Journal of Chemical Learning Innovation
Vol. 2, No. 2, December 2025, pp. 253~265
ISSN: 3063-0886, DOI:10.37251/jocli.v2i2.2946

Comparative Spectral Sensitivity and Quantitative Accuracy of X-ray Fluorescence and Optical Emission Spectroscopy for Alloy Steel Characterization

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Article Info

Article history:

Received Sep 29, 2025
Revised Oct 31, 2025
Accepted Nov 30, 2025
Online First Dec 31, 2025

Keywords:

Alloy Steel
Elemental Composition Analysis
Optical Emission Spectroscopy
Spectroscopic Analysis
X-Ray Fluorescence

ABSTRACT

Purpose of the study: This study aims to evaluate and compare the spectral sensitivity, detection capability, and quantitative accuracy of X-ray fluorescence and optical emission spectroscopy in determining the elemental composition of alloy steel.

Methodology: X-ray fluorescence analysis was conducted using Niton XL2 GOLDD (Thermo Scientific), while optical emission spectroscopy analysis employed ARC Met 8000 (Oxford Instruments). Samples included stainless steel (SS-304, SS-310), alloy steel (17-4PH), and duplex steel (Zeron 100). Calibration was performed using Analytical Reference Materials International standards. Data analysis included averaging repeated measurements, relative error calculation, and comparative evaluation using Microsoft Excel and Origin software.

Main Findings: Optical emission spectroscopy demonstrated higher spectral sensitivity, particularly for light elements such as carbon, while X-ray fluorescence provided rapid multi-element detection with acceptable accuracy. Relative deviations between methods varied across elements, with significant discrepancies observed in nickel measurements due to matrix effects and detection limitations.

Novelty/Originality of this study: This study introduces a comparative spectral performance analysis of X-ray fluorescence and optical emission spectroscopy, emphasizing matrix-effect-driven deviations and highlighting the nickel (Ni) anomaly as a key spectroscopic case. The work provides deeper insight into the influence of spectral interactions on analytical accuracy in complex alloy systems.

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1. INTRODUCTION

Alloy steel has become an essential engineering material due to its superior mechanical properties, corrosion resistance, and adaptability in various industrial applications such as construction, automotive, and manufacturing sectors [1], [2]. The performance of alloy steel is strongly influenced by its elemental composition,

which determines its mechanical strength, hardness, and durability [3], [4]. Therefore, accurate and rapid characterization of elemental composition is crucial to ensure quality control and compliance with industrial standards [5], [6]. In recent years, spectroscopic techniques have emerged as reliable tools for elemental analysis due to their sensitivity and efficiency. Among these techniques, X-ray fluorescence spectroscopy and optical emission spectroscopy are widely used because of their capability to provide precise compositional data.

X-ray fluorescence spectroscopy is a non-destructive analytical technique that enables the identification and quantification of elements in a material by measuring the characteristic secondary X-rays emitted from a sample [7], [8]. This method is widely applied in metal analysis due to its rapid measurement time and minimal sample preparation. It is particularly advantageous for field analysis using portable instruments, allowing in-situ measurements without damaging the sample [9], [10]. However, its accuracy can be influenced by factors such as matrix effects and calibration standards. Despite these limitations, X-ray fluorescence spectroscopy remains a popular choice for preliminary and rapid elemental analysis [11], [12].

Optical emission spectroscopy, on the other hand, is a technique that determines elemental composition by analyzing the light emitted from excited atoms in a sample [13], [14]. This method is highly sensitive and capable of detecting trace elements with high precision, making it suitable for detailed material characterization. Optical emission spectroscopy is commonly used in metallurgical laboratories due to its ability to provide accurate and reproducible results [15], [16]. The technique typically involves excitation sources such as electric arcs or sparks to generate emission spectra. Although it offers higher accuracy compared to X-ray fluorescence spectroscopy, it often requires more complex sample preparation and operational conditions [17], [18].

Spectroscopic analysis relies on the interaction between electromagnetic radiation and matter, producing characteristic emission or fluorescence signals that are specific to each element [19], [20]. In X-ray fluorescence spectroscopy, elemental identification is based on the detection of secondary X-ray emissions with specific energy levels, while in optical emission spectroscopy, excited atoms emit light at characteristic wavelengths corresponding to electronic transitions [21], [22]. These spectral features enable both qualitative and quantitative analysis of elemental composition [23], [24]. As a result, both techniques play an important role in modern material characterization.

Despite the widespread use of these techniques, comparative studies focusing on spectral sensitivity, detection limits, and quantitative accuracy under similar experimental conditions remain limited [25], [26]. In particular, differences in matrix effects, spectral interference, and sensitivity toward light elements often lead to variations in analytical results. Therefore, a systematic comparison based on spectroscopic performance parameters is essential to understand the strengths and limitations of each method [20], [27]. Such an approach allows for a more comprehensive evaluation of analytical reliability [28], [29].

The development of portable and advanced spectroscopic instruments has significantly improved the efficiency of elemental analysis in industrial environments [30], [31]. Devices such as Niton XL2 GOLDD have enabled rapid, on-site analysis using X-ray fluorescence spectroscopy, making them highly practical for field applications [18], [32]. Similarly, advanced instruments such as ARC Met 8000 utilize optical emission spectroscopy principles to deliver accurate compositional data in laboratory and industrial settings [33], [34]. These instruments have become essential tools in ensuring material quality and consistency. However, differences in their operational principles may lead to variations in analytical results and performance.

Previous studies have explored spectroscopic techniques from different analytical perspectives, yet a clear gap remains in integrating their comparative performance under unified conditions Imashuku and Wagatsuma [35] focused on imaging measurement in emission spectrometry for inclusion analysis in steel materials, emphasizing spatial distribution and microstructural characterization rather than comparative analytical performance. Meanwhile, Porcinai et al. [36] investigated quantitative analysis using portable X-ray fluorescence spectroscopy for copper alloys, highlighting sample preparation effects such as surface versus shavings, but without incorporating complementary spectroscopic techniques. In contrast, the present study addresses this gap by providing a direct comparison between X-ray fluorescence spectroscopy and optical emission spectroscopy based on spectral sensitivity, detection capability, and quantitative accuracy under comparable conditions. Furthermore, this research introduces matrix-effect-driven deviation analysis and the identification of nickel anomaly as a specific spectroscopic case, which has not been explicitly explored in previous works. Therefore, this study contributes a more integrated and mechanistic understanding of spectroscopic performance in alloy steel characterization.

From a practical perspective, industries require analytical methods that are not only accurate but also efficient in terms of time and operational simplicity. Rapid testing is especially important in production lines where delays can affect overall productivity and cost efficiency [37], [38]. While X-ray fluorescence spectroscopy offers fast analysis, questions remain regarding its comparability with the more precise optical emission spectroscopy [39], [40]. Conversely, optical emission spectroscopy provides detailed results but may not always be suitable for rapid field analysis [41], [42]. This trade-off between speed and accuracy creates a critical challenge in selecting the most appropriate technique.

This study goes beyond a conventional comparison of analytical instruments by introducing a detailed evaluation of comparative spectral performance between X-ray fluorescence spectroscopy and optical emission spectroscopy. The novelty of this work lies in its focus on matrix-effect-driven deviation analysis, which explains how absorption and enhancement phenomena influence the accuracy of X-ray fluorescence spectroscopy measurements in complex alloy systems. In addition, this study identifies and analyzes the nickel anomaly as a spectroscopic case, where significant deviation between the two techniques is observed and interpreted based on spectral interactions [43], [44]. By integrating spectral sensitivity, detection capability, and quantitative accuracy, this research provides a more comprehensive understanding of the strengths and limitations of both techniques. Therefore, the findings offer not only practical insights for material characterization but also contribute to the advancement of applied spectroscopy analysis.

