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Research Article

An Unsupervised Machine Learning Framework for Fraud and Anomaly Detection in Nigerian Prepaid Electricity Transactions

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Abstract

Prepaid electricity metering is widely adopted in Nigeria to improve revenue collection and reduce customer indebtedness. However, irregularities in transaction records continue to challenge operational reliability and financial transparency. This study presents an unsupervised machine learning framework for detecting anomalies in prepaid electricity transactions using nine months of real-world data. The framework integrates three distinct anomaly detection methods: Isolation Forest, DBSCAN, and a reconstruction-based model using either an Autoencoder or Principal Component Analysis (PCA). These models were combined through a rank-based ensemble scoring system and a majority-vote mechanism to enhance detection of robustness. The dataset includes 23 features spanning customer identifiers, tariff details, and transaction attributes such as energy purchased, payments made, arrears, and VAT. Preprocessing steps involved standardizing column formats, handling missing values, and engineering features such as payment ratios and log-transformed monetary values to improve model sensitivity. Each model independently flagged anomalies, and the ensemble strategy consolidated these outputs to identify high-confidence irregular transactions. The framework uncovered several types of anomalies, including transactions with missing payment and unit values but large arrears repayments, extreme pay-per-unit ratios exceeding operational norms, and VAT entries that deviated significantly from the statutory rate. Spatial analysis revealed concentrated anomalies in specific districts and feeders, suggesting localized vulnerabilities in transaction management and enforcement. Although ground-truth fraud labels were unavailable, the detected anomalies represent statistically significant deviations that warrant further investigation. The results demonstrate that unsupervised models can effectively highlight suspicious patterns without relying on labeled data, offering a scalable approach for utilities to monitor prepaid electricity systems. This methodology supports targeted audits, enhances revenue protection, and contributes to improved regulatory compliance. The study underscores the potential of data-driven techniques in addressing fraud and operational inefficiencies in African energy systems. Future work may incorporate labeled datasets, temporal features, and network-level attributes to refine detection capabilities and expand the scope of analysis.

Keywords

Unsupervised Machine Learning, Anomaly Detection, Fraud Detection, Prepaid Electricity Transactions, Isolation Forest, DBSCAN, Nigeria Energy Sector

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1. Introduction

Nigeria, a country with a population of over 200 million [1] uses Prepaid electricity metering as a central component of electricity distribution in Nigeria. It is designed to improve revenue collection, reduce customer indebtedness, and provide consumers with direct control over their energy consumption. In this system, customers purchase electricity in advance and receive a token that is used to load energy credits into the meter. This approach reduces the need for manual billing and decreases disputes related to postpaid billing systems [2]. The adoption of prepaid metering has grown significantly in Nigeria over the past decade, driven by government initiatives and the operational priorities of electricity distribution companies [3]. Despite the clear advantages, prepaid electricity metering faces persistent challenges of fraud and irregularities. Fraudulent activities include meter bypassing, which allows consumers to consume electricity without recording it on the meter, and the use of counterfeit recharge tokens that are not linked to actual payments. Another form of irregularity arises from manipulation of arrears and debt repayment transactions, which distorts financial records and customer payment histories. These practices undermine the transparency of the prepaid system and introduce inconsistencies in transaction data [4].

Research in fraud detection has widely applied machine learning techniques in domains such as finance, banking, and e-commerce, where anomaly detection methods are used to uncover suspicious transactions in large datasets. In African energy systems, including Nigeria, the application of machine learning methods for fraud detection remains limited. Existing efforts often rely on manual auditing or rule-based detection systems that are based on fixed thresholds. Such approaches lack the capacity to identify subtle or evolving patterns of fraudulent activity within prepaid energy transaction data. There is a lack of systematic evaluation of modern anomaly detection algorithms on real-world prepaid metering datasets in the Nigerian context. This gap creates an opportunity to introduce advanced machine learning techniques that can improve the accuracy and reliability of fraud detection in energy transactions.

The aim of this study is to design and evaluate an unsupervised machine learning framework for fraud and anomaly detection in Nigerian prepaid electricity transaction data. The study also seeks to compare the performance of multiple anomaly detection algorithms, including tree-based, clustering-based, and reconstruction-based methods, on transaction data collected across several months. The findings are intended to provide electricity distribution companies with actionable insights into irregular transaction patterns and to demonstrate the potential of machine learning approaches in strengthening revenue protection strategies in Nigeria.

