

A Reassessment of Portable X-Ray Fluorescence (PXRF) Data for Timurid Silver Coins from the Avicenna Tomb Museum

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Abstract

Timurid coinage functions as a material repository, mirroring the significant economic and political shifts characterizing the era, thereby offering crucial insights into the socio-economic structure of the Timurid Empire. This investigation critically examines a collection of Timurid numismatic artifacts housed in the Avicenna tomb Museum utilizing X-ray Fluorescence (XRF) spectroscopy. The meticulous re-evaluation of preliminary XRF spectroscopic data is paramount, particularly within the discipline of numismatics, as it constitutes a foundational requisite for mitigating analytical errors and augmenting the precision of interdisciplinary assessments. While XRF technology provides a non-destructive means for the precise determination of elemental composition within the coinage, a failure to implement rigorous monitoring and comprehensive data scrutiny risks introducing substantial historical misinterpretation and analytical uncertainty. This study addresses core research questions concerning the substantive value of re-analyzing and interpreting XRF spectral outputs, specifically concerning their utility in authenticity verification (counterfeit identification) and the delineation of underlying economic and cultural characteristics. The central hypothesis asserts that unprocessed XRF spectral data lacks inherent accuracy and necessitates expert-driven, in-depth analysis for conclusive artifact examination. Furthermore, the research underscores the necessity of detailed spectral profiling, acknowledges inherent technical complexities in data interpretation, and advocates for interdisciplinary methodologies to substantially enhance result validity. The findings conclusively demonstrate that a profound reinterpretation of XRF analytical data significantly advances the comprehension of material provenance, safeguards cultural heritage assets, and yields more nuanced understandings of Timurid economic governance.

Keywords: X-Ray Fluorescence Spectroscopy, Timurid Coins, Interdisciplinary Studies, Numismatics, Elemental Composition.



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Introduction

The Timurid coins (1370–1507AD) represent significant economic and political transformations of their era. The study of these coins can provide valuable insights into the economic and social conditions of the Timurid dynasty. The analysis of inscriptions, styles, and patterns used in coin designs, created by skilled calligraphers and prominent artists of the time, reflects the unique artistic and ideological trends of this period (Mirakhourlou & Sharafi, 2022: 160; Bragin & Petrov, 2017: 161). In recent years, specialized studies have increasingly leaned towards interdisciplinary knowledge. One practical approach in this field is analyzing the chemical elements of ancient coins through the method of “X-ray fluorescence spectroscopy”. X-ray fluorescence spectroscopy, as a non-destructive analytical method, has gained considerable attention in numismatics studies, particularly in museums and among numismatic collectors. This method enables rapid and accurate multi-elemental analysis, both quantitatively and qualitatively, without altering or manipulating the sample’s surface, making it highly suitable for preserving valuable artifacts (Mantouvalou *et al.*, 2014: 9774).

The non-invasive and non-destructive nature of X-ray fluorescence spectroscopy ensures the integrity of the coins is preserved without causing any damage, a critical factor in safeguarding cultural heritage. During the process of X-ray fluorescence spectroscopy, X-rays from an external source are directed onto the sample. These high-energy X-rays interact with the atoms in the sample, exciting the electrons in the inner shells of the atoms and ejecting them from their orbits (Streli *et al.*, 1999). To return to a stable state, the atoms transfer electrons from higher-energy shells to the inner shells. This process results in the emission of fluorescent X-rays with characteristic energy levels specific to each element. These fluorescent X-rays are measurable and can help identify the elements present in the sample (Karathanasis & Hajek, 1996: 167). All this information is presented in tables as outputs by the device (Weltje & Tjallingii, 2008: 6). At this stage, these data are considered raw information. Along with these tables, spectra labeled as spectrometer outputs are provided, which, based on the horizontal and vertical axes, indicate various parameters related to X-ray fluorescence (XRF) spectroscopy. The horizontal axis displays the energy scale of X-rays in kilo electron volts (keV). Each element in the sample emits X-ray fluorescence at specific wavelengths or energies due to its unique atomic properties (Shackley, 2010). Therefore, by identifying the energy of different peaks, it is possible to determine the various elements present in the sample. The vertical axis represents the number of photons detected at each specific energy (intensity), referred to as the “count rate”. The height of the peaks in this chart correlates with the concentration of that specific element in the sample. The peaks visible in the spectrum correspond to different elements. Typically, each element has characteristic

