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Implementation of Energy Dispersive X-ray Fluorescence (EDXRF): Its Principle, Advantages, and Drawbacks

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Abstract

Energy Dispersive X-ray Fluorescence (EDXRF) is a widely used technique for the chemical characterisation of materials in different forms, including powders, liquids, and gases, owing to its rapid and non-destructive determination of elemental composition. This review aims to describe the underlying principle of EDXRF and to synthesise its applications, advantages, and limitations across various domains. Drawing on reported uses of EDXRF in archaeology, metallurgy, environmental science, and the food and pharmaceutical industries, the study highlights how both portable and desktop instruments have enabled efficient routine analysis and quality control. In particular, EDXRF has been instrumental in identifying gaps in production processes, especially in food and drug quality control, which in some cases, has led to the withdrawal of non-compliant products from the distribution chain. At the same time, the review underscores key limitations observed in practice, including poor detection of light elements, the impact of moisture, high background noise, spectral interference, and particle-size effects. EDXRF nonetheless offers important advantages such as minimal sample preparation, non-destructive analysis, cost-effectiveness, and operational simplicity. The

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review concludes that, despite these limitations, EDXRF remains a powerful tool for multi-sectoral chemical characterisation and quality control, and it recommends further development of monochromatic EDXRF configurations to reduce spectral interference, improve detection limits, and enhance analytical accuracy, thereby strengthening its role in regulatory and industrial applications.

Keywords: Energy Dispersive X-Ray Fluorescence; Chemical Characterisation; Non-Destructive Analysis; Analytical Limitations; Monochromatic EDXRF

Introduction

Energy Dispersive X-ray Fluorescence (EDXRF) is a simple analysis for the elemental composition of materials such as cultural heritage materials (Tamponi *et al.,* 2020). It detects the level of minor, major, and trace elements. Uniquely, it is capable of detecting the level of various heavy metal contamination in an environment, such as lead, barium, strontium, and antimony. This is primarily done to detect potentially harmful elements that can pose health risks. It can analyze solid materials directly without any sample preparation (Liu *et al.,* 2021). This technique is used to investigate environmental, pharmaceutical, and industrial samples. It is especially popular in mineralogy, archaeology, and geology because of its ability to accurately analyze multiple elements and speed. The EDXRF spectrometer employs simple sample preparation and allows analysis over a broad concentration range, from percent to parts per million (ppm). The EDXRF analysis excited the sample by the light from the radioactive tube to produce the characteristic X-ray and scattered rays. The rays are sent from the detector to the multichannel analyzer (MCA) to detect pulse channels (energy) to identify the element, then record the corresponding count (intensity) and evaluate the elemental content (Figueiredo *et al.,* 2024). The resolution of measurements mainly relies on the detector's X-ray energy resolution and counting rate performance (de Almeida *et al.,* 2019). The EDXRF analyser determines the composition of the sample by measuring the fluorescent X-ray emitted from the sample when excited by an X-ray source (Klisinska-Kopacz, 2024). Analysis of thin, intermediate, and thick samples may involve external calibration, fundamental parameter (FP) methods, sample pretreatment, and quantification based on scattered primary radiation, as outlined by Stefano (2017). Over the decades, various EDXRF spectrometers have been developed, evolving from benchtop models to portable, handheld devices that are commercially

available at moderate costs (Ridolfi, 2017). Advancements in technology have increased in order to minimise the time scientists spend before research is done. A practical example is the invention of handheld EDXRF. The handheld EDXRF can be used for various applications, including analysing paints on walls, alloys, heavy metals in soil, rock, and works of art. It allows geologists and archaeologists to obtain the constituents of elements present in their samples within a short time. The sensitivity of this system is very high compared to medium benchtop systems. These portable spectrometers feature built-in calibration, enabling the conversion of emitted intensities into concentrations, which facilitates on-site field and museum analysis while eliminating the need for sampling. Handheld instruments are sensitive to surface features like morphology and shape, as well as the specific surface area hit by X-rays (Magrini *et al.* 2016). They can reliably measure a limited range of elements with lower precision and accuracy. Nonetheless, handheld EDXRF analysers are expected to improve as further research explores their capabilities. Some researchers have employed the latest portable EDXRF in their studies, such as thermoelectrically cooled and silicon drift X-ray detectors, and a lot of recent high-resolution X-ray detectors (Santos *et al.* 2020; Akter et al., 2023; Li *et al.,* 2023).

