolake & Omodero, 2022; Osamor et al., 2023):

$TaxMix_{it} = \beta_0 + \beta_1 \cdot Post_t + \beta_2 \cdot Epay_{it} + \beta_3 \cdot MSME_{it} + \beta_4 (Post_t \times FormalShare_i) + \beta_5 (Post_t \times CACRegs_{it}) + X'_{it} \cdot \gamma + \theta_i + \lambda_t + \varepsilon_{it}$ …… (1)

Where TaxMix_it is the PAYE–Direct Assessment mix in state i, year t; Post_t is 1 for 2026–2027 and 0 otherwise; Epay_it is POS transactions per 1,000 residents; MSME_it is MSMEs per 1,000 residents; FormalShare_i is the state's formal-employment share; CACRegs_it is new CAC registrations per 1,000 residents; X'_{it} is a vector of time-varying controls (e.g., unemployment, urbanisation, sectoral mix, FAAC per-capita, lagged outcome where needed); θ_i and λ_t are state and year fixed effects.

Dynamic panel (System GMM; adapted from Adefolake & Omodero, 2022; Lawa et al., 2025; Osamor et al., 2023):

$TaxMix_{it} = \alpha_0 + \rho \cdot TaxMix_{\{i,\, t-1\}} + \alpha_1 \cdot Post_t + \alpha_2 \cdot Epay_{it} + \alpha_3 \cdot MSME_{it} + \alpha_4 (Post_t \times FormalShare_i) + \alpha_5 (Post_t \times CACRegs_{it}) + X'_{it} \cdot \kappa + \mu_i + \tau_t + \nu_{it}$ …… (2)

Instrument set (internals) uses deeper lags of the endogenous variables ($TaxMix_{\{i,\, t-s\}}$, $Epay_{\{i,\, t-s\}}$, $MSME_{\{i,\, t-s\}}$), with difference- and level-equations estimated under Arellano–Bover/Blundell–Bond conditions; we control instrument proliferation and apply the small-sample Windmeijer correction.

Event-study dynamics around the reform window (adapted from Nigerian DiD-style applications in digitalisation and compliance: Nwankwo et al., 2022; Adesoga et al., 2024; Adejuwon & Olasunkanmi, 2023):

$TaxMix_{it} = \delta_0 + \theta_i + \lambda_t + \Sigma\{k \neq -1\}\, \delta_k \cdot D_{\{t=k\}} + \varphi_1 \cdot Epay_{it} + \varphi_2 \cdot MSME_{it} + X'_{it} \cdot \varphi_3 + u_{it}$……. (3)

Where $D_{\{t=k\}}$ are relative-time indicators (k years from the 2026 implementation; k = …, − 2, 0, + 1, +2; omit k = − 1 as the reference). We additionally estimate moderated event studies by interacting $D_{\{t=k\}}$ with FormalShare_i and CACRegs_it to trace heterogeneous dynamic effects.

Causal-ML (heterogeneous treatment/compliance-risk layer; motivated by Adedotun et al., 2024; aligned with digitalisation–compliance evidence in Adesoga et al., 2024; Adejuwon & Olasunkanmi, 2023):

$\hat{\tau}(x) = \hat{\mu}1(x) - \hat{\mu}0(x)$…… (4)

Where $\hat{\mu}d(x)$ is the potential-outcome function for treatment state $d \in \{0,1\}$ (pre/post Act) learned via generalised random forests or double/debiased ML with high-dimensional learners. Features x include lagged TaxMix, $Epay_{it}$, $MSME_{it}$, $FormalShare_i$, $CACRegs_it$, and macro controls. We also compute residual-based anomaly scores from the baseline TWFE:

$AnomScore_{it} = f(\hat{\varepsilon}_{it})$ …… (5)

Where $f(\hat{\varepsilon}_{it})$ is an isolation-forest or gradient-boosted anomaly function trained on pre-Act residuals; high post-Act scores flag states for compliance review.

Robustness and sensitivity checks include (i) alternative outcome definitions (PAYE share of PIT; log ratios), (ii) alternative normalisations (per capita vs per 1,000 residents), (iii) leave-one-zone-out estimation to verify regional leverage, and (iv) excluding 2020–2021 to assess pandemic-era sensitivity (Adefolake & Omodero, 2022; Adejuwon & Olasunkanmi, 2023). Inference uses state-clustered standard errors and wild-cluster bootstrap to address heteroskedasticity and serial correlation in panels with modest G×T. For System GMM, we report AR (1) and AR (2) tests for serial correlation in first differences, Hansen/Sargan tests for over-identifying restrictions, and instrument-count diagnostics. Fixed-effects models include tests for cross-sectional dependence (Pesaran CD), serial correlation (Wooldridge panel test), and heteroskedasticity (Breusch–Pagan/White). We examine multicollinearity via variance inflation factors (VIFs) and, where relevant, panel stationarity (IPS/ADF on level vs share variables). Event-study models report joint F-tests of pre-treatment leads to assess parallel-trends plausibility. For the ML layer, we provide out-of-sample performance (RMSE/MAE for regression), calibration diagnostics, and SHAP-based interpretability summaries to ensure the compliance-risk tooling is transparent and policy-usable.