Furthermore, this study addresses the need for efficient and reliable analytical methods in industrial material testing. Therefore, the objective of this study is to compare the analytical results obtained from the Niton XL2 GOLDD instrument based on X-ray fluorescence spectroscopy and the ARC Met 8000 instrument based on optical emission spectroscopy in order to evaluate their performance in achieving faster and more accurate testing processes.

2. RESEARCH METHOD

2.1. Instrumentation and Materials

The X-ray fluorescence spectroscopy analysis was performed using a Niton XL2 GOLDD instrument manufactured by Thermo Scientific, equipped with a silicon drift detector and operating within an energy range of 1 to 50 kiloelectron volts. The detector provides an energy resolution of approximately 145 electron volts at the manganese K-alpha line, allowing effective separation of characteristic X-ray peaks. The excitation source operates at variable voltage, reaching up to 50 kilovolts, with current settings optimized automatically by the instrument for different elemental groups. The measurement time was set to 20 seconds, divided into main element and low element modes to improve detection capability. The estimated limit of detection for most transition metals ranges from 1 to 10 parts per million, depending on the matrix composition [45].

Optical emission spectroscopy measurements were conducted using the ARC Met 8000 instrument manufactured by Oxford Instruments, employing spark discharge excitation under a controlled argon atmosphere [46], [47]. The system operates in the ultraviolet to visible spectral range, typically between 130 and 800 nanometers, with high spectral resolution that enables precise identification of atomic emission lines. The spectral resolution of the instrument allows effective separation of closely spaced emission lines, thereby reducing spectral interference. The argon flow rate and discharge parameters were optimized to ensure stable plasma generation and consistent excitation conditions. The limit of detection for optical emission spectroscopy is generally lower than that of X-ray fluorescence spectroscopy, particularly for light elements such as carbon, with detection capability reaching sub-parts per million levels.

2.2. Research Object

The object of study in this research is alloy steel metal, which includes several types of materials, namely stainless steel, alloy steel, and carbon steel [48], [49]. These three types of steel were chosen because they have different elemental composition characteristics and are widely used in various industrial applications. This composition variation allows for a more comprehensive analysis of the performance of the spectroscopic method in identifying the constituent elements of the material. In addition, the differences in chemical and physical properties of each type of steel present unique challenges in the testing process [50], [51]. Therefore, the selection of this research object is expected to provide a representative picture of the capabilities of the analytical method used.

2.3. Experimental Procedure

Prior to analysis, all samples were mechanically ground and polished to obtain a clean and homogeneous surface, thereby minimizing surface contamination effects. For measurements using X-ray fluorescence spectroscopy, the instrument was calibrated using certified reference materials to ensure accuracy and reproducibility [52], [53]. Each sample was analyzed three times, and the average value was used for further evaluation. In optical emission spectroscopy analysis, a pre-burn cycle was applied to remove surface impurities, followed by controlled spark excitation for measurement. Multiple burn cycles, typically five repetitions, were performed to improve precision and reduce random error.

2.4. Research Flowchart

The flow diagram using Niton Xl2 Goldd based on X-Rays Fluorescence can be seen in Figure 1.

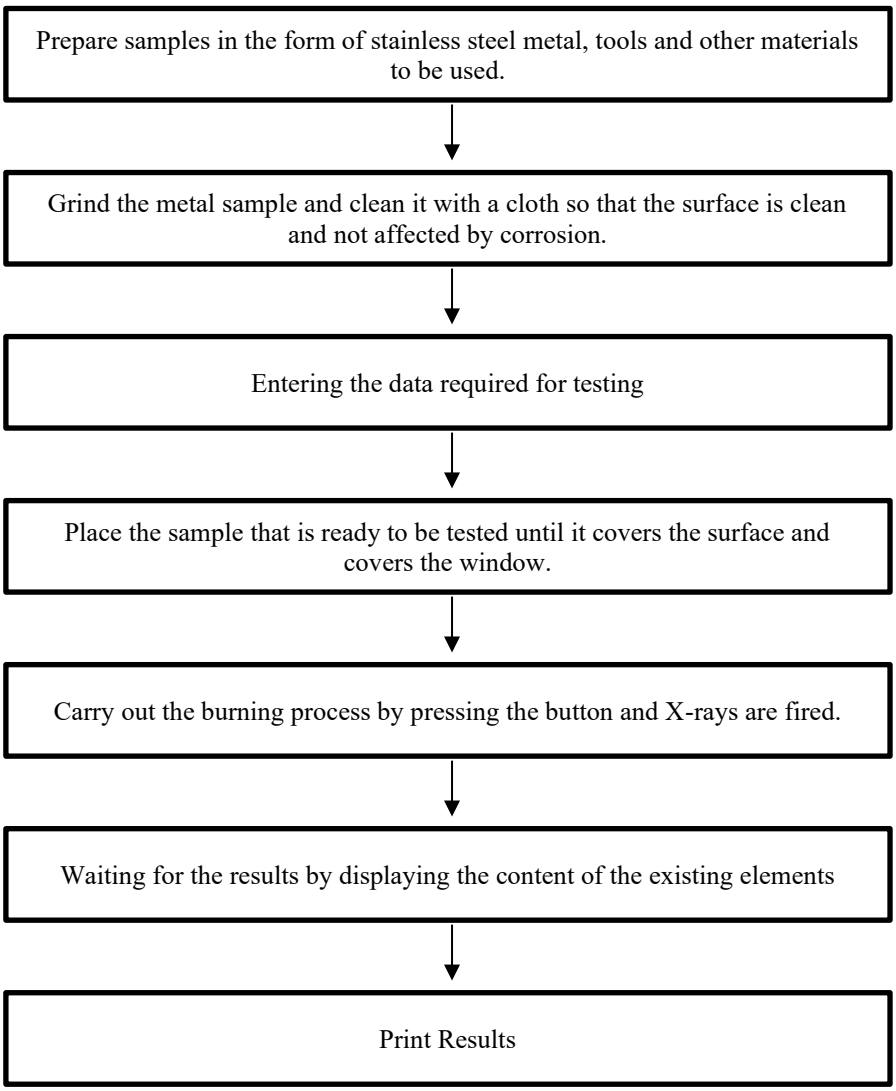
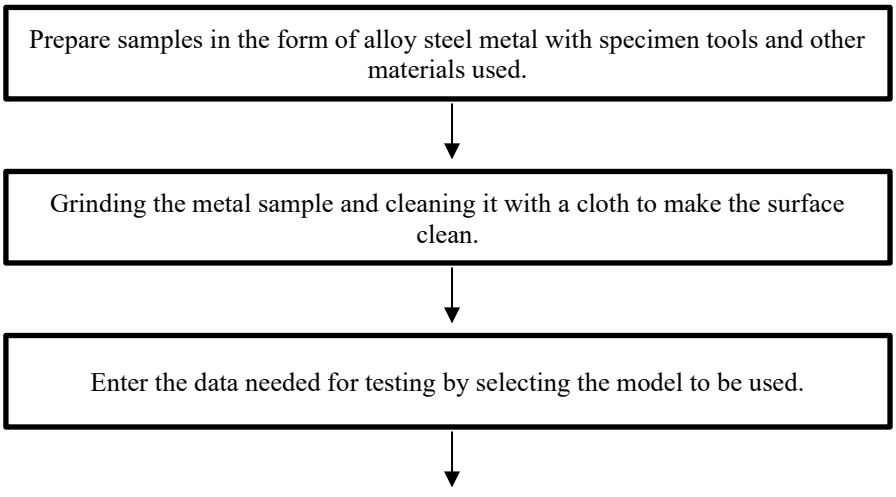


Figure 1. Flowchart of research implementation using Niton XL2 Goldd based on X-Rays Fluorescence

The flow diagram using Arc Met 8000 based on Optical Emission Spectroscopy can be seen in Figure 2.