In EDXRF analysis, the quantitative process of intensity concentration is based on the fundamental parameter (FP) method (Weinberger *et al,* 2022). The technique is employed to evaluate the true element intensity from the measured data, which comprises both the calibration and analysis. Each of the peaks in the spectrum corresponding to an element can be identified using an element library, thereby giving a qualitative analysis. In addition, the efficiency procedure includes the bulk detector efficiency and the metal contact, dead layer, and the entrance of the beryllium window (Markowicz, 2011; Li *et al.*, 2019). This study provides a review on the EDXRF principle, applications in environmental samples, art and archaeology, pharmaceutical industries, and associated limitations.

Principle of Energy Dispersive X-ray Fluorescence (EDXRF)

The Energy Dispersive X-ray Fluorescence (EDXRF) technique is primarily based on the measurement of fluorescence X-rays in an analyte. The analysis requires irradiating the sample with X- or gamma rays produced from an X-ray tube. The X-ray tube strikes particles, such as electrons, protons, or ions, from the sample, and as a result, electrons are

ejected from the inner to outer shells, either from K or L shells (Santos *et al.* 2020). This created a vacancy, and consequently, the electron in the outer shell replaced the inner shell vacancies. When this occurs, energy is released in the form of secondary X-rays (Fernandez *et al.* 2017). The emitted secondary X-ray energy is peculiar to the shell energy levels. The energies of the X-rays produce a spectrum used in identifying and quantifying the elements in the sample.

For quantitative analysis, the multichannel analyser (MCA) detects various energies of the element and records the equivalent intensities to evaluate the element composition. An element detected emits an X-ray line used for calibration, which is characterised by its energy. This qualitative analysis can be carried out using Moseley's law, and the energy equation is given in Equation (1) (Yao *et al.* 2015).

$$\boldsymbol{E_x = RhC(Z-\sigma)^2\left(\frac{1}{{n_1}^2}-\frac{1}{{n_2}^2}\right)} \quad \textbf{(1)}$$

In equation E_x is the characteristic X-ray energy, R is Rydberg constant ($R_\infty = 1.09737 \times 10^7 m^{-1}$), h represents the Planck's constant ($h = 6.6262 \times 10^{-34} J.s$), and C is the speed of photons. Z is the atomic number, σ is Shielding constant and n_1 and n_2 are the energy series. For the spectrum k_{α_1}, if shielding constant $\sigma = 1$, $n_1 = 1$ (K-shell), and $n_2 = 2$ (K-shell), therefore, Equation (1) can be rewritten as Equation (2).

$$\boldsymbol{E_{k_{\alpha_1}} = \frac{3RhC(Z-\sigma)^2}{4}} \quad \textbf{(2)}$$

Moseley's law shows the correlation between the atomic number and X-ray energy. The theoretical basis for qualitative analysis of any sample material using XRF relies on this law. There is a positive relationship between the concentration of the element in the sample analysed and the count rate of the characteristic X-ray as expressed in Equation (3).

$$\boldsymbol{I_K = \frac{KI_o}{\mu_o + \mu_K} \times W_K} \quad \textbf{(3)}$$

In Equation 3, I_o and I_K are the count rates of the incident X-ray, and the K layer characteristics of the X-rays measured elements, respectively. μ_K is the tested elements to the layer K characteristic X-ray and $\mu_o$the absorption coefficients of the tested sample to

the incident X-ray. K is the constant related to the specific measurement device, and $\frac{KI_o}{\mu_o+\mu_K} \times W_K$ measures the concentration of the elements in the sample.