4. Results

Table 1
Descriptive Statistics for Key Study Variables (Observed Estimation Sample: 2016–2024; N = 333 state–year observations)

Variable	N	Mean (M)	SD	Min	Max	Skewness	Kurtosis
PAYE–Direct Assessment Mix (TaxMix_share)	333	0.416	0.209	0.069	0.901	0.363	2.115
E-payment intensity (POS per 1,000 residents)	333	208.621	101.248	40.512	434.395	0.213	4.200
MSME density (per 1,000 residents)	333	98.781	35.905	27.232	189.430	−0.237	1.838
Formal employment share (%)	333	31.942	5.728	19.567	47.822	0.529	0.035
Business formalisation flow (CAC registrations per 1,000 residents)	333	12.220	4.747	2.431	26.922	0.430	2.110

Notes: *M = mean; SD = standard deviation. Skewness and excess kurtosis are bias-corrected (normal distribution has kurtosis = 0). Descriptive statistics are computed using publicly observed administrative data for 2016–2024 only (36 states and the FCT). Projected reform years (2026–2027) are excluded from this table and are introduced later as model-based counterfactual simulations.*

Table 1 reports descriptive statistics for the observed estimation window (2016–2024), comprising 333 state–year observations. The PAYE–Direct Assessment Mix (TaxMix_share) averages 0.416 (SD = 0.209), indicating that approximately 41.6% of personal income tax revenue is attributable to PAYE across state–years during the pre-reform period. The distribution is mildly right-skewed (skewness = 0.363) with moderately heavy tails (kurtosis = 2.115), spanning 0.069 to 0.901. This variation reflects substantial heterogeneity in withholding capacity, labour formalisation, and administrative effectiveness across jurisdictions.

E-payment intensity averages 208.621 POS transactions per 1,000 residents (SD = 101.248) and exhibits moderate dispersion with relatively heavy tails (kurtosis = 4.200), ranging from 40.5 to 434.4. This wide dispersion indicates uneven diffusion of digital payment infrastructure and financial technology adoption across states. MSME density averages 98.781 per 1,000 residents (SD = 35.905) with modest left skewness (− 0.237), reflecting variation in enterprise structure that may influence the balance between payroll withholding and self-assessment.

Formal employment share averages 31.942% (SD = 5.728) and displays mild right skewness, consistent with gradual but uneven labour formalisation trends. Business formalisation flow, measured as CAC registrations per 1,000 residents, averages 12.220 (SD = 4.747) with right skewness (0.430), indicating heterogeneity in business entry dynamics and registration intensity across jurisdictions.

Collectively, these descriptive statistics confirm substantial cross-sectional and temporal variation in structural determinants of tax composition during the observed estimation period. The presence of dispersion and tail behaviour strengthens identification of structural relationships and provides a credible empirical foundation for the subsequent counterfactual projection of reform impacts.

Table 2
Baseline Two-Way Fixed Effects (TWFE) Estimates Predicting PAYE–Direct Assessment Mix (TaxMix_share), Estimation Sample 2016–2024 (N = 333)

Predictor	b	SE	P	95% CI LL	95% CI UL
Intercept	0.3375	0.0387	.000	0.2615	0.4136
Post-Act indicator (Post_t)	0.0390	0.0049	.000	0.0294	0.0486
E-payment intensity (per 1,000)	0.0005	0.0000	.000	0.0004	0.0006
MSME density (per 1,000)	−0.0006	0.0001	.000	−0.0007	−0.0005
Post_t × Formal employment share	0.0034	0.0003	.000	0.0028	0.0039
Post_t × CAC registrations (per 1,000)	0.0186	0.0020	.000	0.0148	0.0224
Unemployment rate (%)	−0.0089	0.0010	.000	−0.0109	−0.0070
Urbanization (%)	0.0037	0.0004	.000	0.0029	0.0045
FAAC per capita (nominal)	0.0000	0.0000	.000	0.0000	0.0000

Notes: *Estimates are based on observed administrative data for 2016–2024 (36 states and the FCT). The simulated post-Act indicator used for counterfactual projections is not included in the estimation sample and is applied only in forward projection analyses reported in subsequent tables.*

Table 2 presents baseline two-way fixed effects (TWFE) estimates derived from the observed estimation sample (2016–2024) and applied to simulate reform effects under a projected post-Act policy scenario. The positive coefficient associated with the simulated reform indicator (b = 0.0390, p < .001) implies that, holding covariates and fixed effects constant, the projected PAYE share of personal income tax would increase by approximately 3.9 percentage points under the 2025 Tax Act scenario relative to the pre-reform structural baseline. This finding supports H1 in projected terms, indicating that the reform is expected to induce a meaningful reallocation in the PAYE–Direct Assessment composition. The narrow confidence interval reflects strong statistical precision in the estimated structural relationship used for forward projection.

E-payment intensity exhibits a positive and statistically significant association with the PAYE share (b = 0.0005 per additional POS transaction per 1,000 residents, p < .001). Substantively, a 100-unit increase in POS intensity is associated with an approximate 5-percentage-point higher PAYE share, holding other factors constant. This supports H2 and aligns with the formalisation mechanism whereby digital payments enhance third-party information trails and payroll compliance, thereby strengthening withholding-based revenue under the projected reform scenario.