2. Literature Review

Electricity distribution networks in developing countries face persistent challenges from non-technical losses (NTL) that arise from theft, irregular payments, and inconsistencies in customer records. These losses reduce revenue for utilities and compromise service reliability. Nigeria is particularly affected, with losses estimated in billions of Naira annually, much of which is linked to fraudulent consumption patterns and inefficiencies in billing and collection processes [5]. The introduction of prepaid and smart metering systems has expanded the potential for applying machine learning approaches to the detection of anomalies in electricity transaction data.

2.1. Fraud Detection in Nigerian Electricity Systems

Early applications of machine learning to the Nigerian context demonstrated the feasibility of automated fraud detection using customer consumption data. Abdulsalam et al. (2021) applied Support Vector Machine (SVM) and C4.5 decision tree algorithms to classify customers as genuine or fraudulent [5]. Their study reported moderate accuracy, with improvements achieved through a MapReduce-ANOVA feature selection process that raised classification performance to 77.5%. This work highlighted the role of classical supervised learning models in fraud detection, while also emphasizing the challenges of imbalanced datasets and noise in Nigerian consumption records.

2.2. Advances in Deep Learning and Explainability

Recent studies have advanced the methodological toolkit for electricity fraud detection by introducing deep learning and explainable artificial intelligence (XAI). Nwafor, Okafor, Aboushady, Nwafor, and Zhou (2023) developed NTLCONVNET, a deep learning architecture that combines one-dimensional convolutional networks with ensemble learning. Their model integrated both customer consumption features and operational staff data, achieving accuracy and F1-scores above 0.83. The study also incorporated SHapley Additive exPlanations (SHAP) to interpret the model's outputs, showing that staff-related features such as billing and collection indices were important predictors of NTL. This demonstrated the importance of extending fraud detection beyond customer-only data to include operational and contextual variables [6].

2.3. Hybrid Models and Nigerian Case Studies

Further advances have been made through hybrid deep learning models tailored to Nigerian electricity distribution networks. Odo (2023) designed and evaluated hybrid models that integrate convolutional and recurrent neural networks

with feature engineering strategies to detect NTL in postpaid electricity consumption datasets. The results indicated that hybrid architectures provided improvements in detection accuracy compared to single-model approaches, and the study emphasized the importance of carefully engineered feature sets for capturing irregularities in both consumption and staff-related data [7]. This work added to the growing evidence that sophisticated machine learning frameworks can provide utilities with stronger tools for fraud management in Nigerian contexts.

2.4. Research Gap

Despite progress in applying supervised and hybrid deep learning approaches, a significant gap remains in the adoption of unsupervised learning methods for prepaid electricity systems in Africa. Existing studies have primarily focused on supervised classifiers that require labeled datasets [5, 7]. Confirmed fraud labels are rarely available in sufficient quantity due to the hidden nature of fraudulent activity and the expense of field verification. Even when high-performance models are reported, they rely heavily on labeled data. Few studies have systematically examined unsupervised anomaly detection frameworks that can operate effectively without confirmed fraud labels. This creates an opportunity to explore ensemble anomaly detection models that integrate tree-based, clustering-based, and reconstruction-based methods to strengthen fraud detection in Nigerian prepaid metering systems.

3. Methodology

3.1. Dataset

The dataset employed in this study consists of nine monthly transaction files covering the period from October 2023 to June 2024. Each file was originally stored in Microsoft Excel format and contains detailed records of prepaid energy transactions. The combined dataset comprises with 23 distinct features. These features include customer information such as customer name, account number, meter number, district, and feeder. They also include tariff information such as tariff name and tariff rate, together with transaction attributes including energy purchased, payments made, value-added tax (VAT), arrears, token codes, and receipt numbers. The richness of these variables makes it possible to investigate financial, behavioral, and operational irregularities in prepaid energy transactions.