Instrumentation of Energy Dispersive X-ray Fluorescence (EDXRF)

The EDXRF instrumentation comprises a radioactive source, a sample chamber, and a detector system. The use of gas counters, hyperpure germanium (HPGe) detectors, and nitrogen-cooled detectors has been replaced with thermoelectrically cooled detectors such as Si-PIN, Si-drift, CdTe, and HgI_2 detectors (Paulino *et al.* 2022). For example, an X-ray tube (Mini-X) connected to an X-ray detector, a Si-PIN model XR-100CR detector with an in-built preamplifier connected with tri-axial cables to the digital pulse processor (model PX5), which in turn is connected to the multichannel analyser (MCA). The MCA is connected with an interface cable to the personal computer (PC). The setup is shown in Figure 1. It is designed to maximise sensitivity and resolution while facilitating straightforward connections in any laboratory environment.

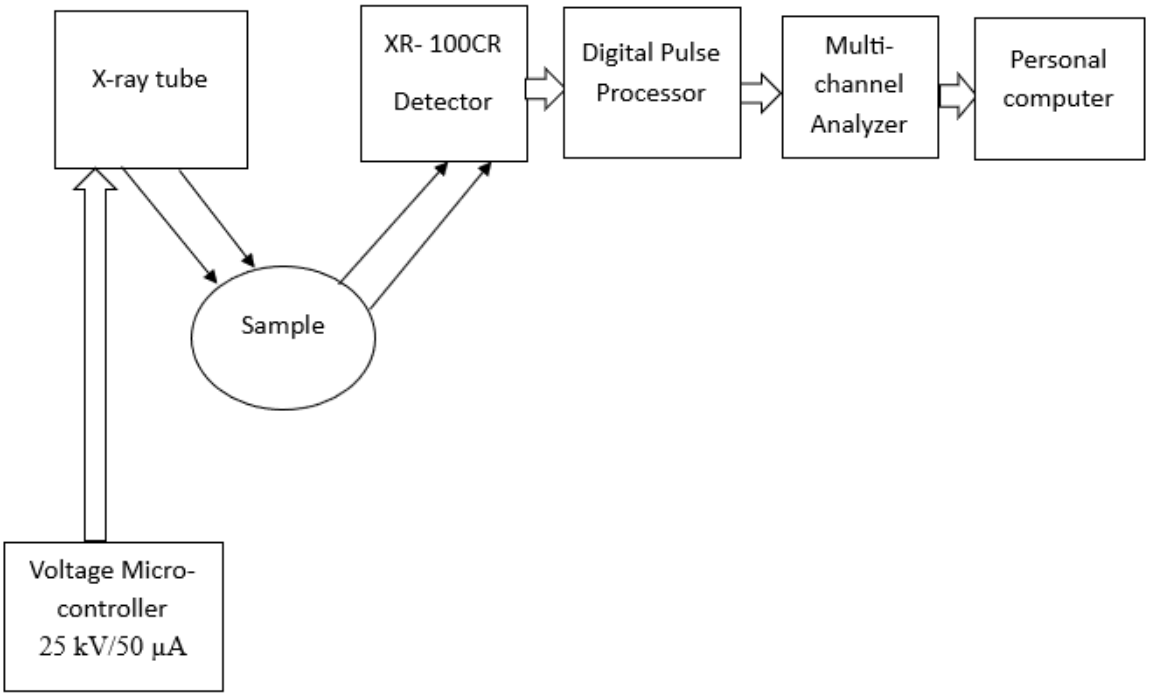

Figure 1: The Block Diagram Setup of the EDXRF Spectrometer

X-ray Tube (Mini- X)

The Mini-X is an excitation tube that emits an X-ray beam coming from a silver (Ag) anode with its power supply. The cathode rod of Tungsten (W) produces electrons after being heated. When a high voltage is applied across the gap between the filament on the cathode and the anode, thermal electrons emitted by the cathode are accelerated to the anode. Bombardment of the Tungsten target (anode) causes a shower of high-energy photons called X-rays. A beryllium window of thickness 0.125 mm was attached to the Mini-X to allow the passage of short-wavelength x-rays produced. The photon output from the X-ray tube relies mainly on voltage, current and anode material. A voltage microcontroller was connected to Mini-X to regulate the voltage and current, and this was set at 25 kV and 50 μA, respectively. The Mini-X X-ray tube is displayed in Figure 2.