peaks in the energy spectrum. For instance, the tall peaks in Figure 1 indicate the matrix elements present in the sample ($K\alpha$ and $K\beta$ of Ag), while smaller peaks may represent trace elements. This chart enables researchers to identify the type and concentration of elements in the sample by observing the energy peaks. To correctly interpret these spectra, understanding the characteristics of the studied materials and utilizing advanced analytical methods is essential. The raw data from X-ray fluorescence spectroscopy only reveal the chemical composition of the coins. However, for a precise and comprehensive understanding of these data, human interpretation and analysis are crucial. This research investigates how human interpretation of X-ray fluorescence spectroscopy data can lead to accurate and meaningful results in understanding the chemical composition and authenticity of coins. This study holds importance for several reasons. First, by analyzing the elemental composition and inscriptions of Timurid coins, it contributes to a deeper understanding of the economic, political, and cultural aspects of this period. Second, the research emphasizes the significance of combining scientific X-ray fluorescence spectroscopy data with expert interpretation to achieve more precise and meaningful results in numismatic studies.

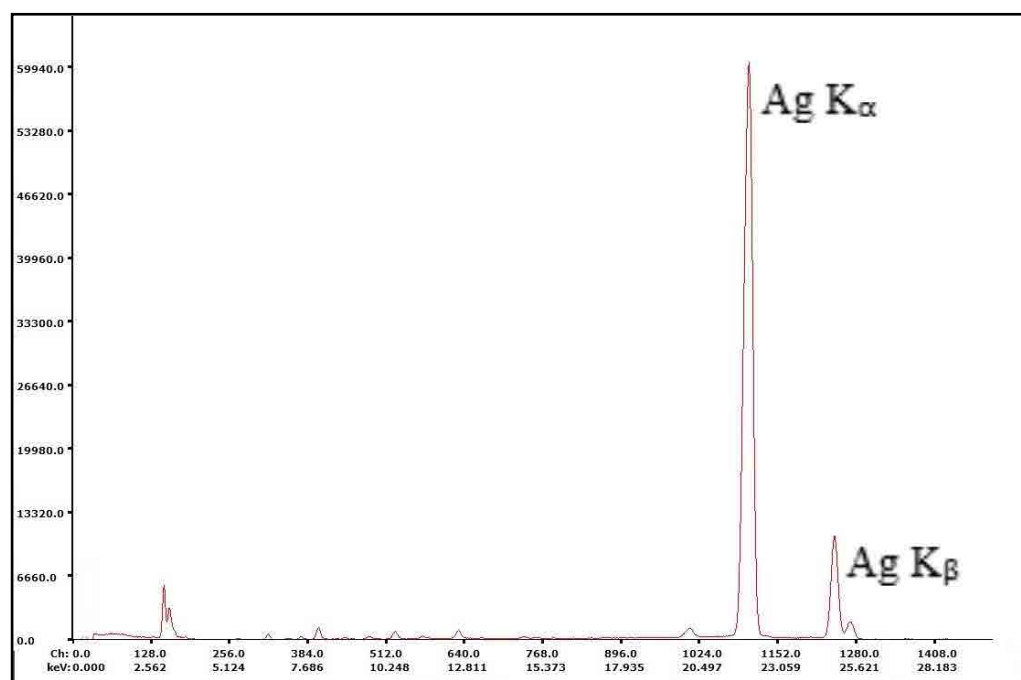


Fig. 1: XRF spectrum of coin No. 8 (Author, 2024).

Additionally, the importance of non-destructive methods like X-ray fluorescence spectroscopy in preserving cultural heritage and historical coins becomes evident through this study. For the coin analysis, a portable X-ray fluorescence (XRF) spectrometer, Bruker S1 TITAN, was utilized. The S1 TITAN is equipped with a 50 kV X-ray tube and a high-precision silicon drift detector (SDD), enabling the detection of elements ranging from magnesium (Mg) to uranium (U). This device is integrated with advanced

software for qualitative and quantitative analysis. For qualitative analysis, spectrum acquisition, and data processing, the built-in S1 TITAN software was employed. This software facilitates spectrum acquisition and qualitative identification of elements. During qualitative analysis, spectra were acquired using the device's default settings, operating at 50 kV voltages and 50 μ A current. The S1 TITAN's capability allows for the excitation and detection of X-ray fluorescence from elements in the sample at concentrations as low as approximately 1 ppm and above. The same conditions, with 50 kV voltage and 50 μ A current, were maintained throughout the analysis to ensure consistency and reliability of all results.

