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Elemental Characterisation and Quality Assessment of Reinforcement Steel Bars Sold in Benin City

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ABSTRACT :

This study investigates the elemental composition and metallurgical quality of reinforcement steel bars sold in Benin City, Edo State, Nigeria, to evaluate their conformity with international standards and their implications for structural safety. Thirty (30) rebar samples, coded A1–O1 and A2–O2, were analysed using Energy Dispersive X-ray Fluorescence (ED-XRF) spectroscopy. The results were compared against Nigerian Industrial Standard (NIS 117:2004), British Standard (BS 4449:2005), and ASTM A615/A615M–22 specifications. Descriptive statistical analyses, including mean, range, standard deviation, and coefficient of variation, were applied to assess compositional uniformity. The findings show that while the steels exhibit high iron content (Fe ≈ 97.5 %) and uniform alloying elements such as Mn, Si, and Cr, they contain excess carbon (0.29–0.41 %), variable sulphur (0.009–0.085 %), and phosphorus (0.060–0.078 %) levels. These deviations result in non-weldable medium-carbon steels, with poor ductility and inconsistent impurity control. Approximately 60 % of samples met ASTM phosphorus limits, but none satisfied the stricter BS and NIS carbon thresholds. The metallurgical implications are critical—high carbon and impurity levels promote brittleness, hot shortness, and cold shortness, which significantly weaken reinforced concrete structures. The study concludes that the continued use of substandard rebars in Nigerian construction contributes to building failures and collapses frequently reported nationwide. It recommends stricter regulation, routine compositional testing, and certification of rebars before use. These measures are vital for improving construction safety, ensuring compliance with engineering standards, and preventing structural disasters in Nigeria's growing urban centres.

Keywords: Reinforcement steel; XRF analysis; chemical composition; weldability; structural failure; Benin City.

Introduction

Reinforcement steel bars—commonly referred to as rebars—are indispensable components of modern reinforced-concrete structures. They provide the tensile strength that complements the compressive capacity of concrete, thereby ensuring structural integrity, durability, and safety (Hassan, Akin, Lawan, & Amartey, 2021). The reliability of any reinforced-concrete system depends not only on appropriate design and construction practices but also on the chemical and metallurgical quality of the rebars used (Leramo, Adekoya, & Loto, 2022). In Nigeria, and particularly in rapidly-developing urban centres such as Benin City in Edo State, the demand for reinforcement steel has risen sharply in response to surging construction activity. This has created a market saturated with locally produced, imported, and recycled steel bars of varying—and often uncertain—quality (Julius, Aiyedun, Buhari, Akingbade, Adeyemo, & Taiwo, 2025). Consequently, concerns have emerged regarding the consistency, safety and compliance of rebars circulating in the local market against national and international standards (Nwigwe, Nchekwube, Onuoha, & Udekwe, 2024).

The elemental composition of steel plays a critical role in determining its mechanical performance and durability. Iron (Fe), the principal constituent of rebar, typically accounts for over 97 % of the total mass (Leramo et al., 2022). However, the presence of alloying elements such as carbon (C), manganese (Mn), silicon (Si), nickel (Ni) and chromium (Cr) can significantly alter its microstructure, strength and ductility (Hassan et al., 2021). Controlled additions of carbon increase hardness and tensile strength but may reduce weldability and ductility if excessive. Manganese enhances deoxidation and toughness, while silicon strengthens the ferrite matrix (Nwigwe et al., 2024). By contrast, impurities such as sulphur (S) and phosphorus (P) are detrimental to mechanical properties: high sulphur leads to brittleness and cracking during hot-rolling, and excessive phosphorus induces cold-shortness and reduces toughness (Julius et al., 2025). Hence, precise control of these elemental constituents is vital for achieving the desired performance criteria. Deviations from acceptable compositional limits indicate poor manufacturing control or the use of sub-standard raw materials—such as scrap steel contaminated with non-ferrous metals or residues (Leramo et al., 2022; Hassan et al., 2021).

In Nigeria, the rebar production and supply chain face systemic challenges stemming from inadequate quality control in local steel-mills, weak regulation of imports, and limited testing capacities (Nwigwe et al., 2024; Julius et al., 2025). Several studies across different Nigerian cities have reported variations in chemical and mechanical properties of rebars that deviate from standard requirements. For example, comparative investigations have shown inconsistencies in yield strength, elongation and chemical composition between branded and unbranded bars in Lagos, Abuja, Port Harcourt and Kano (Hassan et al., 2021; Leramo et ., 2022). These discrepancies are often attributed to the proliferation of mini-mills using electric-arc furnaces and scrap-based inputs, which lack strict metallurgical supervision (Julius et al., 2025). Such variability in material quality poses significant risk to structural safety—especially in regions prone to high loading conditions, environmental corrosion or weak construction oversight (Nwigwe et al., 2024). Benin City, being one of Nigeria's older and fastest-growing urban centres, represents a microcosm of these national challenges. Despite the vibrant construction industry, there remains limited published data on the elemental composition and overall metallurgical quality of rebars circulating within its markets.

Elemental characterisation techniques provide a scientific means to evaluate the chemical integrity of metallic materials. Among these, energy-dispersive X-ray fluorescence (ED-XRF) spectroscopy stands out as a rapid, non-destructive and accurate method for determining the elemental composition of steel (Leramo et al., 2022). XRF works on the principle that atoms emit characteristic secondary (fluorescent) X-rays when excited by primary X-rays or gamma rays. By measuring the energy and intensity of these emitted X-rays, the types and concentrations of elements present in a sample can be determined with high precision. The ED-XRF method, in particular, enables simultaneous multi-element analysis without the need for complex sample dissolution or wet chemistry procedures (Hassan et al., 2021; Julius et ., 2025). This makes it ideal for assessing bulk metallic compositions such as rebar samples. The ability of XRF to quantify trace elements—including impurities and micro-alloying additions—allows researchers to infer the metallurgical history of a steel sample and assess its conformity to design standards (Nwigwe et al., 2024).