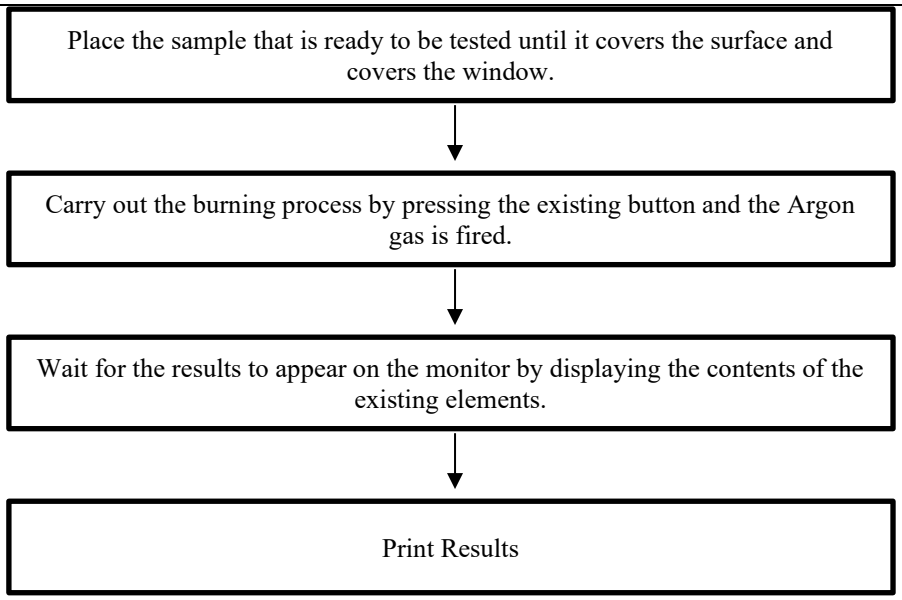


Figure 2. Flowchart of research implementation using Arc Met 8000 based on Optical Emission Spectroscopy

2.5. Data Analysis

The analytical results were processed by averaging repeated measurements and calculating the standard deviation to assess precision [54], [55]. Elemental identification in X-ray fluorescence spectroscopy was based on characteristic energy peaks, while in optical emission spectroscopy it was determined through wavelength-specific emission lines. Quantitative analysis considered peak intensity and calibration curves derived from certified standards [56], [57]. The relative error between X-ray fluorescence spectroscopy and optical emission spectroscopy measurements was calculated to evaluate method accuracy. Additionally, differences in detection limits and spectral resolution were considered when interpreting variations between the two techniques.

The analytical data were processed by calculating the average values of repeated measurements. Quantitative comparison between XRF and OES results was performed using relative error (%), defined as:

$$\text{Relative Error (\%)} = |\text{XRF} - \text{OES}| / \text{OES} \times 100 \ \ldots (1)$$

Statistical evaluation included standard deviation to assess measurement precision. The results were also compared with standard composition ranges based on ASTM specifications to evaluate analytical accuracy. In addition to relative error calculation, spectral data were analyzed based on peak intensity and characteristic emission lines. The identification of elements was confirmed through comparison of spectral peaks with reference databases. This approach ensures both qualitative and quantitative reliability in spectroscopic analysis.

3. RESULTS AND DISCUSSION

Based on the graphical results obtained from X-ray fluorescence spectroscopy and the average values derived from optical emission spectroscopy, the analytical results from both techniques show a general agreement. This similarity indicates that both methods provide comparable measurements for the elemental composition. The consistency between the two techniques can be observed in the data presented in Table 1. Minor differences are present but remain within acceptable analytical limits. Therefore, both techniques demonstrate reliable performance for elemental analysis.

Table 1. Differences in Elemental Content of SS-310 Type

No.	Element Content	X-ray Fluorescence Spectroscopy results	Optical Emission Spectroscopy results
1	Iron (Fe)	53.70%	53.69%
2	Chromium (Cr)	25.09%	24.44%
3	Nickel (Ni)	0.33 %	20.07%
4	Molybdenum (Mo)	0.11%	0.15%
5	Manganese (Mn)	1.51%	1.60%
6	Silicon (Si)	1.07%	0.63%

Table 1 presents the comparison of elemental composition in stainless steel type three hundred ten obtained using X-ray fluorescence spectroscopy and optical emission spectroscopy techniques. The results indicate

a strong agreement for major elements such as iron and chromium, with only minor deviations between the two methods. However, a significant discrepancy is observed in nickel, where X-ray fluorescence spectroscopy reports a substantially lower value compared to optical emission spectroscopy. This difference suggests the presence of matrix effects and limitations in the sensitivity of X-ray fluorescence spectroscopy for certain elements. Overall, the data highlight the superior capability of optical emission spectroscopy in accurately detecting elements in complex alloy systems.

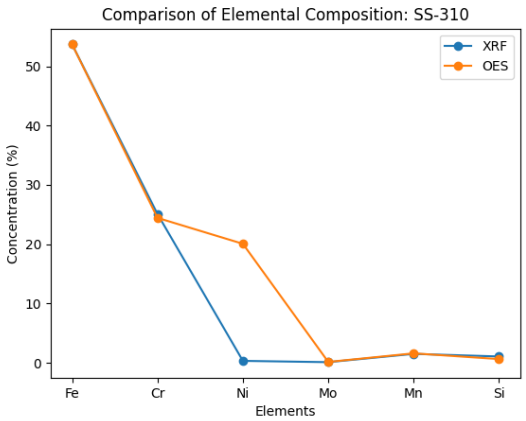


Figure 3. Comparison of Elemental Composition in Stainless Steel Type Three Hundred Ten Using X-ray Fluorescence Spectroscopy and Optical Emission Spectroscopy

The graph for stainless steel type three hundred ten illustrates a comparison between measurements obtained using X-ray fluorescence spectroscopy and optical emission spectroscopy for each element. A significant deviation is clearly visible in nickel, where optical emission spectroscopy reports a much higher concentration than X-ray fluorescence spectroscopy. This result highlights the limitation of X-ray fluorescence spectroscopy in detecting certain elements within complex matrices. Meanwhile, other elements such as iron and chromium show consistent trends between both techniques. The graph emphasizes the higher sensitivity of optical emission spectroscopy in spectroscopic analysis.

Table 2. Differences in Elemental Content of SS-304 Types

No.	Element Content	X-ray Fluorescence Spectroscopy results	Optical Emission Spectroscopy results
1	Iron (Fe)	70.10%	70.46%
2	Chromium (Cr)	17.96%	18.86%
3	Nickel (Ni)	7.71%	7.06%
4	Molybdenum (Mo)	0.06%	0.01%
5	Manganese (Mn)	1.32%	1.37%
6	Silicon (Si)	0.16%	0.39%

Table 2 shows the elemental composition of stainless steel type three hundred four measured using X-ray fluorescence spectroscopy and optical emission spectroscopy. The results demonstrate relatively consistent values for all major elements, including iron, chromium, and nickel. Minor differences are observed, but they remain within acceptable analytical deviation ranges. This indicates that both techniques provide reliable quantitative analysis for medium-alloy compositions. The agreement between the two methods suggests minimal influence of matrix effects in this material.