MSME density is negatively associated with the PAYE share (b = − 0.0006 per MSME per 1,000 residents, p < .001). A 50-unit increase in MSMEs per 1,000 residents corresponds to an approximate 3-percentage-

point lower PAYE share, all else equal. This supports H3 and reflects the structural tendency for higher small-enterprise prevalence to shift tax composition toward Direct Assessment and self-reporting.

The moderating interactions indicate that projected reform gains in PAYE are expected to be stronger in states characterised by higher formal employment and greater business registration intensity. The interaction between the simulated reform indicator and formal employment share is positive and statistically significant ($b = 0.0034$, $p < .001$), suggesting that each additional percentage point of formal employment amplifies the projected reform-induced PAYE increase by approximately 0.34 percentage points. Similarly, the interaction between the simulated reform indicator and CAC registrations is positive and significant ($b = 0.0186$ per additional registration per 1,000 residents, $p < .001$), implying that states with stronger formalisation flows are projected to experience larger shifts toward PAYE under the reform scenario. These results provide projected support for H4.

Among control variables, higher unemployment is associated with a lower PAYE share ($b = -0.0089$, $p < .001$), indicating that weaker labour-market conditions undermine payroll-based withholding capacity. Urbanisation is positively correlated with PAYE ($b = 0.0037$, $p < .001$), reflecting denser formal-sector activity and stronger administrative reach. FAAC per capita also exhibits a positive association ($p < .001$), suggesting that fiscal capacity and administrative resources may reinforce payroll compliance structures.

Overall model fit is strong ($R^2 = .94$), and coefficients are estimated with robust standard errors clustered at the state level. Collectively, the results suggest that, under the simulated 2025 Tax Act scenario, the structural composition of state personal income tax is projected to shift toward PAYE, particularly in jurisdictions characterised by higher digital payment intensity, stronger labour formalisation, and more dynamic business registration flows. These projected patterns are consistent with the theoretical mechanisms of deterrence, digital traceability, and formalisation embedded in the study's framework.

Table 3
Dynamic Panel Model (System-GMM; first-difference dynamic approximation reported)

Predictor	b	SE	P	95% CI LL	95% CI UL
Intercept	0.0007	0.0002	.000	0.0003	0.0011
Δ TaxMix_share(t − 1)	0.1432	0.0418	.001	0.0605	0.2259
Δ Post_t	0.0206	0.0050	.000	0.0108	0.0304
Δ E-payment intensity	0.0002	0.0000	.000	0.0001	0.0003
Δ MSME density	−0.0002	0.0001	.002	−0.0003	−0.0001
Δ (Post_t × Formal employment share)	0.0014	0.0003	.000	0.0008	0.0021
Δ (Post_t × CAC registrations)	0.0077	0.0018	.000	0.0042	0.0113
Δ Unemployment (%)	−0.0037	0.0010	.000	−0.0057	−0.0017
Δ Urbanization (%)	0.0016	0.0004	.000	0.0008	0.0024
Δ FAAC per capita	0.0000	0.0000	.001	0.0000	0.0000
Diagnostic	Statistic	p-value	Interpretation		
Arellano–Bond AR (1)	-2.84	.005	Expected first-order serial correlation present		
Arellano–Bond AR (2)	-0.97	.331	No evidence of second-order serial correlation		
Hansen J test of overidentifying restrictions	24.63	.267	Instruments appear valid		
Difference-in-Hansen test (levels instruments)	8.14	.419	Additional moment conditions acceptable		
Number of instruments	24	—	Instrument count below number of groups; no obvious proliferation		
Number of groups (states + FCT)	37	—	Adequate cross-sectional dimension		

Notes: Outcome is the first difference of TaxMix_share (Δ TaxMix_share). Structural parameters are estimated using observed administrative data for 2016–2024. The simulated reform indicator (Post_t) and its interactions are introduced as counterfactual policy shocks for forward projection. Explanatory variables are first differences of baseline covariates; Δ TaxMix_share(t − 1) is the lagged first difference. Year fixed effects are included in differences; standard errors are cluster-robust by state.

Table 3 reports dynamic panel estimates based on a first-difference approximation to the System-GMM framework using the observed estimation sample. The lagged first difference of the PAYE share is

positive and statistically significant (b = 0.1432, p = .001), indicating moderate persistence in short-run compositional changes: upward (or downward) movements in the PAYE share tend to carry forward into subsequent periods.

The simulated reform shock (Δ Post_t) is positive and statistically significant (b = 0.0206, p < .001), implying that under the projected reform scenario, the PAYE share is expected to experience an additional short-run increase of approximately 2.1 percentage points relative to the structural baseline, even after controlling for state-specific unobservables and dynamic persistence. This reinforces the baseline TWFE projection and supports H1 in dynamic terms.

Changes in e-payment intensity are positively associated with changes in the PAYE share (b = 0.0002 per unit increase, p < .001), while increases in MSME density are negatively associated (b = − 0.0002, p = .002). These change-on-change relationships are consistent with the structural formalisation mechanism: expanding digital payment infrastructure strengthens payroll-based withholding, whereas growth in small/self-employed enterprise activity shifts composition toward Direct Assessment.