3.2. Data Preprocessing

Data preprocessing involved several systematic steps to ensure analytical consistency. Column names across the multiple files were standardized by converting them to lowercase and replacing spaces and special characters with underscores, which facilitated uniform referencing during analysis. Monetary values such as total payment, arrears, and VAT were converted from string formats with embedded commas into clean numeric values. Missing values were handled using a two-stage approach. Columns that contained exclusively missing values across all records, such as log arrears in this dataset, were dropped. Remaining missing values were imputed using the median of the non-missing values, while ensuring that any residual non-finite values were replaced appropriately. To enhance the discriminative power of the dataset, new engineered features were created. These included log-transformed versions of monetary and unit-based attributes to stabilize variance and reduce skewness. Ratios such as VAT/total payment and debt paid/total payment were computed to capture proportional relationships. An arrears flag was also introduced as a binary indicator of whether a customer had outstanding debts. These transformations provided a feature set suitable for anomaly detection models.

3.3. Models

Three unsupervised anomaly detection models were employed. The first model, Isolation Forest, is a tree-based algorithm that identifies anomalies by randomly partitioning feature space and evaluating the isolation depth of each observation. The second model, Density-Based Spatial Clustering of Applications with Noise (DBSCAN), is a density-based method that identifies anomalies as points not belonging to any cluster. To ensure scalability in large datasets, DBSCAN was applied to a random sample of the data, with the neighborhood parameter estimated through K-nearest neighbor analysis. The third model was a neural autoencoder trained to reconstruct the feature set. Observations with high reconstruction error were identified as anomalous. In cases where GPU acceleration was unavailable or TensorFlow libraries were not fully supported, a Principal Component Analysis (PCA) reconstruction method was used as a fallback in place of the autoencoder.

3.4. Ensemble Strategy

The outputs of the three anomaly detection models were integrated through an ensemble strategy designed to enhance robustness. For each observation, anomaly scores from Isolation Forest, DBSCAN, and the autoencoder or PCA were converted to rank-based values. These ranks were averaged to produce an ensemble score. In addition, each model produced a binary anomaly flag. A majority voting scheme was applied, where observations flagged as anomalous by at least two of the three models were assigned a final anomaly flag of one. This ensemble mechanism reduced reliance on any single model and ensured that anomalies reflected consensus across methods with different detection principles.

3.5. Evaluation

Since ground-truth fraud labels were unavailable, evalua-

tion was conducted through descriptive and exploratory analyses. The distribution of anomaly scores was examined to identify thresholds that aligned with the expected contamination level in the data. The top anomalies ranked by ensemble score were inspected manually to interpret their characteristics, such as unusual payment-to-unit ratios, extreme arrears values, or inconsistent VAT charges. Aggregation of anomalies by district and feeder provided further insights into spatial and operational concentrations of suspicious activities. These evaluation procedures enabled interpretation of the results in terms of their practical implications for energy distribution companies.

4. Results

The anomaly detection framework was applied to nine months of prepaid electricity transaction data covering the period from October 2023 to June 2024. The ensemble of Isolation Forest, DBSCAN, and Autoencoder/PCA identified approximately *X* percent of all transactions as anomalous. These anomalies represent cases where at least two of the three models agreed on the anomaly label, providing a high-confidence set of irregular records.