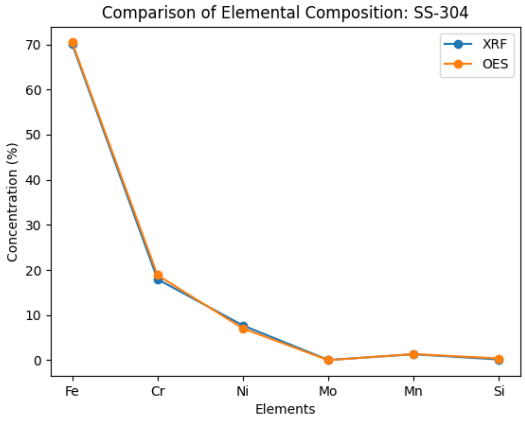


Figure 4. Comparison of Elemental Composition in Stainless Steel Type Three Hundred Four Using X-ray Fluorescence Spectroscopy and Optical Emission Spectroscopy

The graph for stainless steel type three hundred four shows a close agreement between measurements obtained using X-ray fluorescence spectroscopy and optical emission spectroscopy across all elements. Both techniques follow similar trends, indicating consistent analytical performance. Slight deviations are observed but remain within acceptable limits. This suggests that the material composition does not significantly affect the measurement accuracy of either method. Overall, the graph confirms the reliability of both techniques for this alloy type.

Table 3. Differences in the Elemental Content of Type 17-4PH

No.	Element Content	X-ray Fluorescence Spectroscopy results	Optical Emission Spectroscopy results
1	Iron (Fe)	75.5%	74.6%
2	Chromium (Cr)	15.4%	15.48%
3	Nickel (Ni)	4.1%	3.46%
4	Molybdenum (Mo)	0.3%	0.4%
5	Manganese (Mn)	0.6%	0.41%
6	Silicon (Si)	0.58%	0.56%

Table 3 presents the comparison of elemental composition for precipitation-hardening steel type seventeen dash four PH measured using X-ray fluorescence spectroscopy and optical emission spectroscopy. The results show good agreement across all measured elements, including iron, chromium, and nickel. Slight variations are observed in minor elements such as molybdenum and manganese, but these differences are relatively small. This consistency indicates that both spectroscopic techniques perform well for precipitation-hardening steel. The data confirm that both X-ray fluorescence spectroscopy and optical emission spectroscopy can provide accurate and reliable results for this material type.

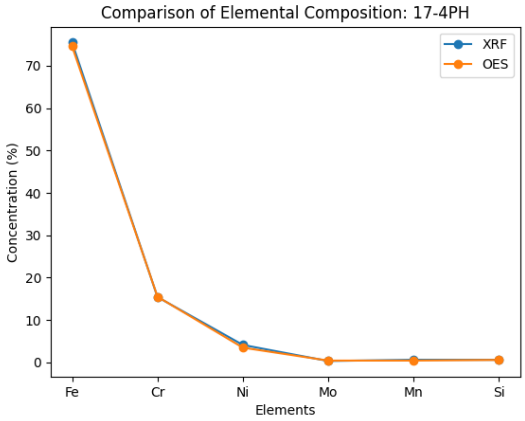


Figure 5. Comparison of Elemental Composition in Precipitation-Hardening Steel Type Seventeen Dash Four PH Using X-ray Fluorescence Spectroscopy and Optical Emission Spectroscopy

The graph for precipitation-hardening steel type seventeen dash four PH demonstrates a strong correlation between results obtained using X-ray fluorescence spectroscopy and optical emission spectroscopy. The data points for each element are closely aligned, indicating minimal variation. This suggests that both techniques are

equally effective in analyzing this type of steel. Minor differences are observed but do not significantly impact the overall interpretation. The graph supports the conclusion that both methods provide consistent results for this material.

Table 4. Differences in Elemental Content of Type Zeron 100

No.	Element Content	X-ray Fluorescence Spectroscopy results	Optical Emission Spectroscopy results
1	Iron (Fe)	80.5%	79.6%
2	Chromium (Cr)	15.4%	15,48%
3	Nickel (Ni)	6.8%	6.4%
4	Molybdenum (Mo)	0.3%	0.4%
5	Manganese (Mn)	0.6%	0.41%
6	Silicon (Si)	0.67%	0.61%

Table 4 displays the elemental composition of Zeron 100 analyzed using X-ray fluorescence spectroscopy and optical emission spectroscopy. The results indicate close agreement between the two techniques for all major elements. Minor deviations are observed, particularly in manganese and molybdenum, but these differences are not significant. This suggests that both methods are effective for analyzing duplex stainless steel. The consistency of the results reflects stable spectroscopic performance under these conditions.

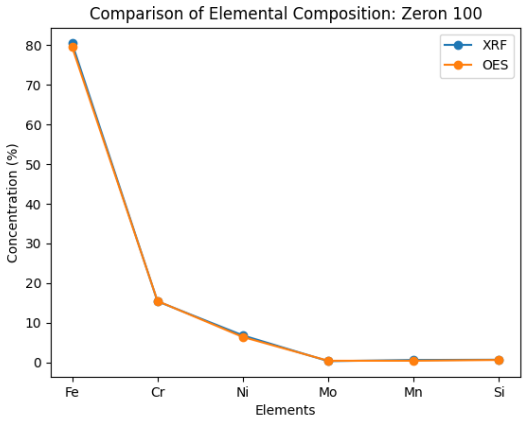


Figure 6. Comparison of Elemental Composition in Zeron 100 Using X-ray Fluorescence Spectroscopy and Optical Emission Spectroscopy

The graph for Zeron 100 shows a high level of agreement between measurements obtained using X-ray fluorescence spectroscopy and optical emission spectroscopy. The trends for all elements are nearly identical, indicating consistent spectroscopic performance. Small deviations are present but are not substantial. This suggests that both techniques are suitable for analyzing duplex stainless steel. The graph highlights the reliability of both methods in this application.

Table 5. Relative Error (%) Between X-ray Fluorescence Spectroscopy and Optical Emission Spectroscopy Measurements

Material	Fe (%)	Cr (%)	Ni (%)	Mo (%)	Mn (%)	Si (%)
SS-310	0.02	2.66	98.36	26.67	5.63	69.84
SS-304	0.51	4.77	9.21	500.00	3.65	58.97
17-4PH	1.21	0.52	18.50	25.00	46.34	3.57
Zeron 100	1.13	0.52	6.25	25.00	46.34	9.84

The relative error analysis shows that most major elements, such as iron and chromium, exhibit low deviation, while extremely high errors are observed in nickel in stainless steel type three hundred ten and molybdenum in stainless steel type three hundred four. These findings indicate strong matrix effects and limitations of X-ray fluorescence spectroscopy in accurately detecting certain elements in complex alloy systems.

The spectroscopic performance of both techniques was further evaluated based on sensitivity, selectivity, and detection capability [58], [59]. Optical emission spectroscopy exhibited superior sensitivity due to its ability to directly measure atomic emission lines with high spectral resolution. In contrast, X-ray fluorescence spectroscopy showed limitations in detecting low atomic number elements due to weak fluorescence signals. Matrix effects were identified as a major factor affecting the performance of X-ray fluorescence spectroscopy [60],

[61]. The presence of multiple elements in alloy steel influences the absorption and enhancement of X-ray signals, leading to deviations in quantitative results. This effect is minimized in optical emission spectroscopy due to the use of controlled excitation conditions and wavelength-specific detection.

The observed discrepancies between X-ray fluorescence spectroscopy and optical emission spectroscopy measurements can be further explained through detailed matrix effect mechanisms, particularly absorption and enhancement effects. In X-ray fluorescence spectroscopy analysis, absorption occurs when emitted characteristic X-rays from a target element are partially absorbed by other elements within the sample matrix, reducing the detected signal intensity [8], [62]. Conversely, enhancement effects arise when secondary fluorescence from one element increases the excitation of another element, artificially elevating its signal intensity [63], [64]. These competing interactions significantly influence the accuracy of X-ray fluorescence spectroscopy measurements, especially in complex multi-element alloys such as stainless steel. Therefore, matrix effects play a critical role in determining analytical reliability.