Figure 2: Amptek Mini-X X-ray tube, 50 μA (Ridolfi, 2017)

Detector (XR-100CR) and Preamplifier

The Si-PIN detector of model XR-100CR is one of the recent high-performance X-ray detectors with its Preamplifier and Cooler system. The detector has a thermoelectric cooling because the Si-PIN Photodiode system requires a very low operating temperature. In the cooling system, there were 2-stage cooler, which are the input Field-Effect Transistor (FET) and a novel feedback circuit. These components are kept at approximately -55°C, and are monitored by an internal temperature sensor. The size of the detector is 7 mm^2 to 25 mm^2. The detector has a multilayer collimator and silicon thicknesses of 300 μm and 500 μm. The detector type area, thickness, and the Beryllium (Be) window thickness are 25 mm^2, 500 μm, and 25 μm, respectively. The detector is mounted behind a vacuum-tight Be window in the front of the 1.5 mm extender. Be windows enable a passage of soft X-ray. The X-ray detector XR-100CR and digital pulse processor are shown in Figure 3.

Figure 3: Amptek XR-100CR X-ray detector and PX5 digital pulse processor (Amptek Inc. 2003)

Power Supply and Digital Pulse Processor (PX5)

The XR-100 CR is powered by the PX5 power supply, which operates on AC and features a spectroscopy-grade Shaping Amplifier. It provides both low and high voltage outputs of 770 V (± HV). The input signal to the PX5 comes from the preamplifier output. The PX5 digitises this output, applies real-time digital processing, detects the peak amplitude digitally, and stores this value in its histogram memory, thereby creating an energy spectrum. This spectrum is then sent via a serial interface to the multichannel analyser (MCA). The digital pulse processor performs the functions of an amplifier.

Multichannel Analyser (MCA)

The MCA is the primary software for display and data acquisition. It is a Windows-based program that manages data collection, visualisation, and control of the PX5 signal processor. The MCA offers full control over all connected hardware features (PX5 and detector) and provides a live display of the spectrum. It supports 8, 8142 channels for display and calibration. Its spectral analysis capabilities include energy calibration, setting regions of interest (ROI), calculating key parameters such as centroid, net peak area, and FWHM, and it maintains an active link with the XRF- FP Quantitative Analysis Software Package, which matches peak intensities to calibration standards.

Energy Resolution

The characteristic X- ray spectrum is displayed in digitised form, with the horizontal axis representing energy (keV) or channel number, and the vertical axis indicating counts or intensity. The energy resolution for the 5. 5.9 keV K- line peak of 55 Fe is 220 eV FWHM at a shaping time constant of 12 μs, and 186 eV at a shaping time of 20 μs (optional).

Energy Calibration

The energy calibration is achieved using calibration curves developed from the reference standards or the fundamental parameter (FP) method. The FP method allows accurate analysis even without closely matched reference standards. Recent works have revealed that the optimisation of sample preparation using pressed pellets, loose powders, or thin film can significantly improve quantification accuracy by minimising matrix effects and ensuring consistent measurements. However, the choice of calibration and matrix correction to use has always been a controversy.

Applications of Energy Dispersive X-ray Fluorescence (EDXRF)

Environmental and Agricultural Samples

Over the years, as the population increased with improved living conditions for people, there has been pressure on the natural resources around us, which has affected the ecosystem (Zhou *et al.,* 2023). Then, research so far has shown that human activities have remained the main source of heavy metals in the soil, such as smelting, mining, chemical industries, vehicle emissions, and agricultural practices (Croffie *et al.,* 2022). Therefore, environmental samples are physical materials collected from their natural habitat to analyse the presence of contaminants and chemical composition. Common examples include soil, sediments, rock, water, air, plants, vegetation, dust and particulates (Salum *et al*., 2021). The EDXRF helps determine their ecological impact, such as pollution level, ecosystem health, and overall environmental quality (Giovanni *et al.,* 2024). It can also detect heavy metals and rare earth metals in various materials. The presence of heavy metals in the environment and soil can affect the quality of life, food safety, and groundwater used for drinking, increase contamination levels, and impede plant growth (Suleiman *et al.,* 2021). To clarify, human health is generally significantly impacted or at risk of unforeseen issues in specific areas, regions, or countries. Several studies have been conducted to ascertain the level of degradation of these contaminants in our environment (Ribeiro *et al.,* 2017). For instance,

