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Application of Neutron Activation Analysis in the Monitoring of Heavy Metals from Tanneries: A Review

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ABSTRACT

Rapid industrialization and urbanization have introduced significant quantities of heavy metals into environmental media of air, water, soil and vegetation. Preserving the chemical integrity of the environment is essential for sustaining ecosystem health, as disruptions in elemental composition can trigger serious biological and ecological fallouts. The tannery industry is a major contributor to this contamination, employing 40–250 chemicals in leather processing, with only about 20% effectively utilized. While conventional techniques of chemical analysis like Atomic Absorption Spectroscopy, Energy Dispersive X-ray Fluorescence, and Inductively Coupled Plasma Mass Spectrometry are commonly applied, Neutron Activation Analysis (NAA) offers distinct advantages. Analyzing over 100,000 samples globally each year, NAA provides precise, multi-element, non-destructive detection, making it ideal for monitoring pollutants such as chromium, cadmium, and lead in tannery waste. This review examines the prospects and feasibility of using NAA as a referee method for monitoring heavy metal pollution from industrial activities, with a primary focus on tanneries. Despite its advantages, NAA faces challenges including high operational costs, limited reactor access, and strict safety requirements. Addressing these through technological innovation, compact neutron sources, and improved analytical workflows will be vital to expanding its environmental applications in the long run.

Key words: Neutron activation analysis, environment pollution, heavy metals, monitoring, tanneries

INTRODUCTION

Environmental pollution by heavy metals has become a concern of global proportion due to its pervasive impacts on ecosystems and human health [1,2]. The accelerated pace of industrialization introduced considerable quantities of heavy metals into the environment [3]. These metals accumulate in the environment, often surpassing natural background concentrations and posing risks of toxicity to living organisms. The contamination is widespread, and its effects spans across multiple environmental matrices [4]. Maintaining the chemical integrity of our environment is necessary for sustainable habitation, since disturbance in elemental composition hardly occurs in isolation but triggers other adverse effects [5,6]. Monitoring and mitigating heavy metal pollution are therefore, indispensable tasks in safeguarding environmental quality.

Conventional analytical approaches to monitoring are often laced with limitations as regards their sensitivity, preparation of samples and multi-element detection [7]. This review forays into the prospects and feasibilities of using NAA as a referee method for monitoring heavy metal pollution from industrial activities with primary focus on tanneries [8, 9].

Tanneries commonly utilize various heavy metals, especially chromium compounds, extensively in the leather tanning process, in order to give the leather its aesthetic and durability features. Besides chromium, other metals like cadmium and lead are also widespread in tannery waste stream [10]. These metals persist in the environment and therefore bioaccumulate, leading to significant toxicological implications for man and other animals [11]. The release of untreated treated tannery effluents usually results in soil and water contamination, which has deleterious effects on the safety of water meant for consumption and on agricultural productivity. The hazardous nature of tannery waste is primarily attributed to the high concentrations of these metals and their potential to cause organ damage, carcinogenicity, and other health complications upon exposure [12]. Thus, rigorous monitoring of heavy metal presence in industrial discharge, particularly in tannery waste, is vital in controlling pollution and preserving public health.

Role of Analytical Techniques in Heavy Metal Assessment

Global economic cost of heavy metal pollution in soil has been estimated to be over US$10 billion per year [13]. Effective monitoring of heavy metals commands the use of sophisticated analytical techniques that are capable of accurate elemental determination, even on trace and ultra-trace levels [14]. Conventional methods like Atomic Absorption Spectroscopy (AAS) and Inductively

Coupled Plasma Mass Spectrometry (ICP-MS) have been widely employed, but challenges related to sample preparation, matrix interferences, and detection limits amongst others have been reported [7,15].

Neutron Activation Analysis, as a nuclear-based technique, offers several advantages like high sensitivity, multi-elemental capability, and low detection limits that extends into parts per billion (ppb) and parts per trillion (ppt) ranges [16]. Importantly, it operates independently of chemical form or matrix effects which enables it to provide reliable elemental quantification even in complex environmental samples [17]. These features present Neutron Activation Analysis as an invaluable tool in environmental studies for heavy metal analysis in tannery wastes. According to Chambhare, Ghaywat & Lohiya [13], global patronage of NAA clicks 100,000 samples annually.