Research Objectives: The principal aims of this investigation are delineated as follows:

- To articulate the inherent limitations of raw data generated by X-ray Fluorescence (XRF) spectroscopy and to substantiate the necessity of specialized human interpretation and analysis within numismatic scholarship.
- To evaluate the consequential impact of interdisciplinary analytical approaches on the accurate identification and comprehensive analysis of Timurid coinage, thereby facilitating a deeper understanding of the corresponding economic and political contexts.
- To underscore the critical importance of precise interpretation of XRF spectra in accurately determining the coins' elemental composition and manufacturing techniques, thereby preempting potential historical and analytical misinterpretations.

Research Questions: This study seeks to address the following fundamental inquiries:

- To what extent can expert human analysis and scholarly contributions enhance the accuracy of identification and interpretation of Timurid numismatic artifacts?
- What significant impact does the specialized interpretation and analysis of XRF spectroscopy data exert on the overall outcomes and conclusions of numismatic research?

Hypotheses: The research is guided by the following core propositions:

- Raw, unprocessed X-ray Fluorescence spectroscopy data is insufficient to yield a comprehensive understanding of the chemical composition of Timurid coinage. Therefore, specialized human interpretation and post-processing of data are essential for accurate authentication and definitive identification.
- The rigorous analysis of X-ray Fluorescence spectroscopy data will demonstrably contribute to the authentication of coins, effectively aid in the identification of counterfeits, and ultimately enhance scholarly knowledge regarding regional trade networks during the Timurid period.

Research Limitations: This investigation is constrained by specific factors that may influence the scope of interpretation and statistical robustness:

The research faces restrictions due to limited access to a statistically representative sample of Timurid coin specimens and a simultaneous scarcity of comprehensive historical documentation pertaining to contemporary minting processes. These constraints are anticipated to present challenges in both the rigorous interpretation of elemental data and subsequent statistical validation.

Literature Review

Recent scholarship has firmly established the efficacy of advanced analytical techniques in cultural heritage studies. [Acquafredda \(2019\)](#) introduced Energy-Dispersive X-ray Fluorescence (EDXRF), characterizing it as a non-destructive, rapid, multi-elemental, and highly precise method for elemental analysis. The author highlighted its extensive applicability across diverse fields, including quality control, environmental monitoring, and crucially, cultural heritage analysis. [Oyedotun \(2018\)](#) provided a thorough review focusing on XRF applications in the analysis of geo-materials, underscoring its speed and accuracy while prudently cautioning against potential calibration errors. In the context of ancient Near Eastern numismatics, [Hajivaliei et al., \(2008; 2012\)](#) employed Particle-Induced X-ray Emission (PIXE) to study Sasanian and Parthian coins, respectively. Further contributions by [Salehi et al., \(2015\)](#) and [Hajivaliei & Sodaee \(2016\)](#) utilized PIXE and Wavelength-Dispersive X-ray Fluorescence (WDXRF), respectively, in the detailed investigation of Sasanian coinage. More contemporary Iranian archaeometric scholarship includes an overview by [Kakooei et al., \(2022\)](#) on the field's potential in Iran, alongside specific applications such as the examination of Khosrow Parviz silver coins by [Hajivaliei et al., \(2022\)](#) and Ilkhanid coins by [Mirsafdari & Hajivaliei \(2022\)](#) using XRF methodologies.

Article Text

The two essential analytical parameters governing XRF performance are accuracy and sensitivity. These principles are essential for unbiased analyses. Accuracy refers to how closely a measurement aligns with the true value, while sensitivity indicates the ability to detect low concentrations of elements. Expert review of the initial results from X-ray fluorescence spectroscopy is crucial to ensure the accuracy and analytical capability of elements in scientific studies. This process aids in identifying potential errors and mistakes in data interpretation, which can significantly impact research outcomes. The following sections elaborate on the importance of expert review in XRF analysis. One of the errors that necessitate a re-examination of results is calibration error. Although a high-precision technique can provide unbiased results, these results may still be incorrect, especially if impurities were introduced during sample preparation or due to calibration errors. To achieve reliable and standardized XRF results, attention must