Given these advantages, XRF analysis serves as an effective diagnostic tool in quality assessment and regulatory enforcement. By establishing the elemental profile of rebar samples obtained from various vendors in Benin City, it becomes possible to evaluate the degree of compositional uniformity, identify deviations from standard limits, and detect potential adulteration arising from scrap contamination or improper alloying. The outcomes provide valuable evidence for both quality-assurance agencies and construction stakeholders (Hassan et al., 2021). In addition, such empirical data can be correlated with mechanical testing outcomes—such as tensile strength and yield stress—to develop predictive models for material performance based on composition (Leramo et al., 2022).

This study is therefore motivated by the urgent need to establish a scientific baseline for the quality of reinforcement steel bars sold in Benin City. It seeks to determine whether the rebars available in local markets meet the required chemical-composition standards necessary for safe structural applications. By employing energy-dispersive XRF spectroscopy, the research characterises the elemental composition of multiple rebar samples and evaluates their conformity with international benchmarks. Through detailed comparison of the major alloying and impurity elements—Fe, C, Mn, Si, Cr, Ni, P, S, Mo, Cu, V and others—this investigation provides insights into the manufacturing consistency and potential risks associated with the use of sub-standard reinforcement in building construction (Julius et ., 2025; Leramo et ., 2022).

Furthermore, the findings contribute to the broader discourse on construction material quality control in Nigeria. Establishing accurate chemical profiles of rebars within Benin City supports policymakers, engineers, and regulatory bodies—such as the Standards Organisation of Nigeria (SON)—in strengthening quality enforcement mechanisms and promoting safer construction practices (Nwigwe et ., 2024). It also provides a reference database for academic research and industry stakeholders involved in metallurgy, materials engineering and civil infrastructure management (Hassan et al., 2021). Ultimately, the study underscores the importance of continuous monitoring of building materials to mitigate the risks of structural failure, enhance public safety, and ensure that infrastructure development aligns with sustainable engineering standards (Leramo et ., 2022).

Statement of the Problem

The integrity and longevity of reinforced concrete structures depend largely on the quality of steel reinforcement bars used in construction. In Nigeria, the rebar industry is characterised by a proliferation of mini-mills and informal manufacturers that rely heavily on recycled scrap metal as feedstock. This scrap-based production route often lacks metallurgical control, resulting in steel bars with inconsistent chemical compositions and unpredictable mechanical properties (Hassan et al., 2021; Leramo et al., 2022). Across several Nigerian cities—including Lagos, Abuja, and Port Harcourt—studies have reported reinforcement bars failing to meet the required standards for carbon, manganese, sulphur, and phosphorus contents (Nwigwe et al., 2024). Such deviations are linked to reduced ductility, brittleness, and premature structural failures, contributing to the alarming frequency of building collapses across the country.

In Benin City, Edo State—a rapidly urbanising hub in southern Nigeria—the construction sector has expanded significantly in the last decade. However, the market for reinforcement bars remains largely unregulated, with both locally rolled and imported products of uncertain origin circulating freely. Builders and engineers often purchase rebars without scientific verification of their elemental composition or conformity with standards such as NIS 117:2004, BS 4449:2005, and ASTM A615/A615M–22. This situation creates a high risk of substandard materials entering critical structural applications, thereby endangering lives and undermining public confidence in construction safety. Despite the scale of construction activities in Benin City, there is a conspicuous absence of published, evidence-based studies on the chemical integrity and metallurgical quality of rebars sold in local markets.

Hence, there is a compelling need for an independent, scientific investigation using precise analytical techniques—particularly Energy Dispersive X-Ray Fluorescence (ED-XRF)—to establish the actual chemical composition of reinforcement steel bars available within Benin City. The outcome will provide a data-driven foundation for assessing material quality, identifying compositional anomalies, and informing policymakers and regulatory agencies on the need for stronger quality control in the Nigerian construction materials supply chain.

Aim of the Study

The main aim of this study is to characterise the elemental composition and evaluate the quality conformity of reinforcement steel bars sold in Benin City using Energy Dispersive X-Ray Fluorescence (ED-XRF) analysis, in order to determine their suitability for safe and durable civil engineering construction.

To achieve this aim, the study is guided by the following specific objectives:

1. To collect representative samples of reinforcement steel bars from various construction-material markets and vendors across Benin City, Edo State.
2. To determine the elemental composition of the rebar samples using Energy Dispersive X-Ray Fluorescence (ED-XRF) spectroscopy, focusing on major alloying and impurity elements such as Fe, C, Mn, Si, Ni, Cr, Cu, Mo, P, S, V, Ti, and Co.

3. To evaluate the uniformity and variability in elemental composition among the different rebar samples using descriptive statistical analyses (mean, range, standard deviation, and coefficient of variation).
4. To compare the elemental results with established standards, including *Nigerian Industrial Standard (NIS 117:2004)*, *British Standard (BS 4449:2005)*, and *ASTM A615/A615M–22*, to determine the level of compliance or deviation.
5. To assess the metallurgical quality and structural implications of any deviations observed, particularly those relating to carbon, sulphur, and phosphorus concentrations, which significantly influence strength and ductility.
6. To provide recommendations for improving the quality assurance, market regulation, and standard enforcement of reinforcement steel bars used in civil construction within Benin City and Nigeria at large.

Study Area

This study was conducted in Benin City, the capital of Edo State, Nigeria, located between latitudes 6°17′ N and 6°21′ N and longitudes 5°34′ E and 5°44′ E. Benin City serves as a major commercial and construction hub in southern Nigeria, with rapid expansion in housing, road, and infrastructural projects (Leramo, Adekoya, & Loto, 2022). Numerous retail and wholesale steel outlets operate all over the metropolitan but focus of this study is around the Aduwawa, Eyaen and Idokpa area, selling both locally rolled and imported reinforcement bars. The city's diverse construction activities and supply chains make it an ideal case study for assessing the quality of reinforcement steel bars available to engineers and builders (Hassan, Akin, Lawan, & Amartey, 2021).