Principle of Neutron Activation Analysis

Neutron Activation Analysis is based on nuclear reactions, where stable atomic nuclei in a sample capture neutron to form excited, and unstable nuclei. Upon neutron capture, this compound's nucleus rapidly de-excites and as result emits characteristic prompt gamma rays which usually results in radioactive isotopes. These radioactive isotopes subsequently decay, emitting delayed gamma radiation in the process with energies unique to each element present in the sample [18]. The process typically involves sample preparation, sample irradiation and sample analysis as shown in Figure 1. The gamma emissions serve as fingerprints for the identification of elements, while the intensity of these emissions correlates with the elemental concentration [19].

Key factors influencing activation efficiency includes neutron flux intensity, neutron capture cross-section of the target nuclei, as well as the duration of irradiation [20]. Higher neutron flux and larger cross-sections enhance the induced radioactivity, which subsequently improves detection sensitivity [14]. In practice, samples are irradiated in a neutron field, typically inside a nuclear reactor, and after appropriately timed decay intervals, the gamma emissions are measured using high-resolution detectors [2]. This nuclear reaction mechanism ensures elemental speciation and quantitative accuracy in Neutron Activation Analysis.

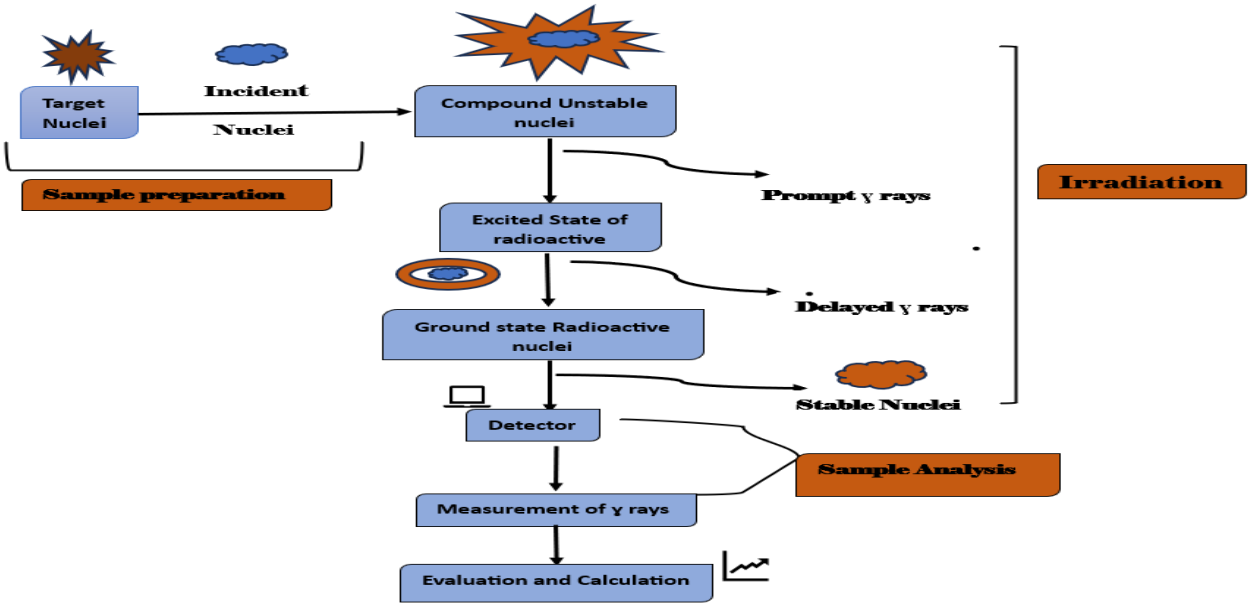

Figure 1: Schematic Representation of the Principle of NAA

Types of Neutron Activation Analysis

Several variants of NAA exist, differentiated by their analytical approach, irradiation type, and post-irradiation treatment. Table 1 shows the various types of NAA and their distinguishing features.