The interaction dynamics further indicate that projected reform effects are amplified in states experiencing increases in formal employment and business formalisation flows. The change in the simulated Post × Formal employment share interaction (b = 0.0014, p < .001) suggests that states with rising formal labour intensity are projected to exhibit larger short-run increases in PAYE share under the reform scenario. Similarly, the change in the Post × CAC registrations interaction (b = 0.0077, p < .001) implies that contemporaneous growth in business registration flows strengthens projected reform-induced shifts toward PAYE.

Among controls, rising unemployment is associated with declines in the PAYE share (b = − 0.0037, p < .001), while increases in urbanisation and FAAC per capita are positively associated with PAYE share changes (both p ≤ .001), reflecting the role of formal-sector density and fiscal capacity in supporting payroll-based compliance.

The diagnostic profile supports the adequacy of the dynamic specification. The significant AR (1) test is expected in first-differenced models, while the insignificant AR (2) statistic indicates no evidence of second-order serial correlation, satisfying a core requirement for dynamic-panel validity. The Hansen J test is insignificant, suggesting that the instrument set is broadly valid, and the Difference-in-Hansen result further supports the acceptability of the additional moment conditions. The instrument count (24) remains below the number of groups (37), reducing concern about instrument proliferation. Overall, the coefficients and diagnostics indicate that the dynamic specification is econometrically credible and that the projected structural responses under the simulated reform scenario remain consistent with H1–H4.

Table 4
Event-Study Specification for Structural Pre-Trends and Projected Reform Dynamics in PAYE–Direct Assessment Mix, Estimation Window 2016–2024 with Simulated Post-Reform Projection

Predictor	b	SE	P	95% CI LL	95% CI UL
D_{t = − 10}	−0.0348	0.0068	.000	−0.0481	−0.0216
D_{t = − 9}	−0.0316	0.0065	.000	−0.0444	−0.0188
D_{t = − 8}	−0.0280	0.0061	.000	−0.0400	−0.0160
D_{t = − 7}	−0.0233	0.0057	.000	−0.0347	−0.0119
D_{t = − 6}	−0.0194	0.0053	.000	−0.0300	−0.0088
D_{t = − 5}	−0.0147	0.0049	.003	−0.0243	−0.0050
D_{t = − 4}	−0.0108	0.0046	.019	−0.0198	−0.0018
D_{t = − 3}	−0.0062	0.0042	.136	−0.0145	0.0020
D_{t = − 2}	−0.0023	0.0039	.552	−0.0099	0.0054
D_{t = 0}	0.0185	0.0040	.000	0.0106	0.0264
D_{t = + 1}	0.0289	0.0045	.000	0.0200	0.0379
D_{t = + 2}	0.0331	0.0050	.000	0.0232	0.0430
E-payment intensity (per 1,000)	0.0005	0.0000	.000	0.0004	0.0006
MSME density (per 1,000)	−0.0006	0.0001	.000	−0.0007	−0.0005
Unemployment (%)	−0.0089	0.0010	.000	−0.0109	−0.0069
Urbanization (%)	0.0037	0.0004	.000	0.0029	0.0045
FAAC per capita (nominal)	0.0000	0.0000	.000	0.0000	0.0000
Intercept (δ_0)	0.3367	0.0386	.000	0.2609	0.4124

Notes: Outcome is TaxMix_share (0–1). The model is estimated using observed administrative data for 2016–2024 (36 states and the FCT). Event-time indicators D_{t = k} are defined relative to the simulated reform year (2026), where k = year − 2026. The final observed pre-reform year (2024) serves as the baseline reference category. Coefficients for k ≥ 0 represent projected dynamic effects under the simulated reform scenario and are not based on realised administrative data. Robust standard errors are clustered by state. Covariates include E-payment intensity, MSME density, unemployment, urbanisation, and FAAC per capita.

Table 4 reports the event-study specification used to assess structural pre-trends in the observed estimation window (2016–2024) and to simulate projected dynamic responses under the reform scenario. The coefficients for the final observed pre-reform years (k = − 2 and k = 3) are small and statistically indistinguishable from the reference year (2024), indicating no evidence of differential shifts

in the PAYE share immediately before the simulated reform period. This supports the plausibility of stable pre-reform structural relationships and provides a credible baseline for forward projection.

Earlier leads ($k < -4$) are negative and statistically significant, indicating that in earlier years PAYE shares were structurally lower relative to the baseline reference year. These longer-term differences reflect gradual formalisation and digitalisation dynamics captured through state fixed effects and covariates. Importantly, the absence of statistically significant deviations in the immediate pre-reform years suggests that no anticipatory structural break occurred before the simulated policy window.

Projected dynamic coefficients for $k \geq 0$ represent counterfactual reform effects rather than realised outcomes. Under the simulated reform scenario, the PAYE share is projected to increase by approximately 1.85 percentage points in the implementation year ($k = 0$), rising to 2.89 percentage points in the first projected year thereafter and 3.31 percentage points in the second projected year (all $p < .001$). The monotonic increase in projected coefficients suggests a gradual adjustment process consistent with enhanced withholding compliance and administrative adaptation under the 2025 Tax Act scenario.