in environmental studies, Fasiku *et al.* (2023) evaluated heavy metals and naturally occurring radionuclides in pegmatite rock samples by EDXRF. Remya *et al.* (2022) evaluated the ratio of Sr to Ca in solid and aqueous carbonate, fluoride, and nitrate samples were analysed using EDXRF. Sykora and Komendova (2024) studied trace metal concentration in water (surface and wastewater) via EDXRF. The results obtained were compared with those from inductively coupled plasma mass spectrometry, and a good correlation was found between them. Rakib *et al.,* (2022) conducted a probabilistic ecological risk assessment and detection of trace elements in salt marsh sediment in Bangladesh by using EDXRF. The authors were able to determine the possible sources and ecological risk associated with the trace elements (Ca, Fe, Ti, Sr, K, Rb, Zn, Zr, Cu, and Pb). The concentrations of the trace elements were under the average shale values of metals in sediment except for Fe, Cu, and Rb. Salum *et al.,* (2021) conducted an assessment of heavy metal in *Ipomoea batatas* (L.) and spinach consumed in Zanzibar by EDXRF. The analysis detected Cu, Mn, Fe, As, Pb, Zn and Ni. However, all the elements except Mn were above the tolerance limit by Food and Agriculture Organization (FAO)/ World Health Organization (WHO) for human consumption. Oketayo *et al.,* (2022) evaluated the concentration of heavy metals in soil and vegetable samples in automobile workshop surroundings in Iworoko-Ekiti, Nigeria. The authors identified 18 heavy metals from the samples analysed. The chromium, manganese, iron, nickel, copper, zinc, and arsenic are higher than permissible limits from WHO and Federal Environmental Protection Agency (FEPA). Therefore, the consumption of vegetables from an environment like that can expose human health to danger.

Pharmaceutical Industries

The energy dispersive X-ray Fluorescence (EDXRF) has been efficient in pharmaceutical industries, particularly in the use of raw material verification, screening of contaminants, and quality control of regular pharmaceutical ingredients and excipients. The essence is to determine the concentrations of all elements of interest in pharmaceutical industries, such as heavy metals, to ensure they are within the recommended values, thereby ensuring the safety of people after consuming them. In addition, analysis of inorganic impurities in drug products is necessary due to the presence of hazardous metals. These impurities are undesirable substances that could have long-term effects on human health and likewise reduce the quality, safety, and potency of other drug products. However, the impurity concentrations can be controlled or reduced to the recommended values. In traditional medicine, Mohapatra and Alim (2025) evaluated the heavy metals in

herbal products from an unlicensed Apothecary using EDXRF. The analysis showed that the elements are within the regulatory limits, such as the World Health Organisation (WHO). An analytical study of Tarakeswara Rasa (herbal mineral) was done via XRD, XRF, EDXRF, and PSA by Rengarajan (2023). The herbal mineral was used as a clinical treatment for diabetic patients. The XRD and EDXRF indicate the presence of Tin-rich Astrophyllite composition, which resembles crystal astrophyllite used in treating metabolic disorders. Kulal *et al.* (2020) reported the content of trace elements in medicinal plants via EDXRF. In their investigation, it was observed that iron had the highest concentration, followed by Manganese and Zinc. In addition, Trace elements in various Dokha and Shisha Tobacco products were determined by EDXRF (Mohammad *et al.,* 2019). This study compared these products to cigarettes and revealed that Ni, Cr, Cu, and Zn were higher, while Al and Mn were lower. However, Fe has the same concentration as cigarettes.