Table 1: Types of Neutron Activation Analysis and their characteristics.

S/N	Type of NAA	Description	Key Advantages	Limitation	Key References
1.	Instrumental Neutron Activation Analysis (INAA)	Non-destructive technique that measures gamma rays emitted during radioactive decay after irradiation without any chemical processing.	• Multi-elemental analysis. • No sample destruction. • No sample destruction. • Minimal sample preparation. • Particularly suitable for tannery waste analysis due to its effectiveness in assessing complex heterogeneous matrices.	• Lower selectivity compared to RNAA. • Interference from radionuclides with similar gamma energies.	• Sununu *et al* [21]. • Samanta, Gupta & Acharya [22].

2.	Radiochemical Neutron Activation Analysis (RNAA)	Involves chemical separation after irradiation to isolate radionuclides of interest for higher analytical selectivity.	• Very high selectivity. • Improved sensitivity due to chemical isolation. • Labor-intensive and time-consuming.	Destructive	• El-Sweify *et al* [23].
3.	Prompt Gamma Neutron Activation Analysis (PGNAA)	Measures prompt gamma rays emitted immediately during neutron capture, enabling real-time elemental analysis.	• Rapid analysis. • Suitable for elements that emit prompt gamma photons.	• Potential spectral interference. • Lower spatial resolution	• Eberhardt [16].
4.	Epithermal Neutron Activation Analysis (ENAA)	Uses epithermal neutrons to enhance detection of elements with resonance absorption peaks, improving sensitivity in complex matrices.	• Enhanced sensitivity for specific elements. • Better detection in complex samples.	• Requires specialized neutron filters. • Not ideal for elements lacking resonance peaks.	• Hossain [2]. • Phelps [24].
5.	Fast Neutron Activation Analys is (FNAA)	Uses high-energy neutrons (not thermal neutrons) to activate light elements such as Carbon, Nitrogen, Oxygen, Fluorine and Sulfur.	• Useful for light elements poorly activated by thermal neutrons. • Applicable to industrial materials.	• Lower sensitivity for heavier elements. • Requires high-energy neutron sources.	• Chambhare, Ghaywat & Lohiya [13]. • Batur [25].

Detection and Measurement Methodology

Detection in NAA predominantly employs gamma-ray spectrometry, utilizing High-Purity Germanium (HPGe) detectors known for superior energy resolution [2]. The irradiated sample emits gamma rays characteristic of the radioactive isotopes formed by neutron activation. The energy and intensity of these gamma rays are measured to qualitatively identify and quantitatively determine elemental concentrations [13]. Comparative analysis involves simultaneous irradiation of the sample along with standards of known composition, enabling relative quantification through the comparator method [2, 26].

Peak areas, corresponding to specific gamma energies, are corrected for decay times, detector efficiency, sample mass, and irradiation parameters to yield accurate elemental concentrations [2]. Timing the measurements to correspond with the decay properties of different radionuclides optimizes sensitivity, which allows for determination of elements spanning a range of half-lives [27]. The advanced capabilities of HPGe detectors combined with precise timing and

well-established calibration protocols underpin the reliability and accuracy of NAA [28]. Using NAA, it is possible to identify and quantify a specific element as it helps identify the elements in samples as well as their concentrations at the same time [4].

Sample Collection and Preparation for Tannery Waste Analysis

Effective application of NAA to tannery waste analysis begins with systematic sample collection encompassing all relevant waste streams, including solid wastes, liquid effluents, and airborne particulates [9]. Protocols demand representative sampling, use of contamination-free containers, and maintenance of sample integrity during transport and storage [29, 30]. Preparation typically involves drying, homogenizing, and grinding samples to uniform particle size, minimizing heterogeneity effects. Due to NAA's minimal chemical preparation requirements, avoidance of reagents reduces contamination risks or analyte loss [31]. Ensuring consistent sample preparation improves reproducibility and comparability of results across studies and laboratories [32].