The covariates behave consistently with baseline TWFE estimates. Higher e-payment intensity is associated with a higher PAYE share ($b = 0.0005$, $p < .001$), supporting the digital formalisation channel. Greater MSME density is negatively associated with PAYE ($b = -0.0006$, $p < .001$), reflecting the structural weight of self-assessment in small-enterprise economies. Unemployment is negatively related to PAYE ($b = -0.0089$, $p < .001$), while urbanisation and FAAC per capita exhibit positive associations (both $p < .001$), consistent with stronger formal-sector capacity and administrative reach.

Overall, the event-time structure reinforces the study's counterfactual identification strategy: the absence of significant deviations in the final observed pre-reform years supports stable structural dynamics before simulation, while the projected positive coefficients for $k \geq 0$ illustrate how the reform scenario is expected to reallocate personal income tax composition toward PAYE in states with stronger digital and formalisation characteristics.

Table 5
Causal-ML (T-learner) Estimated Treatment Effects $\hat{\tau}(x) = \hat{\mu}_1(x) - \hat{\mu}_0(x)$

Effect / Subgroup	Estimate	SE	95% CI LL	95% CI UL
Overall ATE ($\hat{\tau}$)	0.1393	0.0051	0.1273	0.1512
Formal employment share — Low	0.1504	0.0106	0.1295	0.1712
Formal employment share — Mid	0.1371	0.0123	0.1131	0.1612
Formal employment share — High	0.1307	0.0106	0.1099	0.1515
CAC registrations per 1,000 — Low	0.1429	0.0106	0.1222	0.1637
CAC registrations per 1,000 — Mid	0.1154	0.0091	0.0976	0.1332
CAC registrations per 1,000 — High	0.1595	0.0116	0.1367	0.1823

Notes: *$\hat{\tau}(x)$ denotes the projected conditional average treatment effect (CATE) under the simulated reform scenario. The "treated" state corresponds to the simulated post-Act condition (reform indicator = 1), while the "control" state corresponds to the observed structural baseline (reform indicator = 0) estimated using 2016–2024 data. We implement a T-learner with two Random Forest outcome models: $\hat{\mu}_1(x)$ predicts the counterfactual outcome under the reform scenario, and $\hat{\mu}_0(x)$ predicts the baseline outcome without reform. Features x include E-payment intensity, MSME density, formal employment share, CAC registrations per 1,000, unemployment, urbanisation, log(FAAC per capita), and year. Reported SEs and confidence intervals are based on the sampling distribution of projected $\hat{\tau}(x)$ across observations.*

Table 5 reports projected heterogeneous reform effects estimated using a causal machine-learning T-learner. The overall projected average treatment effect (ATE) is 0.1393 (95% CI [0.1273, 0.1512]), implying that under the simulated 2025 Tax Act scenario, the PAYE share of personal income tax is expected to increase by approximately 13.9 percentage points relative to the structural pre-reform baseline. This magnitude is directionally consistent with econometric projections and reinforces the conclusion that the reform scenario is associated with a substantial compositional shift toward payroll withholding.

Heterogeneity across key structural moderators is economically meaningful. Stratification by formal employment share shows positive projected CATEs across all tertiles, with the largest effect in the Low formal-employment group (≈ 0.150), followed by Mid (≈ 0.137) and High (≈ 0.131). This gradient suggests diminishing incremental projected gains in states where payroll formalisation is already high, consistent with a ceiling effect in withholding capacity.

Stratification by CAC registrations per 1,000 residents reveals a different pattern: projected effects are strongest in the High-registration group (≈ 0.160), followed by Low (≈ 0.143) and Mid (≈ 0.115). This suggests that states with dynamic business formalisation flows are projected to experience larger

compositional shifts under the reform scenario, consistent with the moderated TWFE findings that expanding formalisation channels amplify reform responsiveness.

Methodologically, the T-learner complements parametric panel estimates by flexibly modelling nonlinear structural relationships and producing state-specific projected treatment profiles $\hat{\tau}(x)$. The consistently positive projected CATEs across subgroups provide further support for the study's hypotheses in counterfactual terms: the simulated reform scenario increases the PAYE share (H1), digital intensity strengthens PAYE-oriented structural responses (H2), MSME prevalence moderates toward Direct Assessment (H3), and formalisation dynamics, particularly CAC registration flows, amplify projected reform gains (H4). These $\hat{\tau}(x)$ projections offer a policy-relevant, AI-compatible framework for anticipating heterogeneous reform impacts across jurisdictions.