be paid to both accuracy and precision. To address deviations (inaccuracy, whether short-term or long-term), several variables must be considered. These variables include the stability of the XRF device, accuracy in sample preparation, calibration of the device with the most suitable and acceptable reference standards, monitoring and managing room temperature, monitoring voltage fluctuations due to power variations, and considering other external factors (Oyedotun, 2018: 148). In X-ray fluorescence spectroscopy, identifying and distinguishing between different elements in samples can become complex and challenging when they have similar energy characteristics. This issue is particularly prevalent for elements that are close to each other in the periodic table or have similar electronic properties. For example, elements like cobalt (Co) and nickel (Ni) emit fluorescent rays that have closely related energies: the $K\beta$ peak of cobalt (Co) is approximately at energy of 7.650 keV, while the $K\alpha$ peak of nickel (Ni) is around 7.480 keV. Although this difference in fluorescent energies is measurable, its amount is very small, and therefore, we need a high level of precision and experience to analyze and identify these elements. Otherwise, similar energies may overlap, which can lead to misidentification and ultimately inaccurate results. In the analysis of samples using X-ray fluorescence spectroscopy, detecting surface contaminants or thin layers of other materials is very important. This method becomes particularly significant due to its capabilities in identifying chemical elements at the surface of the sample, especially in cases where the samples may have been moved under unusual conditions, such as those seized from traffickers. When contaminants or external layers are present on the surface of the sample, the results obtained from X-ray fluorescence spectroscopy can be affected, as this method fundamentally relies on the energies emitted from within the materials. For this reason, the presence of surface compounds may lead to erroneous or invalid results.

At this point, the role of specialized individuals in interpreting the results of X-ray fluorescence spectroscopy becomes evident. Skilled analysts, with their experience, can determine which data may be invalid due to surface contaminants and what actions should be taken to correct them. Trace elements refer to those elements that are present in very small amounts in samples, typically constituting less than 1 percent by weight of the total sample. In analytical methods such as X-ray fluorescence spectroscopy, detecting these elements is challenging because their intensity is weaker than that of the major or abundant elements in the sample. In other words, since the concentration of these elements in the sample is low, the X-ray energy produced from these elements is also lower, making their identification more prone to error. In spite of this difficulty, one source specifically noted that in a study, the detection limit of the X-ray fluorescence spectroscopy device was approximately 0.1 percent by weight. This means that elements or compounds with amounts below this threshold may be identified with low

accuracy or may even be undetectable in some cases. Detecting trace elements in X-ray fluorescence spectroscopy analysis is considered a challenge due to their weak intensity and competition with the intensity of dominant elements, and improving the accuracy of the analysis requires precise adjustments and specialized interpretation. In the analysis of heavy elements such as gold using X-ray spectroscopy, spectral overlap occurs between the X-ray lines of heavy and light elements, such as K X-ray and L X-ray. For example, the energy of K X-ray from iron (Fe) and L X-ray from the element dysprosium (Dy) are similarly located in the energy range of 6.40 keV. This overlap can significantly impact the accuracy and precision of measuring the concentration of heavy elements in samples. Therefore, a thorough analysis of the results from X-ray fluorescence spectroscopy and the correct interpretation of the obtained data are essential to ensure the validity and accuracy of the results and the proper interpretation of the chemical compositions of the samples. For detailed examination and interpretation within this specialized context, the characteristics of the studied Timurid coin specimens from the Avicenna Tomb collection are delineated across four distinct tables, beginning with their numismatic identity. The initial table provides the numismatic identification and iconographic description of the ten analyzed coins, specifying the ruler's name and presenting visual evidence of the obverse and reverse (see: Table 1). Following this, Table 2 presents the Physical and metrological specifications (Diameter and Mass) for each coin, establishing their crucial quantitative parameters. Finally, the chemical analysis of these specimens was performed using XRF spectroscopy. Compositional analysis of coins is the primary aim; therefore, depending on the coin numbers, the elements titanium (Ti), chromium (Cr), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), arsenic (As), gold (Au), silver (Ag), and lead (Pb) were detected. Table 3 summarizes the Initial raw elemental composition results announced by the XRF device. In the table 4, final results are given.

Table 1: Numismatic identification and iconographic description of the studied Timurid coins (Authors, 2024). (The images have been digitally enhanced for readability using Adobe Photoshop; Table prepared by the authors.)

Coin No.	King's Name	Reverse	Obverse
1	Babur		
2	?		

3	Amir Timur		
4	Shahrokh Bahadur		
5	?		
6	Shah Rukh, the Great Sultan of Samarkand		
7	Suspected of Mahmud Khan or Timur		
8	Mughal Emperor of India		
9	Shahrokh Timuri		
10	Amir Timur		

Table 2: Physical and metrological specifications of the analyzed Timurid coin specimens (Authors, 2024). (All measurements were performed using calibrated precision instruments under controlled laboratory conditions; Table compiled by the authors).