Irradiation Parameters and Counting Strategy

Neutron flux optimization as well as irradiation duration, and decay time plays crucial role in maximizing detection sensitivity and resolving elements with diverse nuclear properties. Reactor neutron fluxes are selected based on desired activation levels, typically ranging between 10^{12} to 10^{14} neutrons/cm^2/s [20]. Irradiation times usually varies depending on element cross-sections and concentration levels, often spanning from seconds to hours. Post-irradiation decay periods are strategically employed to allow short-lived radionuclides to decay, reducing spectral interferences and allow for the measurement of longer-lived isotopes [2]. The use of HPGe detectors and sophisticated counting setups allows simultaneous acquisition of gamma spectra, facilitating multi-element analysis within single measurement runs [2]. These procedural setups optimize accuracy and permit the determination of both short- and long-lived radionuclides within complex tannery waste matrices.

Data Analysis and Quality Assurance

Accurate identification of gamma peaks requires advanced spectral analysis software capable of spectrum unfolding and background subtraction. Corrections for decay during counting and between irradiation and measurement further enhance data reliability. Efficiency calibration of detection systems using standards matched to sample matrices ensures quantitative accuracy [33]. Incorporation of certified reference materials serves as a benchmark for method validation and

quality control [20]. Statistical assessment of measurement repeatability, detection limits, and uncertainty quantification underpins the reliability and scientific credibility of reported findings. These analytical quality assurance practices are needed in order to generate robust data that can inform environmental risk assessments and regulatory compliance [27].

Advantages of NAA in Heavy Metal Analysis

The strength of Neutron Activation Analysis lies in its remarkable sensitivity, outstanding accuracy, and unique ability to detect numerous elements at once without the need for complex or destructive sample preparation which makes it a powerful tool across many scientific fields.

i. Sensitivity and Multi-Element Capability

One of the foremost strengths of NAA lies in its exceptional sensitivity and capability for simultaneous multi-element detection [20]. The technique can accurately quantify more than 60 elements within a single sample, spanning from trace (parts per billion) to ultra-trace concentration levels, without multiple analytical procedures according to the United States Geological Survey [34]. This multi-elemental capacity significantly enhances efficiency and reduces analytical costs in large-scale environmental monitoring. Another advantage is its non-destructive nature which allows for preservation of physical and chemical integrity of samples [35]. Samples subjected to NAA can be archived and be repeatedly analyzed, this facilitates verification and supplemental studies. Given these features, NAA is often regarded as a "gold standard" in elemental analysis and is frequently used to validate results from other methodologies [36]. Table 2 shows a list of elements and their respective Minimum Detection Level in Micrograms according to the USGS TRIGA Reactor [34].

Table 2: List of elements and their respective Minimum Detection Level in Micrograms using the USGS TRIGA Reactor [34].

Element	Minimum Detection Level (µg)	Element	Minimum Detection Level (µg)	Element	Minimum Detection Level (µg)
Ag	0.004	Hf	0.0006	Re	0.0008
Al	0.004	Hg	0.003	Rh	0.005
Ar	0.002	Ho	0.003	Ru	0.04
As	0.0005	I	0.002	Sb	0.007
Au	0.0005	In	0.00006	Sc	0.001

Ba	0.02	Ir	0.0003	Se	0.01
Ca	4	Kr	0.01	Sn	0.03
Cd	0.005	La	0.005	Sr	0.005
Ce	0.2	Lu	0.0003	Ta	0.1
Cl	0.05	Mg	0.5	Tb	0.03
Co	0.01	Mn	0.0001	Te	0.03
Cr	0.3	Mo	0.1	Th	0.2
Cs	0.00003	Na	0.004	Ti	0.1
Cu	0.002	Ne	2	Tm	0.2
Dy	0.00003	Nd	0.03	U	0.003
Er	0.002	Ne	2	V	0.002
Eu	0.0001	Ni	0.7	W	0.004
F	0.4	Os	1	Xe	0.1
Fe	2	Pd	0.03	Yb	0.02
Ga	0.002	Pr	0.03	Zn	0.1
Gd	0.007	Pt	0.1	Zn	0.1
Ge	0.1	Rb	0.02	Zr	0.8