Art and Archaeology

The EDXRF method is utilised in the field of materials science, most especially in the arts and archaeology (Magrini *et al.,* 2016). The EDXRF has numerous advantages of EDXRF such as it does not require any sample preparation, which means the analysis can be done directly on the object. It is a rapid method of analysis that enables the examination of a large number of artefacts within a short period of time (Suda *et al.,* 2021). The non-destructive method enables accurate measurement while the artefact is kept intact. For several decades, investigations into archaeology and cultural heritage have gained new insights with a better understanding of the past (Bottaini *et al.,* 2019). In provenance studies, non-destructive analytical techniques are preferred over destructive ones because they provide adequate resolution for characterising elements. *In situ* analysis is ideal for museum and protected collections, especially those in the process of repatriation. The use of portable EDXRF in this field is favoured because transporting artefacts both within and outside to laboratories involves strict procedures and high costs (Frahm and Tryon, 2018). The process of transporting an artifact can lead to theft or damage of the object. Therefore, the chemical characterisation is conducted where the artefact is stored. The analytical technique can provide art historians, archaeologists the opportunity to acquire information about the composition of the object and how the artefact is made (Bottaini *et al.,* 2017). This investigation makes archaeologists understand the process by which the manufacturing and preservation of the artefact were achieved (Juarez-Rodriguez *et al.,* 2017). In conservation work, information gathered differentiates the authentic artefact

from the latest ones, formally restored, falsified and fakes. Numerous studies have utilised EDXRF, for example, in ceramics, Desanti *et al.* (2024) used both EDXRF and multivariate analysis to investigate the elemental compositions from four sites along the north coast of Peru. The analysis revealed statistical similarities among the four groups of ceramic fragments collected from the sample areas, indicating the use of the same clay deposit fragments from the archaeological sites. The EDXRF was used for the examination of ceramic artefacts from the Tanjung Simpang Mengayau shipwreck in Sabah (Jusoh *et al.,* 2022). The results indicated the presence of quartz and mullite minerals in the jars and bowls, respectively. A comparison between the elemental composition of five Rupee and a Pound coin was studied by Richa *et al.* (2024) using the EDXRF method. The results revealed that both samples showed good correlation with standard compositions with each other.

Minerals and Metallurgy

Energy Dispersive X-ray Fluorescence (EDXRF) is a dependable analytical method used to analyse minerals, ores, and tailings. It is commonly employed in mineralogy, especially by geologists, to identify areas rich in ores for exploration by determining the elemental compositions. Sorting of alloys and metals is mainly carried out by metal industries. These industries are embedded with many areas such as fabrication, inventory control and crap clustering. Examples of common alloys are copper and nickel alloys, stainless steels and precious metals. Oftentimes, handheld and portable instruments are used for the analysis because it is fast, require minimal sample preparation, with reliable identifications. The valuable metals gold (Au), lead (Pb), iron (Fe), zinc (Zn), manganese (Mn), copper (Cu) and rare earth metals. The development of portable EDXRF devices has enabled both mining engineers and geologists to perform *in-situ* elemental analysis in the field, eliminating the need to transport samples to laboratories. This approach reduces both time and exploration costs effectively. In addition, industries where metal identification is necessary, for instance aerospace and automobile, starting from the extraction (scrap sorting), smelting, processing of metals and welding, the use of handheld EDXRF instruments has been there a standard practice. For the determination of impurity in alloys, Zhou *et al.* (2021) evaluated the impurity contents in aluminium alloy using EDXRF. Their work revealed that using the EDXRF technique meets the standard of any industrial production while trying to determine the content of aluminium alloy impurity. Jyothsna *et al.* (2022) investigated the trace element concentrations from a coal mining area using the

EDXRF technique. The trace elements like V, Cr, Mn, Fe and Ni are all found to be high in all the samples analysed. The high concentrations from this study showed that human health as well as the environment are at greater risk. In paper making, the determination of the paper constituents of historical and modern Italian papers via EDXRF, X-ray Diffraction (XRD), and Scanning Electron Microscopy Energy Dispersive Spectrometry (SEM-EDS) was investigated (Manso *et al.,* 2010). These methods have been able to identify the size of the filler materials, and in ink, in both printed and handwritten documents. Among the techniques used, EDXRF gave the best ink identification. Bottaini *et al.,* (2018) investigated the characterisation of archaeological Cu-based artefacts from the early metallurgy of Southern Portugal. Their results from EDXRF and Monte Carlo simulation gave a safe and fast analytical process.