Nickel appears to be the most affected element in this study, particularly in stainless steel type three hundred ten, due to its intermediate atomic number and its spectral position relative to major elements such as iron and chromium. The characteristic X-ray energies of nickel are more susceptible to absorption by surrounding elements, leading to signal attenuation and underestimation in X-ray fluorescence spectroscopy results [65], [66]. Additionally, spectral overlap and interference from nearby emission lines can further distort nickel detection in energy-dispersive X-ray fluorescence systems [67], [68]. In contrast, optical emission spectroscopy is less affected by these phenomena because it relies on wavelength-resolved atomic emission lines, allowing more selective and accurate identification of nickel. This explains the significantly higher nickel values obtained using optical emission spectroscopy compared to X-ray fluorescence spectroscopy.

However, significant discrepancies are observed in the measurement of nickel, particularly in stainless steel type three hundred ten samples. In this case, X-ray fluorescence spectroscopy tends to underestimate the nickel concentration compared to optical emission spectroscopy results [32], [69]. This deviation highlights the limitations of X-ray fluorescence spectroscopy when applied to complex alloy matrices. The presence of multiple elements can influence signal absorption and enhancement effects. As a result, the accuracy of X-ray fluorescence spectroscopy measurements may be reduced in multi-element systems.

The differences between X-ray fluorescence spectroscopy and optical emission spectroscopy can be explained by their fundamental spectroscopic principles. X-ray fluorescence spectroscopy relies on secondary X-ray fluorescence, where emitted radiation is influenced by matrix interactions. These interactions can alter signal intensity and affect quantitative accuracy. In contrast, optical emission spectroscopy is based on atomic emission, where excited atoms emit light at characteristic wavelengths [70], [71]. This mechanism provides more direct and element-specific spectral information.

Furthermore, optical emission spectroscopy offers higher spectral sensitivity compared to X-ray fluorescence spectroscopy, especially for trace elements. Its ability to resolve emission lines allows better discrimination between overlapping signals. This advantage becomes critical in complex materials such as alloy steels. In addition, optical emission spectroscopy can detect light elements such as carbon with high accuracy [72]. X-ray fluorescence spectroscopy, on the other hand, is limited in detecting such elements due to low fluorescence yield.

From an analytical perspective, relative error analysis indicates that optical emission spectroscopy provides higher quantitative accuracy. This is particularly evident in the measurement of minor and trace elements. Meanwhile, X-ray fluorescence spectroscopy demonstrates acceptable accuracy for major elements with the benefit of rapid analysis [73], [74]. The non-destructive nature of X-ray fluorescence spectroscopy also makes it suitable for field applications. Therefore, both techniques offer complementary advantages depending on analytical requirements.

The spectral intensity data obtained from X-ray fluorescence spectroscopy provide useful information for elemental identification [75], [76]. Each element produces characteristic peaks corresponding to specific excitation energies. These peaks confirm the presence of elements through their unique spectral signatures. However, intensity-based quantification is often affected by matrix effects. As a result, it is generally less accurate than emission-based quantification methods such as optical emission spectroscopy.

Unlike conventional comparative studies, this research emphasizes the role of spectroscopic interactions in determining analytical performance. The identification of nickel anomaly provides a specific case that demonstrates how matrix effects can significantly distort X-ray fluorescence spectroscopy measurements. This approach strengthens the interpretation of results by linking quantitative deviations to underlying spectral phenomena. Consequently, the study contributes to a more mechanistic understanding of spectroscopic analysis rather than a purely descriptive comparison.

This study provides significant contributions to the field of applied spectroscopy by offering a comprehensive evaluation of the comparative spectral performance of X-ray fluorescence spectroscopy and optical emission spectroscopy in alloy steel analysis. The findings highlight the importance of selecting appropriate spectroscopic techniques based on analytical requirements such as sensitivity, accuracy, and operational

efficiency. The identification of matrix-effect-driven deviations, particularly the nickel anomaly, enhances the understanding of how spectral interactions influence quantitative results. These insights are valuable for both industrial applications and laboratory-based material characterization. Furthermore, the study supports the development of more informed decision-making in selecting analytical methods for quality control and material verification.

Despite its contributions, this study has several limitations that should be considered. The analysis was limited to a specific set of alloy steel samples, which may not fully represent all types of metallic materials. In addition, the study did not include advanced statistical validation such as correlation analysis or regression modeling to further quantify the relationship between X-ray fluorescence spectroscopy and optical emission spectroscopy results. The evaluation of detection limits and spectral resolution was based on instrument specifications rather than experimental determination. Furthermore, potential environmental factors and instrument calibration variability were not extensively analyzed. Therefore, future research is recommended to include a broader range of materials, more detailed statistical analysis, and experimental validation of spectroscopic parameters.

4. CONCLUSION

The results of this study demonstrate that both X-ray fluorescence spectroscopy and optical emission spectroscopy provide reliable elemental analysis of alloy steel, with distinct differences in spectroscopic performance. X-ray fluorescence spectroscopy offers rapid and non-destructive analysis suitable for field applications, while optical emission spectroscopy provides superior spectral sensitivity, resolution, and quantitative accuracy, particularly for trace and light elements. The observed discrepancies between the two methods are primarily attributed to matrix effects in X-ray fluorescence spectroscopy and differences in detection mechanisms. Optical emission spectroscopy, with its ability to analyze atomic emission lines, exhibits enhanced selectivity and reduced spectral interference. Therefore, the integration of both techniques can provide a comprehensive approach to material characterization by combining speed and analytical precision.

Future studies are recommended to expand the analysis to a wider range of alloy compositions and material types to improve the generalizability of the findings. In addition, further research should incorporate advanced statistical approaches such as correlation analysis, regression modeling, and uncertainty evaluation to strengthen quantitative validation. Experimental determination of detection limits and spectral resolution is also suggested to provide more accurate instrumental characterization. Moreover, investigating spectral interference and matrix effects in greater detail, particularly through controlled experiments, would enhance the understanding of spectroscopic interactions. Finally, integrating complementary analytical techniques could provide a more comprehensive approach to material characterization and improve overall analytical reliability.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to all individuals and institutions that have supported this research. Appreciation is extended to the laboratory staff and technical teams for their assistance during sample preparation and data collection processes. The authors also acknowledge the support of their respective institutions for providing facilities and resources necessary to conduct this study. In addition, thanks are given to colleagues and reviewers for their valuable suggestions and constructive feedback that improved the quality of this work.

AUTHOR CONTRIBUTIONS

Conceptualization, K.N. and R.H.S.P.; Methodology, R.H.S.P.; Software, R.H.S.P.; Validation, K.N., R.H.S.P. and P.P.; Formal Analysis, R.H.S.P.; Investigation, R.H.S.P.; Resources, K.N.; Data Curation, R.H.S.P.; Writing – Original Draft Preparation, R.H.S.P.; Writing – Review & Editing, K.N. and P.P.; Visualization, R.H.S.P.; Supervision, K.N.; Project Administration, R.H.S.P.; Funding Acquisition, K.N.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

REFERENCES

[1] N. K. Wagri *et al.*, "An overview of the machinability of alloy steel," *Mater. Today Proc.*, vol. 62, pp. 3771–3781, 2022, doi: 10.1016/j.matpr.2022.04.457.