Coin No.	1	2	3	4	5	6	7	8	9	10
Diameter (mm)	27	16	17	23	25	17	22	24	23	25
Mass (g)	5	2	1.9	5	3.7	2.8	3	2.3	2.4	2.8

Table 3: Initial raw elemental composition results of Timurid coins determined by X-ray Fluorescence (XRF) spectroscopy (values in weight percent), (Authors, 2024). (< LOD indicates concentration below the Limit of Detection; Table prepared by the authors)

Coin No.	Pb	Ag	Au	As	Zn	Cu	Fe	Mn	Cr	Ti
1	0.07	99.0	0.8			0.44	0.32	0.01	0.07	
2	0.65	97.7	0.2			0.98	0.70	< LOD	0.01	
3	0.08	98.7	0.3			0.52	0.62	0.01	0.01	
4	0.81	97.4	0.3			0.68	1.09	0.01	0.01	0.02
5	0.78	< LOD	0.1	0.5	0.06	98.70	< LOD	< LOD	0.02	
6	0.41	98.4	0.3			0.75	0.44	0.01	0.02	
7	0.69	96.2	0.3			2.15	0.89	0.01	0.09	
8	0.95	97.7	0.1			0.75	0.54	0.01	0.08	
9	0.44	98.7	0.2			0.40	0.44	0.01	0.09	
10	2.12	95.3	0.1			0.56	1.91	0.01	0.01	

1. Titanium

The presence of titanium in base metals may be due to their extraction from areas with mineral deposits containing this element. In the past, the technology for extracting and refining metals was not as precise as it is today, and ores often included impurities such as titanium.

2. Iron

The presence of iron in coins can be attributed to several factors:

Burial conditions: Contact with iron-bearing minerals or chemical reactions in the soil can lead to the accumulation of iron on the surface of the coin.

Surface contamination: Sometimes, iron is reported as surface contamination (Breitenstein *et al.*, 2013). One reason for the presence of iron in the analysis is human sweat. **Corrosion:** Iron present at less than 1% is likely a result of smelting and refining processes and is not due to corrosion. If the percentage of iron exceeds 1%, the possibility of corrosion is raised.

3. Copper and Lead

Copper and lead are often attributed to ancient processes of cupellation:

Cupellation of lead: a technique in which lead and silver ore is melted, then lead is oxidized to obtain pure silver (Casas & Sordo, 2006). One of the applications of lead in coinage is to lower the melting point. In these coins, the edges have a broken appearance.

Low concentration of lead: In cases such as coins number 1, 3, 6, 9, and 10, where the concentration of lead is below 0.5%, this amount indicates an effective smelting and refining process (Civici *et al.*, 2007).

4. Gold

The presence of gold has sometimes been reported as components of silver ore (Gale *et al.*, 1980). This reference is incorrect.

5. Trace Elements and Impurities (some elements at very low percentages)

Trace elements and impurities are usually a result of the production process, but they may also be observed due to surface contamination (Constantinescu *et al.*, 2003). Some elements, such as rhodium (Rh), may be recorded in spectral data due to the lamp radiation conditions of the device and argon (Ar) used as a filler gas in the space between the device and the sample, as well as the presence of air in the environment. This phenomenon is related to external influences and the lack of purity in the analysis environment.

6. Arsenic in Counterfeit Coins

The presence of arsenic in the alloy of counterfeit coin number 5 is likely indicative of its fabrication and the use of minting methods (Hajivaliei *et al.*, 2023).

After a thorough review and reassessment, and based on the errors and information presented in the article, the final results deemed significant in numismatic studies are reported below in Table 4.

Table 4: Percentage of elements in the analyzed Timurid silver coins after matrix correction (Authors, 2024). (Values represent normalized weight percentages; data refined through matrix adjusted calibration to enhance compositional accuracy; Table prepared by the authors.)