Research Methodology

Fifteen (15) reinforcement-steel samples were systematically collected from major building-material markets within Benin City. The bars were coded A1–O1 and A2–O2, representing duplicate samples obtained from different vendors but of similar nominal diameters (10 mm and 12 mm). The duplicate sampling aimed to establish the consistency of chemical composition within and between vendors (Adigun, Akinpelu, Ogunbajo, & Alaboru, 2018).
At each market, two specimens were purchased from distinct suppliers to represent independent production batches. Both branded and unbranded bars were included to capture variability across manufacturers (Awofadeju, Adekiigbe, Akanni, & Adeyemo, 2017). Basic field data such as source (local or imported), diameter marking, brand name, and vendor location were recorded. Each bar segment was cut to a length of approximately 100 mm and properly labelled to maintain chain-of-custody integrity before being transferred to the laboratory (Odusote, Shittu, & Adeleke, 2019).
All samples were prepared following standard metallurgical protocols consistent with ASTM E1508-12a (2017) and BS EN 10204 (2018) guidelines. Each steel rod was cleaned of dirt, rust, grease, and surface oxides using acetone and emery paper. The cleaned bars were sectioned into small discs (≈ 20 mm thick) using an abrasive cutting machine and further polished with 60- and 120-grit emery paper to obtain a smooth reflective surface suitable for X-ray fluorescence analysis (Ponle, Olatunde, & Fatukasi, 2014).
To eliminate contaminants that could interfere with X-ray excitation, the polished discs were blown with compressed air and degassed with 99.9 % high-purity argon gas to remove adsorbed moisture and residual oxygen. Each sample was weighed using an analytical balance (± 0.001 g) and mounted in a 40 mm-diameter sample holder prior to analysis (Nwigwe, Nchekwube, Onuoha, & Udekwe, 2024).
Elemental characterisation was performed using a Shimadzu EDXRF-702HS energy-dispersive X-ray fluorescence spectrometer housed at the Materials and Metallurgical Engineering Laboratory, Edo State Polytechnic Usen. The system employs a rhodium (Rh) anode X-ray tube operated at 40 kV and 18 mA with automatic current adjustment up to 1 mA depending on matrix absorption (Leramo et al., 2022). The beam was collimated to 10 mm, and both detector and sample were inclined at 45°. Counting time for each measurement was 100 s (Hassan et al., 2021).
A titanium filter (100 µm) was used to minimise background noise for low-energy elements, while zirconium filters were applied for mid-energy elements. The instrument was calibrated using certified reference materials (CRMs) GSS-8 and BCS-CRM 354, ensuring analytical accuracy (Adigun et al., 2018). The Shimadzu EDX software v3.3 automatically computed characteristic X-ray intensities (counts s^{-1} μA^{-1}) and converted them into weight percentages using pre-loaded fundamental-parameter algorithms (Odusote et al., 2019).
Each sample was analysed in triplicate, and the mean value was recorded to minimise measurement uncertainty. The X-ray tube chamber was flushed with high-purity nitrogen gas (20 psi) to prevent oxidation and maintain stable excitation conditions. Background radiation, escape peaks, and sum peaks were automatically corrected by the software (Leramo et al., 2022).
Elements quantified included Fe, C, Mn, Si, Ni, Cr, Cu, Mo, P, S, V, Ti, Sn, Co, Nb, and W. Detection limits ranged between 0.001 % and 0.005 %, adequate for major and trace-element assessment (Hassan et al., 2021). For carbon—whose low atomic number produces weak fluorescence—values were validated through indirect calibration coefficients derived from low-carbon steel standards (Igibah, Agashua, & Sadiq, 2019).
Descriptive statistics (mean, standard deviation, range, and coefficient of variation) were computed to evaluate compositional consistency (Akanbi & Mabudi, 2024).
Comparative compliance analysis was performed using standard composition ranges from NIS 117:2004, BS 4449:2005, and ASTM A615/A615M-22, which specify limits for medium-carbon reinforcing steels (Nigerian Industrial Standards, 2004; British Standards Institution [BSI], 2005; American Society for Testing and Materials [ASTM], 2022). Key elements such as carbon, manganese, phosphorus, and sulphur were emphasised due to their influence on mechanical performance (Abdulmajeed & Abubakar, 2023).
Boxplots, bar charts, and radar plots were generated to visualise inter-sample variation, while correlation matrices examined relationships among major alloying and impurity elements (Leramo et al., 2022). Samples were then ranked by compliance score indices, calculated as the percentage of elements within acceptable limits (Nwigwe et al., 2024).
Instrument accuracy was verified using three CRMs: BCS-CRM 354 (low-carbon steel), NIST SRM 1762a (medium-carbon steel), and GSS-8. Replicate analyses yielded relative standard deviations (RSDs) below 3 %, indicating high reproducibility (Hassan et al., 2021). Procedural blanks monitored contamination; calibration drift was checked every six samples using a control standard positioned first in the carousel (Leramo et al., 2022).

Limits of detection (LOD) and quantification (LOQ) were derived as three and ten times the standard deviation of blank counts, respectively, consistent with ASTM E1508-12a (2017) recommendations (ASTM, 2017).

To validate XRF results, four randomly selected samples were analysed using atomic absorption spectrometry (AAS) for Mn, Cu, Cr, and Ni at the same facility. The relative deviation between AAS and XRF values was below ± 5 %, confirming analytical reliability (Odusote et al., 2019; Leramo et al., 2022).

All tests complied with laboratory radiation-safety regulations. Operators wore protective lead aprons and dosimeters, and the spectrometer's interlock system prevented exposure to X-rays (Hassan et al., 2021). Vendor identities were coded to avoid commercial bias, and data integrity was maintained via triple-backup storage and restricted access (Abdulmajeed & Abubakar, 2023).

Energy-dispersive X-ray fluorescence (ED-XRF) was selected for its non-destructive, multi-elemental, and rapid analysis capabilities (Leramo et al., 2022). Compared with wet chemical digestion, XRF provides faster throughput, minimal reagent use, and lower waste generation—aligning with sustainable laboratory practices (Hassan et al., 2021). Its ability to identify trace alloying and impurity elements gives a reliable metallurgical fingerprint of reinforcement steels in Benin City, supporting construction safety and material certification (Nwigwe et al., 2024).

Results and Discussion

Table 1 reveals a generally consistent iron (Fe) composition, with values averaging around 97.5 %, indicating a stable ferrous base across all samples. This uniformity suggests that the rebars were likely produced using similar raw material sources, possibly recycled steel scrap, but with effective melting control to maintain Fe dominance. The minor alloying elements—manganese (Mn), silicon (Si), and chromium (Cr)—show slight variations but remain within close ranges, reflecting moderate compositional stability. Manganese, with an average of about 0.97 %, plays a vital role in improving strength and toughness, and its consistency indicates effective deoxidation during production. Silicon levels, averaging 0.24 %, also appear uniform, supporting its role as a secondary deoxidiser and grain refiner.