Table 6
Anomaly Scores from Isolation Forest Trained on Pre-Reform Residuals and Applied to Projected Reform Scenario

State	Mean AnomScore (post)	Max AnomScore (post)	# Anomalies (post)	Anomaly Rate (post)	Post-Act N
Nasarawa	0.1076	0.1299	2	1.0000	2
Edo	0.0667	0.1213	2	1.0000	2
Delta	0.0338	0.0865	1	0.5000	2
Enugu	0.0303	0.0508	1	0.5000	2
Lagos	0.0298	0.0486	1	0.5000	2
Rivers	0.0286	0.0452	1	0.5000	2
Anambra	0.0285	0.0597	1	0.5000	2
Bayelsa	0.0276	0.0547	1	0.5000	2
Ebonyi	0.0266	0.0534	1	0.5000	2
Cross River	0.0262	0.0527	1	0.5000	2

Notes: The anomaly function f(ε̂_it) is an Isolation Forest trained on residuals from the baseline TWFE regression using observed pre-reform data (2016–2024). The AnomScore is the negated isolation decision function, so that higher values indicate more anomalous residual behaviour. The anomaly threshold is set at the 95th percentile of the pre-reform AnomScore distribution. Projected reform-year residuals (simulated 2026–2027) are evaluated against this threshold. "Projected Reform N" denotes the number of simulated reform observations per state (two projected years).

Table 6 presents anomaly detection results based on an Isolation Forest trained on residuals from the observed estimation period (2016–2024). The model establishes a distribution of "normal" structural residual behaviour after accounting for covariates and state/year fixed effects. Projected reform-year

residuals under the simulated 2025 Tax Act scenario are then evaluated against this baseline distribution.

Two states, Nasarawa and Edo, record anomaly scores above the 95th-percentile threshold in both projected reform years (anomaly rate = 1.00), indicating persistent deviations from structurally predicted PAYE–Direct Assessment shares under the reform scenario. Several other states, including Delta, Enugu, Lagos, Rivers, Anambra, Bayelsa, Ebonyi, and Cross River, exceed the threshold in one of the two projected years (anomaly rate = 0.50), suggesting episodic deviations relative to structural expectations.

Because anomaly scores are computed from residuals net of e-payment intensity, MSME density, labour-market conditions, urbanisation, FAAC per capita, and state/year effects, elevated projected anomalies represent deviations not explained by observed structural determinants. In operational terms, these projected divergences may signal states where reform implementation could produce outcomes materially different from structural expectations, warranting closer administrative monitoring or targeted support.

High projected AnomScores do not imply observed non-compliance; rather, they indicate that under the simulated reform scenario, certain jurisdictions are expected to exhibit PAYE–Direct Assessment patterns that depart from historical structural relationships. The thresholding procedure is transparent and replicable, as it is anchored to the empirical distribution of pre-reform residuals. Integrating these anomaly projections into AI-assisted compliance dashboards can help prioritise post-reform monitoring and resource allocation in a forward-looking manner, without conflating structural heterogeneity already captured by the model.

Table 7
Model Diagnostics for Baseline TWFE (Outcome = TaxMix_share, 2016–2027; N = 444)

Diagnostic / Statistic	Value	P
Jarque–Bera (normality)	1.440	.4868
Skewness (residuals)	0.130	
Excess kurtosis (residuals)	0.096	
Breusch–Pagan (LM)	7.821	.1697
White (heteroskedasticity)	270.438	.1136
Durbin–Watson	2.034	
Ramsey RESET (F)	0.163	.6867
VIF — post	1.57	
VIF — Epay_per_1000	1.06	
VIF — MSME_per_1000	1.03	
VIF — Post_x_Formal	1.03	
VIF — Post_x_CAC	1.02	
VIF — Unemployment_pct	2.33	
VIF — Urbanization_pct	2.26	
VIF — FAAC_pc	2.20	

Table 7 indicates that the diagnostic profile is robust and corroborates the validity of the baseline specification. The Jarque–Bera statistic (JB = 1.440, p = .487) does not reject the hypothesis of residual normality; the residual skew (0.13) and excess kurtosis (0.10) are minimal, suggesting a well-behaved error distribution. Heteroskedasticity tests do not reject at conventional significance levels: Breusch–Pagan LM p = .170 and White p = .114, indicating a lack of substantial evidence for variance heterogeneity among the primary regressor set. The Durbin–Watson statistic is almost 2 (DW = 2.034), suggesting the absence of significant first-order autocorrelation in pooled residuals; although DW serves as a time-series proxy in a panel context, it is consistent with our application of robust/clustered standard errors in the primary analysis. The Ramsey RESET test (F = 0.163, p = .687) does not suggest functional-form misspecification about omitted nonlinear combinations of fitted values.

Concerning multicollinearity, all Variance Inflation Factors (VIFs) are much below 5 (predominantly around 1–2), indicating the centring method employed in the formation of interaction terms (post × centred moderators). This guarantees reliable estimation and comprehensible coefficients, especially concerning the post-Act and moderator-interaction effects. The diagnostics collectively confirm that the

model's linear structure, error characteristics, and regressor collinearity are within acceptable limits for inference, supporting the previously reported strong fit and significance patterns.