Quality Control

The EDXRF is largely used in quality control in various disciplines and industries such as food, pharmaceuticals, metallurgical, cement industries, painting, plastics, and polymers production. This involves sample collection, sample package, sample preparation, and qualitative analysis. To ascertain that the quality assurance of a product is maintained, this must be done for a period of time. In electronics, EDXRF is a major tool to test that printed circuit boards and components are up to standard. According to the Consumer Product Safety Improvement Act (CPSIA), the detection of lead in paints of children's toys was first verified for compliance with manufacturing regulations imposed by the regulators. This is done to know the genuineness of the samples and materials collected so that products meet the expected results by detecting the elements present and possible impurities. In pharmaceutical industries, EDXRF is employed to ascertain the originality of ingredients, the concentrations of impurities and residual catalysts to ensure human health is protected from danger. The reasons for quality control are peculiar to each discipline. For instance, daily consumption products such as milk powder, the potential of heavy metals was investigated by Qadr *et al.* (2025) in order to safeguard the lives of consumers. The authors reported that the concentrations of Pb, Cu, Zn, Ni, and Cd were within the globally recommended limits. However, in some samples the hazard index values exceeded 1 (unity), which connotes that there is a possible health risk in the near future. In food industries, EDXRF analysis was used to determine the contents of heavy metals in potatoes to determine if they meet health and international standards (Liu *et al.,* 2021). The results gave baseline data to detect the heavy metals in the potato planting environment if they had

exceeded the recommended limit. As it is known that coffee intake is admired by a lot of people due to the nutrients and health benefits, therefore Weinberger *et al.* (2024) analysed the multielemental composition of coffee samples by EDXRF. This technique helps to determine the quality, nutritional purposes and the origin of the type of coffee used.

Advantages of Energy Dispersive X-ray Fluorescence (EDXRF)

Non-destructive: In general, EDXRF analysis does not alter or damage the sample after being exposed to X-rays. It analyses the sample elemental constituents. The sample can undergo further analysis in the future, especially in pharmaceutical industries and artefacts.

Minimal sample preparation: Comparing EDXRF to other techniques, it reduces preparation time, which requires little or no pretreatment before analysis and low operational cost. After the samples have been collected, it is taken to the EDXRF laboratory for analysis. The sample preparation was done by crushing and pulverising the sample material, which was then pressed into a pellet. For the samples that had fallen apart, the powder was wetted with a binder solution from dissolved pure polystyrene in toluene. This was allowed to dry and later pressed into a pellet. Note that a very small amount of binder must be used.

Fast and Efficient: The EDXRF spectrometer determines the elemental compositions in the samples within seconds to minutes. Each of the samples can be irradiated in less than or equal to 1000 s. EDXRF allows a large number of samples to be screened within a short period of time, which could help to facilitate the reduction in time of the experiment and could also give room for adjustment of the research if necessary.

Portability: Due to demand in increase in work efficiency with reduced analysis cost, portable and handheld EDXRF is introduced. This enables *in-situ* analysis of environmental samples, or archaeological material and geological surveys right on the site without the need to take them to a laboratory.

Cost effectiveness: The cost of analysis of samples using EDXRF, when compared to other techniques such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or Atomic Absorption Spectrometry (AAS), is relatively low, including the sample

preparation. This has made the EDXRF spectrometer accessible for extensive research work in different disciplines.

Drawbacks of Energy Dispersive X-ray Fluorescence

The detectability of EDXRF to light elements is relatively low: The EDXRF method is not sensitive to measuring light elements (those with low atomic numbers) below sodium (Z = 11). This is because these elements release low-energy X-rays, which are absorbed by either the detector window or the sample matrix. For the sample matrix, this means information about the sample's composition is obtained from a small part of the sample, especially at the surface. As a result, signals are weak.