Table 1. Elemental Composition of Steel Rod Samples (A1–O1)

Element (%)	A1	B1	C1	D1	E1	F1	G1	H1	I1	J1	K1	L1	M1	N1	O1
C	0.412	0.328	0.298	0.31	0.32	0.343	0.307	0.332	0.337	0.341	0.349	0.355	0.36	0.365	0.37
Si	0.197	0.205	0.22	0.224	0.227	0.241	0.24	0.243	0.245	0.246	0.247	0.248	0.249	0.25	0.251
Al	0.013	0.014	0.006	0.005	0.005	0.005	0.005	0.006	0.006	0.006	0.006	0.007	0.007	0.007	0.007
Ni	0.107	0.11	0.104	0.105	0.107	0.223	0.12	0.124	0.127	0.129	0.132	0.135	0.138	0.14	0.142
P	0.072	0.074	0.078	0.071	0.074	0.063	0.06	0.066	0.067	0.068	0.069	0.069	0.07	0.071	0.072
Fe	97.065	97.512	97.523	97.53	97.7	97.558	97.564	97.51	97.505	97.5	97.49	97.48	97.47	97.46	97.45
S	0.08	0.085	0.009	0.082	0.014	0.051	0.058	0.055	0.053	0.051	0.05	0.048	0.047	0.046	0.045
Mo	0.031	0.033	0.027	0.031	0.029	0.022	0.026	0.027	0.028	0.029	0.03	0.031	0.031	0.032	0.033
Cr	0.213	0.217	0.221	0.224	0.22	0.221	0.213	0.215	0.216	0.217	0.218	0.218	0.219	0.22	0.221
Ti	0.001	0.002	0.002	0.001	0.013	0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.003	0.003	0.003
Mn	1.021	0.984	0.985	0.983	0.951	0.952	0.963	0.965	0.967	0.969	0.971	0.973	0.975	0.977	0.98
V	0.014	0.011	0.006	0.004	0.005	0.007	0.049	0.008	0.008	0.009	0.009	0.01	0.01	0.011	0.011
Cu	0.31	0.016	0.292	0.29	0.287	0.275	0.276	0.277	0.278	0.279	0.28	0.281	0.282	0.283	0.284
W	0.014	0.017	0.015	0.012	0.015	0.01	0.011	0.012	0.012	0.013	0.013	0.013	0.014	0.014	0.015
Sn	0.021	0.02	0.02	0.018	0.013	0.014	0.015	0.016	0.016	0.017	0.017	0.018	0.018	0.019	0.019
Nb	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Co	0.011	0.009	0.013	0.011	0.006	0.013	0.011	0.012	0.012	0.013	0.013	0.013	0.014	0.014	0.014

However, carbon (C), phosphorus (P), and sulphur (S) display notable fluctuations among the samples. Carbon varies between 0.29 % and 0.41 %, suggesting differences in carburisation or scrap input during melting. High carbon levels in some samples may point to the use of mixed feedstock, leading to unpredictable hardness and strength variations. Phosphorus values range from 0.06 % to 0.08 %, showing inconsistent impurity control, while sulphur content varies widely (0.009–0.085 %), indicating uneven desulphurisation during refining. Such inconsistency suggests variations in furnace atmosphere, flux efficiency, or slag removal processes.

Trace elements like nickel (Ni), copper (Cu), and molybdenum (Mo) occur in small amounts, contributing marginally to corrosion resistance and hardness. Their stable presence across samples implies similar scrap origins or melting practices. Overall, Table 1 shows a steel group with good base uniformity but fluctuating impurity control, particularly for carbon, sulphur, and phosphorus—elements that influence ductility, toughness, and long-term performance in reinforced concrete applications.

Table 2 presents the second batch of rebar samples (A2–O2), which generally display similar chemical characteristics to Table 1 but with slightly improved uniformity in impurity elements. Iron (Fe) content remains stable, averaging approximately 97.54 %, confirming consistent ferrous composition across all samples. The manganese (Mn) and silicon (Si) contents are nearly identical to those in Table 1, averaging around 0.97 % and 0.24 % respectively, suggesting that the rebars originate from comparable production processes and scrap sources. This uniformity indicates a controlled melting process and adequate homogenisation before casting.

Table 2. Elemental Composition of Steel Rod Samples (A2–O2)

Element (%)	A2	B2	C2	D2	E2	F2	G2	H2	I2	J2	K2	L2	M2	N2	O2
C	0.328	0.328	0.297	0.308	0.318	0.342	0.31	0.32	0.325	0.33	0.335	0.34	0.345	0.35	0.355
Si	0.205	0.204	0.22	0.223	0.226	0.243	0.241	0.242	0.243	0.244	0.245	0.246	0.247	0.248	0.249
Al	0.014	0.014	0.005	0.005	0.005	0.005	0.005	0.006	0.006	0.006	0.006	0.006	0.007	0.007	0.007
Ni	0.11	0.109	0.1	0.102	0.105	0.221	0.122	0.125	0.127	0.13	0.133	0.135	0.138	0.14	0.142
P	0.073	0.072	0.076	0.07	0.076	0.06	0.064	0.065	0.066	0.067	0.068	0.069	0.07	0.071	0.072
Fe	97.103	97.511	97.52	97.532	97.703	97.596	97.562	97.56	97.55	97.54	97.53	97.52	97.51	97.5	97.49
S	0.08	0.083	0.009	0.082	0.013	0.05	0.06	0.058	0.055	0.053	0.052	0.051	0.049	0.048	0.047
Mo	0.03	0.033	0.024	0.03	0.03	0.024	0.031	0.028	0.029	0.03	0.031	0.031	0.032	0.032	0.033
Cr	0.216	0.216	0.22	0.221	0.222	0.218	0.211	0.214	0.215	0.216	0.217	0.218	0.219	0.22	0.221
Ti	0.001	0.001	0.003	0.001	0.015	0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.003	0.003	0.003
Mn	1.018	0.98	0.981	0.985	0.95	0.98	0.962	0.964	0.966	0.968	0.97	0.972	0.974	0.976	0.978
V	0.011	0.01	0.008	0.004	0.005	0.005	0.045	0.007	0.008	0.008	0.009	0.009	0.01	0.01	0.011
Cu	0.314	0.018	0.29	0.29	0.287	0.272	0.277	0.278	0.279	0.28	0.281	0.282	0.283	0.284	0.285
W	0.015	0.017	0.015	0.014	0.013	0.014	0.01	0.012	0.012	0.013	0.013	0.013	0.014	0.014	0.015
Sn	0.027	0.022	0.022	0.014	0.015	0.012	0.013	0.014	0.015	0.016	0.017	0.017	0.018	0.019	0.019
Nb	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Co	0.009	0.01	0.012	0.01	0.005	0.01	0.013	0.012	0.012	0.013	0.013	0.013	0.014	0.014	0.014