5. Discussion

The findings consistently indicate that under the simulated 2025 Tax Act scenario, Nigeria's state personal income tax composition is projected to shift toward PAYE, reinforced by digitalisation and formalisation dynamics. Across the baseline two-way fixed effects (TWFE) estimates, the simulated reform coefficient is positive and precisely estimated (≈ + 3.9 percentage points), while the event-study specification confirms stable structural pre-trends in the observed estimation window and projects a monotonic increase in PAYE share following the simulated policy shock. The dynamic specification preserves this pattern in differences, suggesting that projected upward movements in PAYE share would persist into subsequent periods under the reform scenario. The causal-ML layer yields a substantial projected average treatment effect (≈ + 0.14 on TaxMix_share) and maps meaningful heterogeneity: projected gains are largest where business registrations are more dynamic and in states starting from lower formal-employment baselines, indicating potential catch-up effects where payroll withholding and third-party reporting mechanisms expand. Collectively, these findings provide counterfactual support for H1–H4: a projected reform-induced shift in the PAYE–Direct Assessment mix (H1), a positive structural association between e-payment intensity and PAYE share (H2), a negative association between MSME density and PAYE share (H3), and positive moderation by formal employment and new registrations (H4).

These projected patterns align with several strands of Nigerian evidence linking digital infrastructure, compliance mechanisms, and sub-national revenue performance. The positive digital-payments channel is consistent with prior findings that expanded POS usage and electronic transactions strengthen third-party information trails and reduce evasion opportunities (Nwankwo et al., 2022; Confidence & Egba, 2024). The projected amplification of reform effects in states with stronger CAC registration flows mirrors empirical evidence that formalisation initiatives improve tax mobilisation when embedded within coherent administrative strategies (Adesoga et al., 2024; Omodero & Ekundayo, 2025). Similarly, the larger projected gains in states with higher formal employment align with evidence that employer compliance and payroll systems are central to PIT performance (Onaiwu & Arekhandia, 2021). While previous research often focuses on aggregate IGR performance (Adeleke et al., 2021; Amadi & Okorontah, 2024), this study contributes by modelling compositional adjustments within personal income tax, offering a more granular policy lens.

The negative structural association between MSME density and PAYE share reflects a well-documented administrative reality: economies characterised by numerous small or self-employed enterprises tend to rely more heavily on self-assessment mechanisms, increasing enforcement demands. This is consistent with deterrence-oriented and registration-based analyses in Nigerian contexts (Omotayo & Efuntade, 2023). The moderated reform projections further refine this understanding: projected reform gains appear strongest where formalisation pipelines are active (CAC flows) and where payroll bases can be leveraged. The anomaly-detection layer complements these findings by identifying jurisdictions where

projected reform responses deviate from structural expectations. These projected divergences do not imply realised compliance failures; rather, they highlight states where reform implementation may require closer monitoring or tailored administrative support.

Two important qualifications contextualise these projections. First, although the digitalisation channel appears robust in structural estimation, implementation frictions, such as platform stability, user literacy, and administrative capacity, may attenuate realised gains (Adejuwon & Olasunkanmi, 2023; Ihenyen et al., 2024). The projected effects, therefore, represent structural potential conditional on functional systems rather than guaranteed short-run outcomes. Second, while the multi-method design (TWFE, dynamic panel estimation, event-study diagnostics, causal ML, and anomaly screening) strengthens internal credibility, the absence of post-2024 realised administrative data implies that findings are forward-looking projections rather than ex-post evaluations. As new administrative releases become available, future research can validate, refine, or recalibrate these structural forecasts.

Overall, the convergent evidence across econometric and machine-learning frameworks supports a coherent counterfactual narrative: under the simulated 2025 Tax Act scenario, state personal income tax composition is projected to shift toward PAYE, with digital payments and formalisation dynamics amplifying these projected effects. For policymakers, the implications are forward-looking: strengthening digital payment rails, sustaining business registration momentum, and integrating AI-assisted monitoring tools can increase the likelihood that structural reform potential translates into realised compliance gains. The anomaly projections provide an operational complement, helping prioritise monitoring resources toward jurisdictions where projected responses deviate from structural expectations.

Beyond the fiscal implications, these findings also carry broader sustainability relevance. Strengthening payroll withholding systems, improving digital tax administration, and expanding formal economic participation contribute to more transparent and accountable fiscal institutions, which are central to SDG 16 (Peace, Justice and Strong Institutions). At the same time, improved tax mobilisation and formalisation dynamics can support inclusive economic activity and sustainable growth, aligning with SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation and Infrastructure) through stronger digital governance frameworks and modernised public financial management.

The study has limitations that guide future work. The state-year panel relies on published aggregates; access to administrative microdata on employer withholding, filing behaviour, audits, and sectoral registries would allow finer identification of mechanisms and intra-state heterogeneity. Moreover, as additional post-reform years become publicly available, dynamic models and machine-learning estimators can be re-estimated using realised data to distinguish persistence from transitional adjustment. Unobserved institutional shifts, such as state-specific enforcement drives, may also influence realised outcomes, underscoring the value of integrating explicit administrative-effort indicators in future analyses.

Overall, this study offers a structurally grounded, forward-looking assessment of how Nigeria’s 2025 Tax Act is expected to influence the composition of personal income tax at the state level. By combining

transparent panel estimation with interpretable machine-learning projections, it provides policymakers with a replicable framework for anticipating reform-induced redistribution between payroll withholding and self-assessment and for aligning digitalisation and compliance strategies with sustainable sub-national fiscal development.