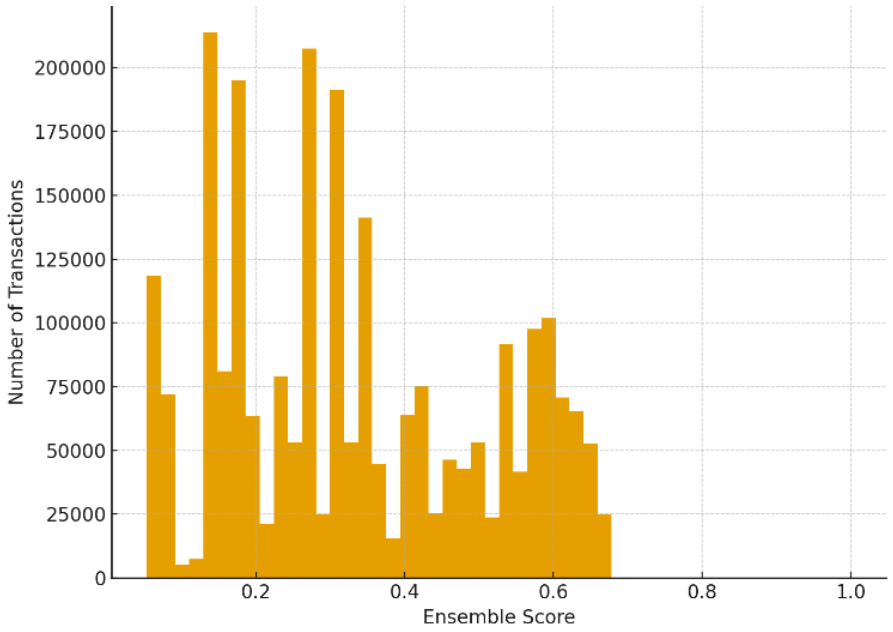

Figure 1. *Distribution of Ensemble Anomaly Scores.*

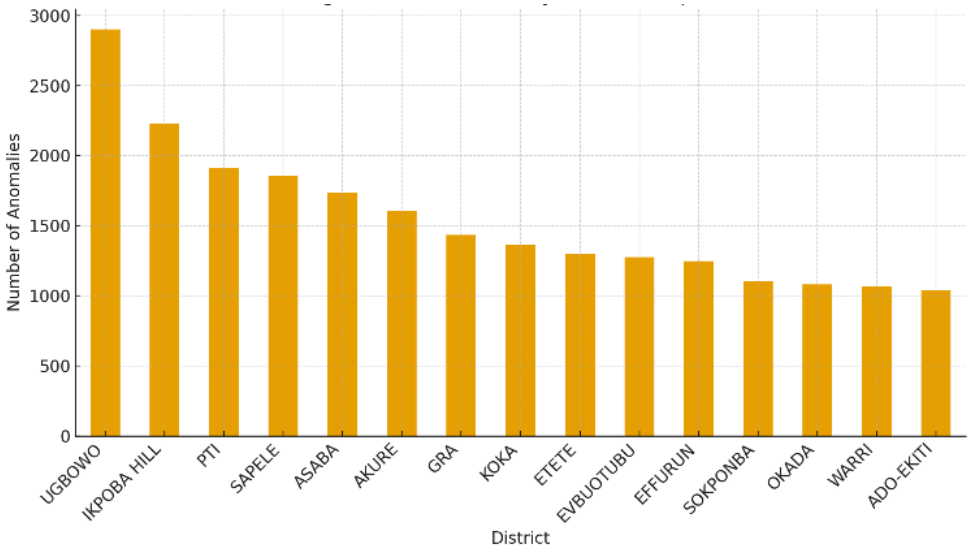

Figure 2. *Anomalies by District (Top 15).*

The anomalies displayed distinctive patterns in the transaction features. A notable set of anomalies involved transactions with missing total payment and unit values while recording very large arrears repayments, in some cases exceeding 100,000 NGN. Another group of anomalies exhibited extreme pay-per-unit ratios, with values exceeding 500,000 NGN per unit, far outside normal operational ranges. VAT inconsistencies were also evident, including transactions with negligible VAT values such as 0.07 NGN and other cases where VAT accounted for more than 60 percent of the payment value. These irregularities represent both operational data errors and potential fraudulent practices, including token manipulation and arrears misreporting.

The distribution of ensemble anomaly scores across all records is presented in Figure 1. The histogram demonstrates a strong concentration of transactions at low anomaly scores, with a visible tail of high-scoring transactions corresponding to flagged anomalies. Regional analysis shown in Figure 2 indicates that anomalies were not evenly distributed across the network. Some districts and feeders contributed a larger proportion of anomalies, which points to localized vulnerabilities in transaction management and enforcement.