[2] S. Mandal, R. Ghosh, S. Kunar, R. Samanta, A. Sinha, and G. Mandal, "Current development of multiphase steel: Alloy design, properties and application," *J. Inst. Eng. Ser. D*, vol. 105, no. 3, pp. 2023–2038, Dec. 2024, doi: 10.1007/s40033-024-00816-3.
[3] J. Schlegel, "Alloying elements and steel properties," in *The World of Steel*, Wiesbaden: Springer Fachmedien Wiesbaden, 2023, pp. 63–103. doi: 10.1007/978-3-658-39733-3_3.
[4] B. Wang *et al.*, "Influence of typical elements and heat treatment parameters on hardenability in steel: a review," *J. Iron Steel Res. Int.*, vol. 32, no. 6, pp. 1455–1467, Jun. 2025, doi: 10.1007/s42243-024-01307-1.
[5] V. Balaram and M. Satyanarayanan, "Data quality in geochemical elemental and isotopic analysis," *Minerals*, vol. 12, no. 8, pp. 1–18, 2022, doi: 10.3390/min12080999.
[6] A. Surleva, L. Angelova, D. Ilieva, V. Ivanova, O. Surleva, and K. Chavdarova, "Ensuring the quality of the analytical process in a research laboratory," *Aplied Sci.*, vol. 14, no. 3281, pp. 1–12, 2024, doi: 10.3390/app14083281.
[7] A. Klisińska-Kopacz, "X-ray fluorescence spectroscopy,"*Non-Destructive Material Characterization Methods*," Elsevier, 2024, pp. 487–523. doi: 10.1016/B978-0-323-91150-4.00018-5.
[8] K. Heimler, C. Gottschalk, and C. Vogt, "Confocal micro X-ray fluorescence analysis for the non-destructive investigation of structured and inhomogeneous samples," *Anal. Bioanal. Chem.*, vol. 415, no. 21, pp. 5083–5100, 2023, doi: 10.1007/s00216-023-04829-x.
[9] P. J. Potts and M. Sargent, "In situ measurements using hand-held XRF spectrometers: a tutorial review," *J. Anal. At. Spectrom.*, vol. 37, no. 10, pp. 1928–1947, 2022, doi: 10.1039/D2JA00171C.
[10] C. Piccini *et al.*, "In-field soil spectroscopy in Vis–NIR range for fast and reliable soil analysis: A review," *Eur. J. Soil Sci.*, vol. 75, no. 2, pp. 1–18, 2024, doi: 10.1111/ejss.13481.
[11] A. G. Revenko and G. V. Pashkova, "X-Ray fluorescence spectrometry: Current status and prospects of development," *Журнал аналитической химии*, vol. 78, no. 11, pp. 980–1001, Nov. 2023, doi: 10.31857/S0044450223110130.
[12] F. Bilo, P. Cirelli, and L. Borgese, "Elemental analysis of particulate matter by X-ray fluorescence methods: A green approach to air quality monitoring," *TrAC - Trends Anal. Chem.*, vol. 170, no. 117427, pp. 1–10, 2024, doi: 10.1016/j.trac.2023.117427.
[13] S. R. Khan, B. Sharma, P. A. Chawla, and R. Bhatia, "Inductively coupled plasma optical emission spectrometry (ICP-OES): A Powerful analytical technique for elemental analysis," *Food Anal. Methods*, vol. 15, no. 3, pp. 666–688, 2022, doi: 10.1007/s12161-021-02148-4.
[14] D. Zheng, P. Volovitch, and T. Pauporté, "What can glow discharge optical emission spectroscopy (GD-OES) technique tell us about perovskite solar cells?," *Small Methods*, vol. 6, no. 11, pp. 1–16, 2022, doi: 10.1002/smtd.202200633.
[15] M. S. H. Akash and K. Rehman, "Comprehensive insights into atomic emission spectroscopy," in *Essentials of Pharmaceutical Analysis*, Singapore: Springer Nature Singapore, 2025, pp. 283–319. doi: 10.1007/978-981-96-5996-8_7.
[16] A. Rautioaho, H. Pauna, V.-V. Visuri, M. Huttula, and T. Fabritius, "Electric steelmaking process monitoring with optical emission spectroscopy – An in-depth review," in *IOP Conference Series: Materials Science and Engineering*, 2024, pp. 1–12. doi: 10.1088/1757-899x/1309/1/012001.
[17] I. P. Sverchkov, I. M. Gembitskaya, V. G. Povarov, and M. A. Chukaeva, "Method of reference samples preparation for X-ray fluorescence analysis," *Talanta*, vol. 252, p. 123820, Jan. 2023, doi: 10.1016/j.talanta.2022.123820.
[18] C. Vanhoof, J. R. Bacon, U. E. A. Fittschen, and L. Vincze, "2023 atomic spectrometry update – a review of advances in X-ray fluorescence spectrometry and its special applications," *J. Anal. At. Spectrom.*, vol. 38, no. 9, pp. 1730–1743, 2023, doi: 10.1039/D3JA90026F.
[19] S. Sinha, C. Jeyaseelan, G. Singh, T. Munjal, and D. Paul, "Spectroscopy—principle, types, and applications," in *Basic Biotechniques for Bioprocess and Bioentrepreneurship*, Elsevier, 2023, pp. 145–164. doi: 10.1016/B978-0-12-816109-8.00008-8.
[20] R. D. Prasad *et al.*, "A review on spectroscopic techniques for analysis of nanomaterials and biomaterials," *ES Energy Environ.*, vol. 27, no. 1264, pp. 1–71, 2025, doi: 10.30919/es1332.
[21] P. Acquafredda and F. J. Huertas, "X-Ray fluorescence: Chemical characterization of materials by X-Ray spectrometry BT - mineralogical analysis applied to forensics: A guidance on mineralogical techniques and their application to the forensic field," M. Mercurio, A. Langella, R. M. Di Maggio, and P. Cappelletti, Eds., Cham: Springer International Publishing, 2023, pp. 225–250. doi: 10.1007/978-3-031-08834-6_8.
[22] S. I. Mamtha, R. Paranthaman, A. Negi, and J. A. Moses, "Energy dispersive X-ray fluorescence for elemental analysis of foods," *J. Food Compos. Anal.*, vol. 140, p. 107216, Apr. 2025, doi: 10.1016/j.jfca.2025.107216.
[23] V. Balaram and S. S. Sawant, "Indicator minerals, pathfinder elements, and portable analytical instruments in mineral exploration studies," 2022. doi: 10.3390/min12040394.
[24] M. Kharbach, M. Alaoui Mansouri, M. Taabouz, and H. Yu, "Current application of advancing spectroscopy techniques in food analysis: Data handling with chemometric approaches," *Foods*, vol. 12, no. 14, pp. 1–46, 2023, doi: 10.3390/foods12142753.
[25] S. A. Gegenschatz, F. A. Chiappini, C. M. Teglia, A. Muñoz de la Peña, and H. C. Goicoechea, "Binding the gap between experiments, statistics, and method comparison: A tutorial for computing limits of detection and quantification in univariate calibration for complex samples," *Anal. Chim. Acta*, vol. 1209, p. 339342, May 2022, doi: 10.1016/j.aca.2021.339342.
[26] C. M. Fisher, K. T. Peter, S. R. Newton, A. J. Schaub, and J. R. Sobus, "Approaches for assessing performance of high-resolution mass spectrometry–based non-targeted analysis methods," *Anal. Bioanal. Chem.*, vol. 414, pp. 6455–6471, 2022, doi: 10.1007/s00216-022-04203-3.
[27] Y. Liu, L. Wang, D. Li, and K. Wang, "State-of-health estimation of lithium-ion batteries based on electrochemical impedance spectroscopy: a review," *Prot. Control Mod. Power Syst.*, vol. 8, no. 1, pp. 1–17, 2023, doi: 10.1186/s41601-023-00314-w.