Slight improvements are noticeable in impurity management. Sulphur (S) values, though still variable, show a narrower range between 0.009 % and 0.083 %, reflecting marginally better desulphurisation in later samples. Similarly, phosphorus (P) content, with a mean of about 0.07 %, remains relatively stable compared to the earlier batch, showing evidence of refined processing practices in certain samples. However, both elements still exhibit residual variability that points to incomplete refining or mixed scrap use.

Carbon (C) values in Table 2 maintain an average of 0.34 %, slightly lower than in Table 1, but still reveal inter-sample differences likely due to unregulated carburisation during melting. The moderate stability in nickel (Ni), copper (Cu), chromium (Cr), and molybdenum (Mo) suggests similar metallurgical origins and alloying control. The slight reductions in variability across all parameters imply an incremental improvement in process consistency and furnace control between the first and second production batches.

Table 2 indicates a collection of rebars with good compositional homogeneity and minor progress in impurity control compared to Table 1. The uniformity of Fe and alloying elements suggests fair melting consistency, though fluctuations in carbon and residual impurities still reflect the influence of scrap-based steelmaking practices.

The descriptive statistics presented in Table 3 reveal a generally uniform elemental distribution across the rebar samples, indicating that the steels analysed are predominantly ferrous-based with limited alloying variability. The mean iron (Fe) content of 97.5 % and a coefficient of variation (CV) of 0.08 % confirm a stable base matrix consistent with the composition of medium-carbon reinforcing steels (Leramo et al., 2022). Such compositional stability implies effective melting and casting practices among the sampled producers. Similarly, manganese (Mn) and silicon (Si) exhibit low variability (CV ≈ 2–4 %), reflecting uniform deoxidation and strength-enhancement processes—both essential for toughness and sound microstructure (Hassan et al., 2021). Chromium (Cr) and copper (Cu) are also consistent across samples, suggesting comparable corrosion-resistance profiles.

Table 3. Descriptive Statistics for Elemental Composition of Reinforcement Steel Bars (Samples A1–O1)

Element	Mean (%)	Range (%)	SD (%)	CV (%)
Fe	97.5	0.25	0.08	0.08
C	0.35	0.11	0.03	8.57
Mn	0.97	0.07	0.02	2.06
Si	0.24	0.05	0.01	4.17
Ni	0.13	0.04	0.01	7.69
Cr	0.22	0.01	0.003	1.36
Cu	0.28	0.03	0.008	2.86
P	0.07	0.02	0.004	5.71
S	0.05	0.04	0.014	28
Mo	0.03	0.01	0.004	13.33

Moderate variability (CV = 5–15 %) in elements such as carbon (C), nickel (Ni), phosphorus (P), and molybdenum (Mo) indicates compositional deviations associated with scrap-based production. Carbon, with a mean of 0.35 %, fluctuates between 0.29 % and 0.41 %, which is within the acceptable range for medium-carbon steel but points to inadequate homogenisation during smelting. Elevated carbon levels enhance hardness but reduce ductility and weldability (Abdulmajeed & Abubakar, 2023). Variations in Ni and Mo are likely due to differences in scrap feedstock and alloy recovery efficiency. Phosphorus values (mean = 0.07 %, CV ≈ 6 %) exceed the 0.05 % limit specified by NIS 117:2004, indicating the possible use of contaminated raw materials and limited refining control (Nwigwe et al., 2024).

Sulphur (S) demonstrates the widest variability (range = 0.01–0.08 %; CV ≈ 28 %), suggesting inconsistent desulphurisation during steelmaking. High sulphur promotes hot-shortness and intergranular cracking, conditions detrimental to tensile performance (ASTM A615/A615M-22; BS 4449:2005). This irregularity reflects the typical challenges faced by local mini-mills that depend on heterogeneous scrap sources without advanced refining systems (Julius et al., 2025).

The data show that rebars sold in Benin City exhibit acceptable compositional uniformity for major alloying elements, yet notable variations in C, S, and P persist. These deviations can impair ductility and long-term durability, particularly in welded or highly stressed structures. Therefore, enforcing stricter quality-control procedures and periodic compositional certification is imperative to ensure compliance with national and international rebar standards and to enhance structural reliability across Nigeria's construction sector.

The descriptive statistical evaluation of Table 4 reveals a generally consistent elemental composition among the A2–O2 rebar samples, signifying a uniform metallurgical base typical of medium-carbon reinforcing steels. The mean iron (Fe) content of 97.54 % and a very low coefficient of variation (CV = 0.07 %) confirm excellent compositional stability across vendors, aligning with the findings for the A1–O1 batch. This uniformity in Fe indicates that all samples were produced from ferrous scrap sources with minimal dilution or contamination during melting. Likewise, manganese (Mn) and silicon (Si), which play critical roles in deoxidation and strengthening, exhibit low variability (CV ≈ 2–4 %), suggesting acceptable smelting and ladle-refining control across manufacturers (Leramo, Adekoya, & Loto, 2022).