Coin No.	% Ag	% Au	% Cu	% Pb	% Fe	% As
1	98.7	0.70	0.50	0.10	-	-
2	97.4	0.20	1.00	0.70	0.70	-
3	98.5	0.30	0.50	0.08	0.60	-
4	97.4	0.30	0.70	0.80	0.80	-
5	-	0.10	98.60	0.80	-	0.5
6	98.1	0.30	0.80	0.40	0.40	-
7	96.1	0.30	2.10	0.70	0.80	-
8	97.7	0.10	0.70	1.00	0.50	-
9	98.6	0.20	0.40	0.40	0.40	-
10	95.3	0.10	0.60	2.10	1.90	-

Conclusion

Compared to other analytical methods, X-ray fluorescence spectroscopy can quickly identify the chemical compositions of valuable historical samples without causing damage. However, as researchers (Mantouvalou *et al.*, 2014) have pointed out, more precise analysis is essential for the correct interpretation of the data. According to the findings, spectral overlap among certain elements and challenges arising from surface contamination of the samples may reduce the accuracy of the results. Trace elements present at very low concentrations may also remain undetected or not be accurately identified due to weaker intensity. This issue clearly highlights the importance of fine-tuning the equipment and the need for specialized interpretation of the data by experts. Interdisciplinary research that combines archaeology and technical expertise can provide better solutions for analyzing and understanding the historical and cultural contexts of numismatics. The overlap of various elements, challenges arising from surface contaminants and the presence of trace elements are among the factors that affect the accuracy of results. Therefore, integrating archaeological knowledge with technical expertise can aid in more precise identification of chemical compositions and a deeper understanding of Timurid coins and their historical contexts. Additionally, this research emphasizes the importance of expert analysis and the processing of raw data from X-ray fluorescence spectroscopy to obtain reliable and meaningful information from historical artifacts. It is worth mentioning that coin number 5 has been mistakenly listed among the silver coins of the museum, and this coin is actually made of copper.

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Conflict of Interest

The results obtained in this research do not conflict with any individual or organization.

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بازبینی داده‌های FRXP برای سکه‌های نقره تیموری از موزه آرامگاه بوعلی سینا: تضمین دقت با تحلیل تخصصی

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چکیده

سکه‌های تیموری، آینه‌ای از وقایع اقتصادی و سیاسی مهم تیموریان هستند و مطالعه آن‌ها می‌تواند به فهم عمیق‌تر وضعیت اقتصادی و اجتماعی این دوره کمک کند. این پژوهش با استفاده از طیف‌سنجی فلورسانس اشعه ایکس به بررسی سکه‌های تیموری موزه آرامگاه بوعلی سینا پرداخته است. بازبینی تخصصی نتایج اولیه دستگاه طیف‌سنجی فلورسانس اشعه ایکس (PXRF) به‌ویژه در مطالعات سکه‌شناسی، از اهمیت بالایی برخوردار است و می‌تواند به عنوان یک گام اساسی در راستای کاهش خطا و افزایش دقت در تحلیل‌های میان‌رشته‌ای موردتوجه قرار گیرد. فناوری PXRF به عنوان یک روش غیرمخرب، قابلیت بررسی دقیق ترکیب شیمیایی و تعیین عنصرهای موجود در سکه‌ها را فراهم می‌آورد؛ اما بدون پایش دقیق و بازبینی جامع نتایج به دست آمده، ممکن است به تفسیر نادرست و عدم قطعیت در تحلیل‌های تاریخی منجر شود. پرسش‌های پژوهش درباره ارزش بازخوانی و تفسیر داده‌های طیف‌سنجی فلورسانس اشعه ایکس و نقش آن‌ها در شناسایی سکه‌های جعلی و درک ویژگی‌های اقتصادی و فرهنگی در مطالعات سکه‌شناسی است. فرضیه کلیدی پژوهش می‌گوید که داده‌های خام طیف‌سنجی فلورسانس اشعه ایکس نتایج دقیقی ارائه نمی‌دهد و برای مطالعه دقیق سکه‌ها نیاز به واکاوی تخصصی توسط افراد متخصص وجود دارد. این پژوهش هم‌چنین به اهمیت بررسی دقیق طیف‌ها و چالش‌های فنی در بازخوانی داده‌ها پرداخته و شیوه‌های میان‌رشته‌ای را برای افزایش دقت نتایج به کار می‌بندد. یافته‌ها نشان دادند که بازخوانی ژرف‌تر داده‌های طیف‌سنجی فلورسانس اشعه ایکس، در شناخت بهتر ترکیب شیمیایی سکه‌ها و نگه‌داری از گنجینه‌های فرهنگی کارساز است و می‌تواند به درک عمیق‌تری از سیاست‌ها و کنش‌های اقتصادی دوره تیموری بینجامد.

کلیدواژگان: فلورسانس پرتو ایکس، سکه‌های تیموری، مطالعات میان‌رشته‌ای، سکه‌شناسی، ترکیب عنصری سکه‌ها.

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