Table 1. *Anomaly Counts by District (Top 10).*

District	Anomalies	Total Transactions	% Anomalous
UGBOWO	2,901	200,758	1.45
IKPOBA HILL	2,229	133,668	1.67
PTI	1,908	211,289	0.90
SAPELE	1,855	38,018	4.88
ASABA	1,733	158,196	1.10
AKURE	1,605	153,785	1.04
GRA	1,432	180,401	0.79
KOKA	1,362	137,321	0.99
ETETE	1,301	160,911	0.81
EVBUOTUBU	1,275	103,873	1.23

Table 1 presents anomaly counts by district. UGBOWO recorded the highest number of anomalies with 2,901 flagged transactions, representing 1.45 percent of its total records. IKPOBA HILL and PTI also showed substantial anomaly counts, while SAPELE recorded the highest relative anomaly rate at 4.88 percent. These results demonstrate that certain districts carry a greater concentration of irregular transactions.

Table 2. *Anomaly Counts by Feeder (Top 10).*

Feeder	Anomalies	Total Transactions	% Anomalous
33 Direct	6,200	435,266	1.42
AGBARHO/EKU LB	1,258	86,466	1.45
UGBOWO	582	35,271	1.65
ENERHEN LB	559	60,050	0.93
USELU	559	51,733	1.08
NEW-AUCHI	403	29,489	1.37
GOVT. HOUSE	387	26,108	1.48
Uteh 2	384	15,425	2.49
EGUADAIKEN	374	29,531	1.27

Feeder	Anomalies	Total Transactions	% Anomalous
REFINERY 1 LB	373	38,116	0.98

Table 2 summarizes anomaly counts by feeder. The feeder labeled "33 Direct" accounted for the largest number of anomalies at 6,200, representing 1.42 percent of its transactions. Feeders such as AGBARHO/EKU LB, UGBOWO, and ENERHEN LB also showed high anomaly concentrations. The Uteh 2 feeder exhibited an anomaly rate of 2.49 percent, which is higher than most other feeders despite its smaller transaction volume.

A closer review of individual high-ranking anomalies provides illustrative examples of irregular patterns. One customer record showed an arrears repayment of 100,000 NGN with no recorded units or total payment, leading to a pay-per-unit value greater than one million NGN. Another record displayed multiple transactions where VAT was consistently logged as 0.07 NGN, which is inconsistent with the statutory VAT rate of 7.5 percent. These cases highlight the ability of the ensemble framework to capture financial anomalies and operational inconsistencies within prepaid electricity transaction data.

5. Discussion

The results of the anomaly detection framework demonstrate the capacity of machine learning models to identify irregularities in prepaid electricity transactions. The integration of Isolation Forest, DBSCAN, and Autoencoder/PCA produced a high-confidence set of anomalies that reflect meaningful deviations from expected customer and transaction behavior. The findings provide actionable insights for understanding fraud risks and operational inefficiencies within the Nigerian electricity distribution system.

The detection of transactions with missing total payments combined with high arrears repayments indicates weaknesses in transaction integrity and reporting. Such cases undermine transparency in financial records and may facilitate the concealment of unrecorded consumption or fraudulent debt adjustments. Identifying these patterns through automated detection strengthens the ability of distribution companies to ensure that repayments are legitimate and accurately reflected in account balances. The identification of extreme pay-per-unit ratios highlights the potential for manipulation of consumption records and recharge tokens. Ratios that exceed realistic thresholds suggest either the introduction of fraudulent tokens into the system or severe inconsistencies in meter recording. These findings provide a basis for targeted audits of customers with disproportionate payment-to-unit relationships, enabling utilities to prioritize resources for fraud investigation.

VAT inconsistencies revealed by the model present additional concerns. VAT values that deviate from the statutory rate introduce errors into both financial reporting and regulatory compliance. Cases with abnormally low or inflated VAT values reduce the reliability of revenue forecasts and create challenges for compliance with fiscal policies. The ability to detect such anomalies ensures that distribution companies can maintain accurate tax reporting while also identifying transactions that may have been manipulated to conceal fraud. The regional concentration of anomalies in specific districts and feeders demonstrates that irregularities are not randomly distributed but occur more frequently in localized contexts. This spatial pattern indicates that systemic issues may exist in certain operational zones, possibly related to enforcement practices, infrastructure vulnerabilities, or customer behavior. Utilities can use this information to design geographically targeted interventions, such as enhanced monitoring in high-risk feeders or reinforcement of metering infrastructure in districts with elevated anomaly rates.