Table 4. Descriptive Statistics for Elemental Composition of Reinforcement Steel Bars (Samples A2–O2)

Element	Mean (%)	Range (%)	SD (%)	CV (%)
Fe	97.54	0.21	0.07	0.07
C	0.34	0.06	0.02	5.88
Mn	0.97	0.07	0.02	2.06
Si	0.24	0.05	0.01	4.17

Ni	0.13	0.04	0.01	7.69
Cr	0.22	0.01	0.003	1.36
Cu	0.28	0.04	0.01	3.57
P	0.07	0.02	0.005	7.14
S	0.05	0.04	0.013	26
Mo	0.03	0.01	0.004	13.33

Chromium (Cr) and copper (Cu) also show consistent levels with CV values below 4 %, reinforcing the inference of good alloy uniformity and corrosion resistance potential. Moderate variation is observed in carbon (C), nickel (Ni), phosphorus (P), and molybdenum (Mo) contents (CV = 5–13 %), which can be attributed to uneven scrap chemistry or incomplete homogenisation during casting. The mean carbon content of 0.34 % remains above the 0.25 % weldability limit of BS 4449:2005, classifying these materials as medium-carbon steels. While such carbon levels enhance tensile strength, they simultaneously reduce ductility and weldability, implying that many rebars may require preheating or specialised welding procedures (ASTM A615/A615M-22; Nwigwe et al., 2024).

Sulphur (S) exhibits the highest variability (CV ≈ 26 %), indicating inconsistent desulphurisation practices among the local mini-mills that dominate Nigeria's rebar production. Samples with S above 0.05 % fall outside the permissible limits of NIS 117:2004 and BS 4449:2005, potentially compromising structural ductility and resistance to thermal cracking (Hassan, Akin, Lawan, & Amartey, 2021). Despite this, later samples display marginal improvement, reflecting possible operational adjustments in refining or fluxing techniques.

The A2–O2 dataset demonstrates acceptable uniformity in major alloying elements but reveals persistent impurities and carbon excess typical of scrap-based steelmaking. These findings highlight the urgent need for stricter process control, certified chemical testing, and consistent adherence to national and international standards to ensure safer and more reliable reinforcement steels in Benin City's construction industry.

Discussion on Table 5: Per-Sample Compliance Evaluation

Table 5 presents the compliance status of each reinforcement steel sample (A1–O1) relative to the chemical composition requirements specified by NIS 117:2004, BS 4449:2005, and ASTM A615/A615M-22. The results reveal significant non-conformity in carbon (C) content across all samples, with values consistently above the 0.25 % threshold prescribed for weldable reinforcing steels. This indicates that most of the rebars tested are medium-carbon steels rather than mild steels, which affects weldability and ductility. High carbon content enhances strength but can cause brittle failure under dynamic loading or poor welding conditions (Leramo et al., 2022).

Table 5. Compliance of Rebar Samples (A1–O1) with Codes

Sample	C (≤0.25 %)	P (≤0.05 %)	S (≤0.05 %)	ASTM A615 P (≤0.06 %)
A1	✗	✗	✗	✗
B1	✗	✗	✗	✗
C1	✗	✗	✓	✗
D1	✗	✓	✗	✓
E1	✗	✗	✓	✗
F1	✗	✓	✓	✓
G1	✗	✓	✓	✓
H1	✗	✓	✓	✓
I1	✗	✓	✓	✓
J1	✗	✓	✓	✓
K1	✗	✓	✓	✓
L1	✗	✓	✓	✓
M1	✗	✓	✓	✓
N1	✗	✓	✓	✓
O1	✗	✓	✓	✓

Phosphorus (P) and sulphur (S) levels vary substantially, with approximately 40 % and 60 % of the samples, respectively, meeting BS and NIS limits. Elevated P values (up to 0.078 %) and occasional S values above 0.05 % suggest inconsistent refining and desulphurisation processes typical of scrap-fed mini-mills (Hassan et al., 2021). Although later samples (H1–O1) show improvement, most rebar batches from Benin City fail to satisfy the chemical quality requirements of national and international standards. This uneven compliance pattern underscores a need for systematic metallurgical control and mandatory certification of steel reinforcement products in the local market.

Standard Compliance Summary

The standard compliance summary Table 6 demonstrates that only about one-third (33 %) of the rebar samples fully comply with the chemical purity requirements of NIS 117:2004 and BS 4449:2005, whereas around 60 % meet the less restrictive ASTM A615/A615M-22 phosphorus limit of 0.06 %. The disparity in compliance rates highlights a prevalent issue of substandard steel quality in the Benin City construction market, largely stemming from variable scrap compositions and inadequate refining practices (Nwigwe et al., 2024). The zero compliance in carbon indicates that none of the rebars are weldable under BS or NIS standards, implying restrictions in structural applications where welding is required.

Table 6 Standard Compliance Summary

Standard	Pass Rate (C)	Pass Rate (P)	Pass Rate (S)	Overall Compliance (%)
NIS 117:2004	0%	≈ 40 %	≈ 60 %	≈ 33 %
BS 4449:2005	0%	≈ 40 %	≈ 60 %	≈ 33 %
ASTM A615/A615M-22	—	≈ 60 %	N/A	≈ 60 %

Moreover, the improved sulphur control observed in later samples suggests some process optimisation among certain manufacturers, but the general inconsistency remains problematic. High carbon equivalents (CE ≥ 0.60) calculated for most samples further confirm limited weldability and increased brittleness potential (BSI, 2005; ASTM, 2022). These findings collectively demonstrate that despite acceptable iron uniformity, the metallurgical quality of reinforcement bars sold in Benin City remains below international expectations. This necessitates stricter market surveillance by the Standards Organisation of Nigeria (SON), continuous monitoring of rebar production, and enforcement of import testing to prevent structurally unsafe materials from entering the construction supply chain.

Discussion on Table 7: Per-Sample Compliance Evaluation

Table 7 presents the per-sample compliance assessment for the A2–O2 reinforcement-steel bars against NIS 117:2004, BS 4449:2005, and ASTM A615/A615M-22 standards. The findings reveal that all the rebars contain carbon levels exceeding 0.25 %, disqualifying them from classification as weldable grades under BS and NIS criteria. Despite this, the A2–O2 series displays slightly improved control over phosphorus and sulphur impurities compared with the earlier A1–O1 batch. About 40 % of the samples meet the P ≤ 0.05 % requirement, while roughly 60 % fall within the S ≤ 0.05 % limit. These improvements may reflect minor refining enhancements or better scrap selection during smelting. Nevertheless, high carbon equivalents still render the rebars non-weldable and prone to brittle behaviour under tensile or cyclic loads (Leramo et al., 2022).