ii. Minimal Sample Preparation and Matrix Independence

Unlike many conventional analytical techniques, NAA generally requires minimal sample preparation, precluding the need for chemical digestion, dissolution, or separation steps. This absence of preliminary chemical treatment minimizes risks of contamination, analyte loss, or introduction of artifacts, thereby preserving sample representativity and originality [37]. Moreover, NAA's nuclear-based detection principle confers matrix independence, as gamma-ray emissions depend on nuclear properties rather than chemical composition or physical form [20]. This feature eliminates interference from complex matrices that otherwise compromise accuracy in techniques sensitive to chemical species, such as AAS or ICP-MS [15]. As a result, NAA delivers highly accurate and precise quantification across diverse sample types; an indispensable feature when analyzing heterogeneous tannery waste consisting of mixed solids, sludges, and liquids [15].

iii. Unique Nuclear-Based Analytical Principle

The underlying nuclear principle of NAA confers several distinctive advantages that make it uniquely valuable in elemental analysis. Since the detection relies on nuclear reactions and subsequent radioactive decay, the results are independent of the chemical state, bonding, or

oxidation form of elements within the sample [26, 38]. This contrasts with most chemical techniques that measure total element concentration differently based on chemical state, thereby complicating interpretation [15].

NAA is internationally recognized as a "referee method" owing to its precision, reliability, and independence from chemical biases. Revered organizations such as the International Atomic Energy Agency (IAEA) and the National Institute of Standards and Technology (NIST) utilize NAA for generating and certifying reference materials. This underscores its role in standardization and quality assurance [2, 20 & 21].

Limitations of NAA

The use of NAA is tempered by certain limitations: access to a nuclear reactor is essential, operational costs can be high, and strict radiation safety protocols must be followed. Moreover, NAA cannot reveal chemical speciation and may induce radiation-related alterations in samples, and there can be Nuclear Interferences factors that can restrict its suitability for some analytical applications.

i. Instrumentation and Cost

Despite its analytical superiority, NAA is not without significant logistical and economic challenges which constrains its widespread application. Foremost is the need for specialized infrastructure comprising nuclear reactors or neutron sources, high-purity detection systems, and radiation shielding facilities. These installations demand substantial capital investment and maintenance costs [39]. Additionally, operating these infrastructure demands highly skilled personnel trained in nuclear physics, radiochemistry, and analytical techniques [40]. The limited number of available nuclear reactors worldwide and their allocation priorities introduce bottlenecks and arrangement constraints for sample irradiation [41]. Consequently, the accessibility of NAA facilities remains directed mainly to research institutions and specialized laboratories. These factors collectively diminish the technique's feasibility for routine or decentralized monitoring activities.

ii. Radiation-Induced Sample Alteration and Safety

Exposure of samples to intense neutron and gamma radiation during NAA can trigger changes that may affect the physical or chemical properties of these samples [42]. Structural alterations such as

volatilization, decomposition, or loss of sample mass can happen, particularly when organic or thermally sensitive samples are involved [13]. These changes might compromise sample integrity and limit subsequent analyses. Furthermore, handling irradiated samples poses inherent radiological hazards for personnel due to induced radioactivity [43]. Strict safety protocols like controlled access, shielding, and decay time management, are very important in protecting laboratory personnel and curtailing environmental contamination [44]. These safety considerations add complexity to operational logistics and necessitate rigorous regulatory compliance.

iii. Analytical Challenges Related to Nuclear Interferences

NAA spectra can present complications arising from overlapping gamma-ray emission lines of varied radionuclides [45]. Such spectral interferences require sophisticated spectrum unfolding techniques and expertise in gamma spectroscopy to accurately apportion peaks. Additionally, isotopes produced via competing neutron reactions or decay chains may mask or overlap with target signals, thereby complicating elemental identification and quantification [46]. Importantly, since NAA measures total elemental content based on nuclear properties, it cannot decipher between different chemical species or oxidation states of detected elements [26]. This limitation impedes direct assessment of bioavailability, chemical form, or toxicity. Hence, the need for complementary analytical approaches when detailed chemical characterization is required.