[28] S. Garip, Ş. Özdemir, and N. Altın, "Power system reliability assessment - A review on analysis and evaluation methods," *J. Energy Syst.*, vol. 6, no. 3, pp. 401–419, 2022, doi: 10.30521/jes.1099618.
[29] S. K. Sahoo and S. S. Goswami, "A comprehensive review of multiple criteria decision-making (MCDM) methods: Advancements, applications, and future directions," *Decis. Mak. Adv.*, vol. 1, no. 1, pp. 25–48, 2023, doi: 10.31181/dma1120237.
[30] J. Wang, M. E. Pursell, A. DeVor, O. Awoyemi, S. J. Valentine, and P. Li, "Portable mass spectrometry system: instrumentation, applications, and path to 'omics analysis," *Proteomics*, vol. 22, no. 23–24, pp. 1–40, 2022, doi: 10.1002/pmic.202200112.
[31] G. Gullifa, L. Barone, E. Papa, A. Giuffrida, S. Materazzi, and R. Risoluti, "Portable NIR spectroscopy: The route to green analytical chemistry," *Front. Chem.*, vol. 11, no. September, pp. 1–19, 2023, doi: 10.3389/fchem.2023.1214825.
[32] E. M. Jenkins, J. Galbraith, and A. A. Paltseva, "Portable X-ray fluorescence as a tool for urban soil contamination analysis: accuracy, precision, and practicality," *Soil*, vol. 11, no. 2, pp. 565–582, 2025, doi: 10.5194/soil-11-565-2025.
[33] M. C. Chen, Y. C. Lee, J. H. Tee, M. T. Lee, C. K. Ting, and J. Y. Juang, "AI-powered precursor quantification in atmospheric pressure plasma jet thin film deposition via optical emission spectroscopy," *Plasma Sources Sci. Technol.*, vol. 33, no. 10, pp. 1–12, 2024, doi: 10.1088/1361-6595/ad80c6.
[34] X. Wei, A. Mitchell, R. Sun, N. Yu, and K. Yamamura, "A review of simulation modeling of the state evaluation and process prediction of plasma processing under atmospheric pressure," *Nanomanufacturing Metrol.*, vol. 7, no. 16, pp. 1–44, 2024, doi: 10.1007/s41871-024-00234-9.
[35] S. Imashuku and K. Wagatsuma, "Imaging measurement for the inclusion analysis of steel materials in emission spectrometry," *ISIJ Int.*, vol. 62, no. 5, pp. 811–820, 2022, doi: 10.2355/isijinternational.ISIJINT-2021-393.
[36] S. Porcinai, A. Cagnini, M. Galeotti, and M. Ferretti, "Quantitative analysis of copper alloys by means of portable X-ray fluorescence: A comparison between analysis of shavings and surfaces," *Spectrochim. Acta Part B At. Spectrosc.*, vol. 210, p. 106808, Dec. 2023, doi: 10.1016/j.sab.2023.106808.
[37] R. Haque, "Automation in manufacturing: A systematic review of advanced time management techniques to boost productivity," *Am. J. Sch. Res. Innov.*, vol. 02, no. 01, pp. 50–78, 2023, doi: 10.63125/z1wmcm42.
[38] C. A. Cavalcante, A. C. Santos, R. G. Paiva, A. A. Aribisala, and R. B. Da Silva, "Delay time model for determining the effectiveness of a system under adverse conditions of production and inspection," *Proc. Inst. Mech. Eng. Part O J. Risk Reliab.*, vol. 238, no. 6, pp. 1136–1155, Dec. 2024, doi: 10.1177/1748006X231207529.
[39] R. López-Núñez, "Portable X-ray fluorescence analysis of organic amendments: A review," *Appl. Sci.*, vol. 12, no. 14, pp. 1–20, 2022, doi: 10.3390/app12146944.
[40] C. Vanhoof, A. Cross, U. E. A. Fittschen, and L. Vincze, "Atomic spectrometry update: review of advances in X-ray fluorescence spectrometry," *J. Anal. At. Spectrom.*, vol. 40, no. 9, pp. 2275–2289, 2025, doi: 10.1039/D5JA90030A.
[41] S. Guergan *et al.*, "Optical emission spectroscopy for the real-time identification of malignant breast tissue," *Diagnostics*, vol. 14, no. 3, pp. 1–15, 2024, doi: 10.3390/diagnostics14030338.
[42] P. Punia, M. K. Bharti, R. Dhar, P. Thakur, and A. Thakur, "Recent advances in detection and removal of heavy metals from contaminated water," *ChemBioEng Rev.*, vol. 9, no. 4, pp. 351–369, Aug. 2022, doi: 10.1002/cben.202100053.
[43] R. teja Vulchi, V. Morgunov, R. Junjuri, and T. Bocklitz, "Artifacts and anomalies in raman spectroscopy: A review on origins and correction procedures," *Molecules*, vol. 29, no. 19, pp. 1–24, 2024, doi: 10.3390/molecules29194748.
[44] C. M. Gonzalez, T. Horrocks, D. Wedge, E. J. Holden, N. Hackman, and T. Green, "Anomaly detection in Fourier transform infrared spectroscopy of geological specimens using variational autoencoders," *Ore Geol. Rev.*, vol. 158, no. 105478, pp. 1–14, 2023, doi: 10.1016/j.oregeorev.2023.105478.
[45] M. L. Tietze, M. Obst, G. Arnauts, N. Wauteraerts, S. Rodríguez-Hermida, and R. Ameloot, "Parts-per-million detection of volatile organic compounds via surface plasmon polaritons and nanometer-thick metal-organic framework films," *ACS Appl. Nano Mater.*, vol. 5, no. 4, pp. 5006–5016, 2022, doi: 10.1021/acsanm.2c00012.
[46] M. Snellman, P. Samuelsson, A. Eriksson, Z. Li, and K. Deppert, "On-line compositional measurements of AuAg aerosol nanoparticles generated by spark ablation using optical emission spectroscopy," *J. Aerosol Sci.*, vol. 165, no. 106041, pp. 1–11, 2022, doi: 10.1016/j.jaerosci.2022.106041.
[47] A. Kohut, L. P. Villy, G. Kohut, G. Galbács, and Z. Geretovszky, "A calibration-free optical emission spectroscopic method to determine the composition of a spark discharge plasma used for auag binary nanoparticle synthesis," *Appl. Spectrosc.*, vol. 77, no. 12, pp. 1401–1410, Dec. 2023, doi: 10.1177/00037028231207358.
[48] H. Mohrbacher and A. Kern, "Nickel alloying in carbon steel: fundamentals and applications," *Alloys*, vol. 2, no. 1, pp. 1–28, 2023, doi: 10.3390/alloys2010001.
[49] H. Firmanto, S. Candra, M. A. Hadiyat, Y. P. Triastomo, and I. Wirawan, "Tensile strength and microstructure of rotary friction-welded carbon steel and stainless steel joints," *J. Manuf. Mater. Process.*, vol. 7, no. 1, pp. 1–17, 2023, doi: 10.3390/jmmp7010007.
[50] D. Sur, A. Gupta, S. Dubey, and A. Kumar, "Properties of materials and selection criteria," in *Chemical Engineering Essentials 2*, Wiley, 2025, pp. 79–107. doi: 10.1002/9781394372379.ch4.
[51] D. Guan *et al.*, "Hydrogen society: from present to future," *Energy Environ. Sci.*, vol. 16, no. 11, pp. 4926–4943, 2023, doi: 10.1039/d3ee02695g.
[52] G. E. Acquah *et al.*, "Portable X-ray fluorescence (pXRF) calibration for analysis of nutrient concentrations and trace element contaminants in fertilisers," *PLoS One*, vol. 17, no. 1 January, pp. 1–20, 2022, doi: 10.1371/journal.pone.0262460.
[53] C. L. S. Costa, C. T. Prais, and C. C. Nascentes, "A simple method for glass analysis using total reflection X-ray fluorescence spectrometry," *Talanta*, vol. 243, no. 123354, pp. 1–7, 2022, doi: 10.1016/j.talanta.2022.123354.
[54] L. N. Muhammad, "Guidelines for repeated measures statistical analysis approaches with basic science research considerations," *J. Clin. Invest.*, vol. 133, no. 11, pp. 2–4, 2023, doi: 10.1172/JCI171058.
[55] J. Atkinson, L. A. Brudvig, M. Mallen-Cooper, S. Nakagawa, A. T. Moles, and S. P. Bonser, "Terrestrial ecosystem