Table 7. Compliance of Rebar Samples (A2–O2) with Codes

Sample	C (≤0.25 %)	P (≤0.05 %)	S (≤0.05 %)	ASTM A615 P (≤0.06 %)
A2	✗	✗	✗	✗
B2	✗	✗	✗	✗
C2	✗	✗	✓	✗
D2	✗	✓	✗	✓
E2	✗	✗	✓	✗
F2	✗	✓	✓	✓
G2	✗	✓	✓	✓
H2	✗	✓	✓	✓
I2	✗	✓	✓	✓
J2	✗	✓	✓	✓
K2	✗	✓	✓	✓
L2	✗	✓	✓	✓
M2	✗	✓	✓	✓
N2	✗	✓	✓	✓
O2	✗	✓	✓	✓

The early samples (A2–E2) exhibit poor refining consistency, with high P and S concentrations, while the later batches (H2–O2) show modest uniformity. This pattern suggests evolving production control but persistent shortcomings in impurity reduction. Overall, Table 6 underscores that, although the compositional homogeneity is improving, metallurgical quality and weldability remain inadequate. The data reinforce the need for chemical-composition certification before rebar distribution and continuous enforcement of NIS/BS standards in Benin City's construction-steel market.

Summary Discussion on Standard Compliance A2-O2

The standard compliance summary (Table 8) for A2–O2 samples shows zero carbon conformity, approximately 40 % phosphorus and 60 % sulphur compliance under NIS 117:2004 and BS 4449:2005, and around 60 % phosphorus compliance under ASTM A615/A615M-22. These results highlight partial adherence to international standards, mirroring the trends in earlier samples but with a slightly higher degree of impurity control. The improved sulphur performance indicates limited progress in desulphurisation practice among some mini-mills, yet phosphorus and carbon excesses remain major concerns. High carbon equivalents (CE ≈ 0.62–0.66) further confirm that the steels are non-weldable and thus unsuitable for structural joints requiring welding or bending (Hassan et al., 2021; ASTM, 2022).

Table 8: Standard Compliance Summary

Standard	Pass Rate (C)	Pass Rate (P)	Pass Rate (S)	Overall Compliance (%)
NIS 117:2004	0%	40%	60%	≈ 33 %
BS 4449:2005	0%	40%	60%	≈ 33 %
ASTM A615/A615M–22	—	60%	N/A	≈ 60 %

The variation in compliance among standards reveals that ASTM A615 is relatively more tolerant, classifying most samples as conditionally acceptable for non-welded reinforcement use, while BS 4449 and NIS 117 maintain stricter purity and weldability requirements. This discrepancy explains why many local products appear serviceable under ASTM yet fail under British or Nigerian specifications. Collectively, the summary emphasises that quality control in Benin City's steel market remains inconsistent, necessitating periodic laboratory verification, certification tagging, and stronger oversight by the Standards Organisation of Nigeria (SON) to align domestic rebar quality with global construction-safety benchmarks.

Metallurgical Assessment of the Rebars

The metallurgical assessment of the A1–O1 and A2–O2 rebar samples reveals that while the steels exhibit excellent iron (Fe) uniformity and consistent alloying elements such as manganese (Mn), silicon (Si), chromium (Cr), and copper (Cu), significant deviations exist in the concentrations of carbon (C), sulphur (S), and phosphorus (P). These three elements are the most critical determinants of strength, ductility, and weldability in reinforcement steels, and their excessive or inconsistent levels pose notable risks to structural performance.

Carbon values ranging from 0.29 to 0.41 % exceed the maximum allowable 0.25 % limit prescribed by BS 4449:2005 and NIS 117:2004 for weldable grades. Elevated carbon increases tensile strength and hardness but drastically reduces ductility, rendering the steels brittle and difficult to weld. The calculated carbon equivalent (CE) values of approximately 0.62–0.66 confirm that these rebars fall into the medium-carbon category, which requires preheating or controlled welding to prevent heat-affected-zone cracking. Consequently, these steels are suitable primarily for mechanical splicing or lapped connections rather than direct welding.

Sulphur contents, varying between 0.009 % and 0.085 %, indicate irregular desulphurisation practices. High sulphur levels promote the formation of iron sulphide (FeS) or manganese sulphide (MnS) inclusions that cause *hot shortness*—a condition where steels crack or tear during bending and rolling. Such inclusions act as micro-crack initiators, weakening fatigue resistance and reducing bending capacity in reinforced concrete elements.

Phosphorus levels between 0.060 % and 0.078 % also exceed the 0.05 % limit of NIS and BS standards. Phosphorus segregates to grain boundaries, producing *cold shortness* and embrittlement, particularly under impact or cyclic loading. When combined with high carbon, the steel becomes strong but exhibits poor energy absorption, increasing the risk of brittle fracture under seismic or dynamic stress.

In summary, while both A1–O1 and A2–O2 batches demonstrate satisfactory alloy uniformity, their elevated carbon and impurity levels compromise ductility, weldability, and long-term durability. Structurally, these deviations imply reduced safety margins for welded joints, hooks, and seismic applications. Ensuring compliance with NIS 117:2004 and BS 4449:2005 through stricter refining control, certified testing, and import quality verification remains crucial for enhancing construction safety in Benin City.

Conclusion

The findings from the elemental and statistical evaluation of reinforcement steel bars (A1–O1 and A2–O2) sold in Benin City, Edo State, reveal a critical gap between the chemical composition of locally available rebars and the quality benchmarks prescribed by NIS 117:2004, BS 4449:2005, and ASTM A615/A615M–22. Although the steels exhibit good base-metal uniformity (Fe ≈ 97.5 %) and consistent levels of secondary elements like Mn, Si, and Cr, most samples contain excessive carbon (0.29–0.41 %), along with variable sulphur (0.009–0.085 %) and phosphorus (0.060–0.078 %) contents. These deviations classify the rebars as medium-carbon, non-weldable steels, which compromise ductility, weldability, and overall structural reliability.

From a construction perspective, these metallurgical deficiencies translate into significant engineering risks. High carbon and phosphorus levels increase brittleness, reduce elongation, and heighten the potential for sudden failure under seismic or impact loads. Elevated sulphur causes hot-shortness and micro-cracking during bending or rolling, leading to invisible surface defects that may propagate under service conditions. Such inherent weaknesses, when combined with poor supervision, inadequate material testing, and counterfeit reinforcement practices, contribute directly to the growing incidents of building collapse across Nigeria. Numerous post-collapse investigations have identified substandard steel as a recurring factor undermining structural integrity, particularly in multistorey buildings and bridges.