Application of NAA in Tannery Waste Analysis

Tannery waste is typified by elevated concentrations of heavy metals, principally chromium, which is used extensively in leather tanning processes [47]. Depending on the specific process, 40 to 250 different chemicals may be used to achieve desired leather quality while only 20% of the chemicals are absorbed by the leather, the remaining 80% is released as waste [30, 48 & 49]. These metals accumulate due to chemical reagents used in tanning, waste processing, and supportive industrial activities. Elevated levels of chromium are often predominant, especially in leather shavings and wastewater discharged from tanneries [50]. The persistence and toxicity of these metals are a cause for severe environmental concerns, necessitating the need for accurate and comprehensive elemental profiling of tannery waste streams [51, 52]. Understanding the elemental composition facilitates assessment of pollution load, environmental risks, and formulation of remediation measures.

Numerous studies have employed instrumental Neutron Activation Analysis to characterize heavy metal content in tannery waste matrices [4]. For instance, analyses of chromium-tanned leather shavings using miniature neutron source reactors have revealed high chromium concentrations along with presence of other metals like barium, cobalt, iron, antimony, and zinc [9, 12]. Also, concentration of heavy metals in soils located around tanneries have been investigated using similar methods. The results have been further processed to yield environmental pollution indices like Geo-Accumulation Index and Enrichment Factor [53, 54].

Water samples have not been left out in this sequence as findings from such analysis point to the need for ground water preservation and management [55]. Validation of such findings against certified reference materials ensured analytical accuracy. Similarly, investigations of textile and tannery waste employing NAA have delineated the elemental distribution profiles critical for pollution assessment [30]. Comparative studies have leveraged the independence of NAA from chemical matrix effects to reliably detect trace and ultra-trace metals, contributing to effective environmental monitoring programs and pollution control efforts.

While techniques such as AAS, EDXRF, and ICP-MS are routinely applied in tannery waste analysis, NAA offers distinctive advantages [9, 12]. It's trifling?? sample preparation avoids potential contamination and analyte loss intrinsic to digestion procedures common in AAS or ICP-MS [15, 20]. Moreover, NAA's high multi-element throughput and sensitivity provides for comprehensive profiling with negligible interference [38]. Some alternative techniques offer speciation capabilities or faster turnaround times but are very prone to matrix interferences, higher detection limits, or insufficient accuracy for ultra-trace elements [20]. Thus, integrating NAA with complementary methods provides a robust and reliable framework for comprehensive assessment of heavy metal contamination from tannery waste.

Environmental and Health Implications of Heavy Metals in Tanneries

Chromium, especially hexavalent chromium, wields significant toxicological effects including carcinogenesis, organ toxicity that affects kidneys and liver, and respiratory complications [51, 52]. Chronic exposure can also impersonate neurological disorders such as Parkinson's disease and multiple sclerosis, reflecting its systemic impact. Other heavy metals found in tannery waste, such as lead and cadmium, contribute to neurotoxicity, renal impairment, and bone demineralization. These metals accumulate in our food chain and environment, signaling

bioaccumulation and biomagnification phenomena and exposure pathways [53]. The public health challenges posed by heavy metal contamination from tanneries necessitate stringent pollution controls and continuous monitoring to safeguard both human and ecological health [10].

To mitigate the environmental impact of heavy metals from tannery operations, regulatory standards have been established governing permissible discharge levels into water bodies and soils. These standards mandate treatment processes prior to effluent release, and aims to reduce heavy metal concentrations to safe thresholds. Technologies employed include chemical precipitation, adsorption, ion exchange, and membrane filtration all designed to remove heavy metals effectively [54]. Worker safety guidelines and occupational health measures are also mandated to curtail personnel exposure risks within tannery facilities. Compliance monitoring relies heavily on accurate analytical techniques, with NAA offering a robust tool for verifying acclaimed adherence to environmental norms, it serves to evaluate the efficacy of pollution abatement interventions [4, 21, 55].