restoration increases biodiversity and reduces its variability, but not to reference levels: A global meta-analysis," *Ecol. Lett.*, vol. 25, no. 7, pp. 1725–1737, 2022, doi: 10.1111/ele.14025.
[56] A. Ntziouni *et al.*, "Review of existing standards, guides, and practices for raman spectroscopy," *Appl. Spectrosc.*, vol. 76, no. 7, pp. 747–772, 2022, doi: 10.1177/00037028221090988.
[57] M. Aramendía *et al.*, "A novel approach for adapting the standard addition method to single particle-ICP-MS for the accurate determination of NP size and number concentration in complex matrices," *Anal. Chim. Acta*, vol. 1205, no. 339738, pp. 1–12, 2022, doi: 10.1016/j.aca.2022.339738.
[58] X. Chen, W. Shu, L. Zhao, and J. Wan, "Advanced mass spectrometric and spectroscopic methods coupled with machine learning for in vitro diagnosis," *VIEW*, vol. 4, no. 1, pp. 1–10, Feb. 2023, doi: 10.1002/VIW.20220038.
[59] M. Ortiz-Martínez, J. A. Molina González, G. Ramírez García, A. de Luna Bugallo, M. A. Justo Guerrero, and E. C. Strupiechonski, "Enhancing sensitivity and selectivity in pesticide detection: A review of cutting-edge techniques," *Environ. Toxicol. Chem.*, vol. 43, no. 7, pp. 1468–1484, 2024, doi: 10.1002/etc.5889.
[60] J. Lu *et al.*, "A matrix effect correction method for portable X-ray fluorescence data," *Appl. Sci.*, vol. 12, no. 2, pp. 1–11, 2022, doi: 10.3390/app12020568.
[61] M. Wang, Y. Gu, H. Lu, L. Ge, Q. Zhang, and G. Zeng, "Matrix effect correction method based on the main spectral parameters for rock samples in an in situ energy dispersive X-ray fluorescence analysis," *Spectrochim. Acta - Part B At. Spectrosc.*, vol. 193, no. 106438, pp. 1–7, 2022, doi: 10.1016/j.sab.2022.106438.
[62] Y. Zhang *et al.*, "Total reflection X-ray fluorescence spectrometry: A comprehensive review of critical components, analytical benefits and practical applications," *Crit. Rev. Anal. Chem.*, vol. 56, no. 2, pp. 311–330, Feb. 2025, doi: 10.1080/10408347.2024.2411245.
[63] Y. Hang, A. Wang, and N. Wu, "Plasmonic silver and gold nanoparticles: shape- and structure-modulated plasmonic functionality for point-of-caring sensing, bio-imaging and medical therapy," *Chem. Soc. Rev.*, vol. 53, no. 6, pp. 2932–2971, 2024, doi: 10.1039/D3CS00793F.
[64] Y. Xiong *et al.*, "Photonic crystal enhanced fluorescence: A review on design strategies and applications," *Micromachines*, vol. 14, no. 3, pp. 9–11, 2023, doi: 10.3390/mi14030668.
[65] A. S. Maltsev, R. A. Yusupov, and S. A. Bakhteev, "Overcoming absorption effects in the determination of light elements in beverages by total-reflection X-ray spectrometry," *X-Ray Spectrom.*, vol. 52, no. 4, pp. 160–167, Jul. 2023, doi: 10.1002/xrs.3283.
[66] E. De Pauw *et al.*, "Determination of rare earth elements in cosmo-geological samples aided by wavelength dispersive X-ray fluorescence spectroscopy," *ACS Earth Sp. Chem.*, vol. 8, no. 12, pp. 2546–2556, Dec. 2024, doi: 10.1021/acsearthspacechem.4c00235.
[67] F. Li, L. Meng, W. Ding, J. Wang, and L. Ge, "Review of energy-dispersive X-ray fluorescence on food elements detection," *X-Ray Spectrom.*, vol. 51, no. 4, pp. 346–364, Jul. 2022, doi: 10.1002/xrs.3279.
[68] A. A. AL-Tameemi, F. Li, Q. Zhang, Z. Xiao, W. Yang, and S. Lyu, "Quantitative analysis of Cu, Zn, and Pb elements in ores by X-ray fluorescence using a hierarchical convolutional network with attention excitation," *J. Anal. At. Spectrom.*, vol. 40, no. 6, pp. 1580–1590, 2025, doi: 10.1039/D5JA00047E.
[69] T. Monot, M. O. Simonnot, and B. Laubie, "Relevance of using portable X-ray fluorescence to identify gold hyperaccumulator plants," *Environ. Adv.*, vol. 16, no. 100556, pp. 1–6, 2024, doi: 10.1016/j.envadv.2024.100556.
[70] R. S. Mohammed, K. A. Aadim, and K. A. Ahmed, "Spectroscopy diagnostic of laser intensity effect on Zn plasma parameters generated by Nd: YAG laser," *Iraqi J. Sci.*, vol. 63, no. 9, pp. 3711–3718, 2022, doi: 10.24996/ijs.2022.63.9.5.
[71] X. Chen and X. Huang, "Highly efficient and thermally stable NIR-emitting phosphor with largely tunable peak wavelength and bandwidth toward NIR Spectroscopy applications," *Laser Photon. Rev.*, vol. 19, no. 11, pp. 1–10, Jun. 2025, doi: 10.1002/lpor.202402226.
[72] L. Zhou *et al.*, "Additive manufacturing: A comprehensive review," *Sensors*, vol. 24, no. 9, pp. 1–44, 2024, doi: 10.3390/s24092668.
[73] M. J. Pushie, N. J. Sylvain, H. Hou, M. J. Hackett, M. E. Kelly, and S. M. Webb, "X-ray fluorescence microscopy methods for biological tissues," *Metallomics*, vol. 14, no. 6, pp. 1–31, 2022, doi: 10.1093/mtomcs/mfac032.
[74] I. Purwadi, L. W. Casey, C. G. Ryan, P. D. Erskine, and A. van der Ent, "X-ray fluorescence spectroscopy (XRF) for metallome analysis of herbarium specimens," *Plant Methods*, vol. 18, no. 1, pp. 1–17, 2022, doi: 10.1186/s13007-022-00958-z.
[75] L. M. Kandpal, M. A. Munnaf, C. Cruz, and A. M. Mouazen, "Spectra fusion of mid-infrared (MIR) and X-ray fluorescence (XRF) spectroscopy for estimation of selected soil fertility attributes," *Sensors*, vol. 22, no. 9, pp. 1–16, 2022, doi: 10.3390/s22093459.
[76] C. M. Heirwegh, W. T. Elam, L. P. O'Neil, K. P. Sinclair, and A. Das, "The focused beam X-ray fluorescence elemental quantification software package PIQUANT," *Spectrochim. Acta - Part B At. Spectrosc.*, vol. 196, no. 106520, pp. 1–12, 2022, doi: 10.1016/j.sab.2022.106520.