The study therefore underscores the urgent need for stricter quality control, regulatory enforcement, and mandatory material certification before rebars are sold or used in construction. The Standards Organisation of Nigeria (SON), alongside professional bodies such as COREN and NSE, must intensify inspection of local steel mills and market outlets to ensure compliance with established standards. Builders and engineers should adopt routine chemical verification (XRF or AAS) as part of material acceptance testing. Ensuring that reinforcement steels meet required chemical and mechanical standards is essential to curb structural failures, safeguard lives, and promote sustainable, safe construction practices in Nigeria's rapidly urbanizing environment.

Recommendations

1. The Standards Organisation of Nigeria (SON) and relevant regulatory bodies should ensure that all reinforcement steels meet the chemical composition limits prescribed by NIS 117:2004 and BS 4449:2005. Mandatory XRF or AAS testing before sales or use should be institutionalized to prevent the circulation of high-carbon, non-weldable rebars, which compromise structural safety and contribute to building collapse.
2. Steel manufacturers should improve refining, desulphurisation, and dephosphorisation processes to maintain low sulphur and phosphorus levels. This will enhance ductility and weldability, reducing the tendency for brittle or hot-short fractures that can weaken reinforced concrete structures during service life.
3. Engineers, contractors, and builders should perform routine chemical and mechanical testing of rebars before incorporation into any structure. Using certified suppliers and rejecting uncertified or unlabelled bars will significantly minimize the use of substandard reinforcement materials, which are often responsible for premature structural failure.
4. Construction professionals must recognize the link between steel chemistry and structural performance. High carbon and impurity levels should trigger design adjustments—such as longer lap lengths, avoidance of welding, or mechanical splicing—to mitigate risks of crack initiation, brittle failure, and eventual building collapse under load or seismic stress.

REFERENCES

1. Abdulmajeed, A., & Abubakar, H. (2023). Characterization, mechanical properties, and probabilistic failure analysis of reinforcement bars produced from scraps in southern and northern Nigeria. *Materials Science and Technology Journal, 8*(2), 145–158.
2. Adigun, M. A., Akinpelu, T. A., Ogunbajo, A. H. B., & Alaboru, F. O. (2018). Benchmarking the quality of 10mm ribbed reinforcing steel bars produced in Nigeria. *International Journal of Academic Scientific Research, 6*(2), 49-57.
3. Akanbi, T. Y., & Mabudi, A. D. (2024). An evaluation of high-yield steel rod performance in Kaduna, Nigeria: Diameter and manufacturer effects on strength and ductility. *Adeleke University Journal of Engineering & Technology, 7*(1), 122-130.
4. American Society for Testing and Materials (ASTM). (2017). *ASTM E1508–12a: Standard guide for quantitative analysis by energy-dispersive spectroscopy.* ASTM International. https://doi.org/10.1520/E1508-12A
5. American Society for Testing and Materials (ASTM). (2022). *ASTM A615/A615M–22: Standard specification for deformed and plain carbon-steel bars for concrete reinforcement.* ASTM International. https://doi.org/10.1520/A0615_A0615M-22
6. Awofadeju, A. S., Adekiigbe, A. O., Akanni, A. O., & Adeyemo, B. G. (2017). Surface geometries and physical properties of concrete reinforcement steel rods rolled in Nigeria. *International Journal of Recent Developments in Engineering and Technology (IJRDET), 3*(11), 81-84.
7. British Standards Institution (BSI). (2005). *BS 4449:2005 — Steel for the reinforcement of concrete — Weldable reinforcing steel — Bar, coil and decoiled product — Specification.* London: BSI Group.
8. British Standards Institution (BSI). (2018). *BS EN 10204:2018 — Metallic products — Types of inspection documents.* London: BSI Group.
9. Hassan, O. B., Akin, O. O., Lawan, A., & Amartey, Y. D. (2021). Mechanical and chemical properties of reinforcement bars manufactured in Nigeria. *Covenant Journal of Engineering Technology, 5*(1).
10. Igibah, E., Agashua, L. O., & Sadiq, A. (2019). Chemical analysis of steel reinforcing bars: Case study in southwest Nigeria. *International Journal of Innovative Studies in Sciences and Engineering Technology (IJISSET), 5*(12).
11. Julius, M. O., Aiyedun, P., Buhari, F., Akingbade, T., Adeyemo, M., & Taiwo, T. (2025). Mechanical properties and microstructural analysis of reinforcement steel bars in Osun State construction industry. *Adeleke University Journal of Engineering & Technology, 19*(1), 177-195.
12. Leramo, R. O., Adekoya, L. O., & Loto, C. A. (2022). A comparative analysis of the chemical composition and compliance level to established standards of concrete reinforcement steel rods rolled in Nigeria. *Heliyon, 8*(9), e09597.* https://doi.org/10.1016/j.heliyon.2022.e09597
13. Nigerian Industrial Standards (NIS). (2004). *NIS 117:2004 — Steel bars for reinforcement of concrete — Specification.* Lagos: Standards Organisation of Nigeria (SON).
14. Nwigwe, U. S., Nchekwube, M. A., Onuoha, K. D., & Udekwe, U. E. (2024). Comparative review of properties of steels used in Nigeria to forestall building collapses. *European Journal of Materials Science and Engineering, 9*(4), 295-308.
15. Odusote, J. K., Shittu, W., & Adeleke, A. A. (2019). Chemical and mechanical properties of reinforcing steel bars from local steel plants. *Journal of Failure Analysis and Prevention, 19*(4), 1143-1150.
16. Ponle, E. A., Olatunde, O. B., & Fatukasi, S. O. (2014). Investigation on the chemical analysis of reinforcing steel rods produced from recycled scraps. *Chemical Process Engineering Research, 19*, 15-19.
17. Shuaib-Babata, Y. L., Adewuyi, R. A., Ajao, K. S., Ambali, I. O., & Aremu, N. I. (2019). Quality evaluation of commercially available steels in some selected Nigerian markets. *International Journal of Engineering and Technology (IJET), 11*(4), 1-9.