Accurate quantification and continuous monitoring of heavy metal contamination in tannery waste underpins sustainable environmental management [32, 56]. Precise data on pollution levels guides towards the formulation of effective remediation strategies, policy frameworks, and enforcement mechanisms [57]. NAA, with its sensitivity, multi-element capability, and minimal matrix effects, contributes significantly to this effort by providing reliable analytical benchmarks. Integration of NAA into environmental monitoring programs enhances the capacity to detect emerging pollution trends and evaluate long-term ecological impacts [58]. Such informed management supports sustainable industrial development which balances economic growth with environmental stewardship and public health protection.

Advances and Innovations in NAA Relevant to Tannery Waste

Recent advancements in gamma spectrometry have significantly enhanced the resolution, sensitivity, and throughput of NAA. Improvements in HPGe detector design, including larger crystals and improved cooling techniques, yield superior energy resolution, enabling finer discrimination of overlapping peaks [59]. Automation technologies, such as robotic sample handlers and computerized data acquisition systems can facilitate rapid and reproducible analysis of large sample batches. Software developments incorporating machine learning algorithms improve peak identification and reduce analyst workload [60]. Conglomerating these innovations

makes for faster turnaround times, reduced human error, and higher analytical precision, thereby strengthening NAA's effectiveness in environmental monitoring of tannery wastes.

Since NAA detects elemental atoms irrespective of chemical form, information pertinent to metal bioavailability, mobility, and toxicity remains inaccessible [26]. For instance, differentiating between trivalent and hexavalent chromium species, which vary drastically in toxicity, cannot be accomplished through NAA alone. Addressing these gaps requires complementary analytical techniques capable of speciation, such as chromatography coupled with ICP-MS or X-ray absorption spectroscopy [61]. Such integrated approaches would enhance comprehensive risk assessments and facilitate targeted remediation strategies.

Combining Neutron Activation Anayis with X-ray fluorescence (XRF) or inductively coupled plasma mass spectrometry (ICP-MS) enables cross-validation and improved speciation insights beyond total elemental quantification [62]. Application of epithermal and prompt gamma NAA techniques allows targeting of specific elements or reduction of matrix effects in complex tannery waste samples [63, 64].

Radiochemical neutron activation analysis (RNAA), though resource-intensive, can isolate radionuclides to improve selectivity essential for trace element detection in challenging matrices. These multimodal approaches expand the analytical horizon, offering comprehensive characterization of heavy metal pollution in tannery environments. Results from these integrations yields holistic data that can be used for bold comparisons and assertions [65].

Prospects for *In Vivo* and In *Vitro* NAA Applications

Evolving developments in portable neutron sources and compact detection systems hold promise for *in vivo* and in vitro NAA applications. Such technologies could facilitate rapid field-based assessment of heavy metal exposure in biological samples or environmental matrices related to tannery operations on the spot [66]. Challenges concerning neutron source safety, measurement sensitivity, and regulatory compliance remain, but outcomes from ongoing researches are expected to proffer leeway that can overcome these barriers. Deployment of in vivo NAA methodologies might enable direct monitoring of human exposure to toxic metals among tannery workers, providing real-time exposure data to guide occupational health interventions [66]. Similarly, in vitro NAA could streamline environmental assessments, reduce sample transport time and enable immediate decision-making.

CONCLUSION

Neutron Activation Analysis as a referee method of analysis remains one of the most dependable and sensitive analytical tools for investigating heavy metal contamination associated with tannery operations. By providing highly reliable data, it equips regulators, researchers, and environmental managers with the evidence needed to design stronger pollution mitigation strategies and conduct more credible assessments of tannery-impacted ecosystems. In spite of these strengths, NAA faces notable challenges, including high operational costs, limited availability of research reactors, and stringent radiation safety requirements, while analytical constraints particularly the inability to determine chemical speciation and the potential for radiation-induced transformations highlight the need for complementary techniques. These limitations, however, present opportunities for scientific innovation, as advancements in compact neutron sources, improved detector technologies, and streamlined analytical workflows are steadily reshaping the future of NAA and enabling its integration into broader environmental monitoring systems and national pollution control programs to better safeguard public health and restore degraded ecosystems. With sustained technological progress, targeted capacity building, and supportive policy measures, NAA can continue to evolve as a powerful cornerstone of environmental science, driving evidence-based decision-making and promoting long-term ecological resilience in regions burdened by tannery pollution.

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