Limited Sample mass: The effective mass of the sample part is a few 10 mm or less. The EDXRF technique uses a monochromatic excitation beam, ranging from 5-30%, which becomes less effective when the concentration approaches the detection limit (LOD).

Physical characteristics of the sample: The sensitivity of fluorescent X-rays is always high concerning physical features such as particle size and the inhomogeneity of pulverised samples. Variability in sample presentation can lead to analytical errors.

High background noise: This problem directly affects the spectrum results. The spectrum generated by primary X-ray scattering in the sample creates a continuous background spectrum. Different absorption limits of each nuclide in the analyte result in various background spectrum distributions. Consequently, escape peak, characteristic X-ray peak, and electronic noise superimpose on the background spectrum, complicating spectral analysis. The method of extracting the net peaks of characteristic X-ray fluorescence spectra from the full spectrum data has been a major concern to this day (Chowdhury *et al.,* 2020).

Calibration Standards: It is important that when selecting standards, they should cover the entire range of elemental concentrations expected in the sample matrix considered. Therefore, purchasing standards for different samples may require a lot of money. In addition, EDXRF instruments are calibrated through the fundamental parameter method, which is sometimes not adequate for the accuracy expected in geological and archaeological studies (Sudarshan *et al.,* 2011).

Pigment characterisation Limitations: Pigment characterisation is particularly relevant in analysing pigments from different paintings, often limited by depth resolution during the analysis.

Spectrum overlapping: Most EDXRF detectors exhibit low energy resolution, leading to overlaps of characteristic X-ray peaks from different elements. This overlap complicates accurate element quantification.

Environmental background effect: The analysed results are easily affected by the sample geometry (surface roughness) and external factors such as air absorption and temperature. Since the X-ray intensity relies on the consistency of the sample-detector geometry. When the shape is irregular, large object or field measurements can reduce precision repeatability.

Future Improvements

For improved analysis of various materials, technological advancements must be adopted. The recommendations include the following: Monochromatic energy-dispersive X-ray Fluorescence (MEDXRF) offers an improved detection limit by reducing spectral interferences and ensures the determination of trace elements, resulting in better signal-to-background noise (Dekeyrel *et al.,* 2024; Johnson-Restrepo *et al.,* 2025). Applying modern SSD micro XRF will aid in extensive investigations, especially within forensic contexts. Recent technological progress has shown that micro XRF using SDDs provides superior sensitivity and precision (Corzo *et al.,* 2022). It is also cost-effective and can be used by laboratories for analysing trace elements and small samples (Ovide *et al.,* 2023). Artificial Intelligence (AI) and Deep Learning (DL), utilising Convolutional Neural Networks (CNN), offer significant advantages for mineral exploration. This innovative AI produces XRF data at a low cost, especially for mineral prediction, minimising reliance on expensive analytical methods and improving decision-making in mining exploration (Najafabadipour *et al.,* 2025).

Conclusion

This review explains the Energy Dispersive X-ray Fluorescence as a versatile technique to analyse elemental composition of samples in various areas such as environmental, pharmaceutical, art and archaeology, and metallurgical and quality control laboratories. This technique can give an analysis that is fast, non-destructive, and requires minimal sample preparation. Energy Dispersive X-ray Fluorescence is used to determine

the origin of a material, monitor production processes, detect contaminants in samples to ensure environmental protection, product safety, and a reliable process. There is no analytical technique without its challenges. Therefore, Energy Dispersive X-ray Fluorescence mostly encounters different limitations, such as low sensitivity to light elements, matrix effect, spectral overlap, and physical characteristics of the sample, which can affect the accuracy and precision of the outcomes. However, the potentials of Energy Dispersive X-ray Fluorescence outweigh its drawbacks. The advantages so far have enabled it to be an important tool for elemental analysis and serve as quality control. Advancements in Energy Dispersive X-ray Fluorescence spectrometers and calibrations have improved it operations, and that makes it reliable and a widely adopted technique in various scientific and industrial fields.

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