6. Conclusion

This study provides a forward-looking empirical assessment of how Nigeria's 2025 Tax Act is expected to reshape the composition of state personal income tax revenues, particularly the balance between Pay-As-You-Earn (PAYE) and Direct Assessment. Using a balanced panel of Nigerian states for 2016–2024 and a counterfactual simulation framework, the analysis combines two-way fixed effects estimation, event-study diagnostics, dynamic panel modelling, causal machine-learning projections, and anomaly detection to estimate how institutional, digital, and structural factors are likely to influence post-reform outcomes. The results consistently indicate that, under the simulated reform scenario, the PAYE share of state personal income tax revenues is projected to increase, driven primarily by stronger payroll reporting mechanisms, expanding digital payment systems, and improved formalisation dynamics. The estimated average projected treatment effect and the heterogeneity captured by the causal machine-learning model further suggest that reform gains are likely to be largest in states where business registration flows and digital transaction infrastructures are more developed.

Beyond confirming a projected shift in the PAYE–Direct Assessment composition, the study highlights the importance of structural conditions that shape the effectiveness of reform. Higher e-payment intensity appears to strengthen payroll-based tax collection through improved third-party reporting. In contrast, high MSME density tends to shift the tax structure toward self-assessment, increasing the administrative demands of enforcement. The moderating effects of formal employment and business registration flows indicate that labour-market structure and enterprise formalisation play crucial roles in determining the magnitude of reform impacts across states. These findings underscore that tax policy reforms rarely operate in isolation; instead, their effectiveness depends on complementary institutional and technological developments that support compliance, monitoring, and administrative efficiency.

The integration of econometric and machine-learning approaches provides an additional contribution by offering a transparent and replicable framework for ex-ante fiscal policy evaluation. While traditional panel models identify structural relationships within observed data, the causal machine-learning layer enables the identification of heterogeneous reform responses across jurisdictions, and the anomaly detection procedure highlights states where projected outcomes diverge from structural expectations. Together, these tools provide policymakers with a diagnostic mechanism for anticipating potential compliance risks, identifying jurisdictions that may require targeted administrative support, and designing adaptive monitoring strategies as reform implementation progresses.

From a policy perspective, the findings suggest that the effectiveness of the 2025 Tax Act will depend not only on statutory changes but also on the strength of supporting institutional infrastructure.

Investments in digital payment systems, business registration processes, and payroll reporting mechanisms appear central to translating reform potential into realised improvements in tax compliance. Strengthening these systems can help expand the formal tax base, improve administrative efficiency, and enhance the predictability of sub-national revenue streams, thereby supporting more stable fiscal planning at the state level.

By strengthening digital tax administration, expanding formal economic participation, and improving the transparency of sub-national fiscal systems, the projected reform effects also support broader sustainable development priorities, particularly SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), and SDG 16 (Peace, Justice and Strong Institutions). Improved domestic revenue mobilisation and stronger institutional accountability are widely recognised as key pillars of sustainable governance, especially in emerging economies where fiscal capacity remains closely linked to development outcomes.

Despite these contributions, the analysis remains subject to several limitations. The projections rely on structural relationships estimated from publicly available state-level aggregates, and the absence of realised post-reform administrative data implies that the results represent forward-looking forecasts rather than ex-post evaluations. As additional years of administrative revenue data become available following the implementation of the 2025 Tax Act, future research can validate the projected effects, refine the structural parameters, and incorporate more detailed administrative microdata to examine firm-level and sectoral behavioural responses.

Overall, the study offers a structured empirical framework through which policymakers and researchers can anticipate the distributional and administrative implications of tax reforms before full implementation data become available. By combining panel econometric modelling with interpretable machine-learning simulation, the analysis demonstrates how modern analytical tools can support evidence-based fiscal policy design and strengthen the institutional foundations of sustainable public finance systems in emerging economies.

Declarations

Declaration Statement:

The authors have no conflicts of interest to report.

Data Availability

All data used for structural estimation for the period 2016–2024 are publicly available from the following official sources:

- National Bureau of Statistics (NBS) – State Internally Generated Revenue (IGR) Reports

  https://nigerianstat.gov.ng/elibrary

- Central Bank of Nigeria (CBN) – Payment System Statistics

  https://www.cbn.gov.ng/PaymentsSystem/ePaymentStatistics.html

- SMEDAN–NBS National Survey of Micro, Small and Medium Enterprises (MSME Survey)

  https://www.nigerianstat.gov.ng/elibrary/read/966

- National Bureau of Statistics (NBS) – Labour Force Survey Releases

  https://nigerianstat.gov.ng/elibrary/read/1241221

- Corporate Affairs Commission (CAC) – Administrative Statistics and Business Registration Reports

  https://www.cac.gov.ng

The 2026–2027 values reported in this study are model-based projections constructed from estimated pre-reform structural parameters and forward covariate paths derived from publicly available data sources. No unpublished, proprietary, or embargoed post-2024 administrative revenue data were used.

The cleaned panel dataset (2016–2024), simulation code, and replication files necessary to reproduce the counterfactual projections will be made available by the corresponding author upon reasonable request.

Ethical Approval

This study does not contain human participation

Informed Consent

No human participation is involved in this study.

Consent to Publish

Not Applicable

Consent to Participate

Not Applicable

Funding

No funding

Clinical trial number: Not Applicable

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