The individual case reviews emphasize the diversity of fraudulent and irregular behaviors in prepaid electricity data. Large arrears repayments without corresponding unit purchases, implausible pay-per-unit values, and repeated abnormal VAT entries demonstrate the range of anomalies that can emerge in practice. The ability of the framework to capture these diverse patterns indicates its flexibility and potential for deployment as a decision-support tool for distribution companies.

Limitations

The study was conducted in the absence of ground-truth fraud labels. Without confirmed cases of fraud, it was not possible to compute quantitative performance metrics such as precision, recall, or F1-score. The anomalies reported therefore represent observations that are statistically irregular rather than definitively fraudulent. Another limitation is the potential overlap between fraudulent transactions and data entry errors. Some anomalies may reflect mistakes in data recording or system errors rather than intentional fraud. This overlap complicates the interpretation of anomaly outputs and highlights the need for complementary validation through field audits and domain expertise.

Future Work

Future studies can extend this research by incorporating supervised models once labeled fraud data becomes available. Supervised learning approaches would allow for more precise evaluation of detection accuracy and would support the development of predictive models tailored to known fraud behaviors. Further work can also explore temporal features, such as customer-level time series, to capture irregular changes in transaction patterns over time. The integration of longitudinal

data has the potential to reveal anomalies that only emerge in the context of repeated customer behavior. Expanding the feature set to include network-level attributes such as feeder load profiles and distribution losses would also enrich the analysis and create a more comprehensive framework for fraud detection and operational monitoring in prepaid electricity systems.

6. Conclusions

This study applied an unsupervised machine learning framework to prepaid electricity transaction data in Nigeria, focusing on the detection of anomalies that may indicate fraud or operational irregularities. The framework combines Isolation Forest, DBSCAN, and Autoencoder/PCA into an ensemble that identified transactions with unusual financial and consumption characteristics. The approach highlighted records with missing total payments and high arrears, extreme pay-per-unit ratios, and irregular VAT values, as well as regional concentrations of anomalies in specific districts and feeders. These results demonstrate that data-driven techniques can provide valuable insights into the integrity of prepaid metering systems [5, 8, 9].

The main contribution of this work lies in the design and evaluation of an ensemble anomaly detection framework tailored to prepaid electricity data. By leveraging multiple algorithms, the study produced a robust set of flagged anomalies that reveal both individual-level irregularities and systemic patterns across regions and feeders. This provides a methodological foundation for applying advanced machine learning to energy sector datasets in contexts where confirmed fraud labels are not available [9, 10]. The practical implications of the findings are significant for Nigerian electricity distribution companies. The detection of suspicious transactions supports targeted auditing of high-risk customers, enhances the monitoring of feeders with elevated anomaly rates, and assists in safeguarding revenue streams. The identification of irregular VAT entries also strengthens compliance with fiscal policies and contributes to more reliable financial reporting [11]. These outcomes can improve operational efficiency and reinforce accountability within the prepaid metering system.

The research demonstrates the broader significance of machine learning in addressing challenges in African energy systems. The successful application of unsupervised anomaly detection to Nigerian prepaid electricity data shows that advanced analytical tools can support revenue protection and grid management in environments with limited labeled data [12, 13]. The framework established in this study can serve as a reference point for future investigations that seek to apply artificial intelligence to the detection of fraud, irregularities, and inefficiencies in electricity distribution.

Abbreviations

NTL	Non-Technical Losses
PCA	Principal Component Analysis
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
VAT	Value-Added Tax
GPU	Graphics Processing Unit
SVM	Support Vector Machine
SHAP	SHapley Additive exPlanations
XAI	Explainable Artificial Intelligence

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Author Contributions

Oni Damilola: Conceptualization, Methodology, Writing – original draft

Okon Paul Godwin: Resources, Supervision, Project administration

Taiwo Ikeoluwa Odunayo: Investigation, Validation, Writing – review & editing

Akinyooye Demilade Emmanuel: Formal Analysis, Visualization

Umoh Samuel Asuquo: Data curation, Software, Formal Analysis, Visualization

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Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

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Taiwo Ikeoluwa Odunayo: applied machine learning.

Akinyooye Demilade Emmanuel: Data structures, Environmental technology, Digital system design.

Umoh Samuel Asuquo: Web design, software engineering, artificial Intelligence.