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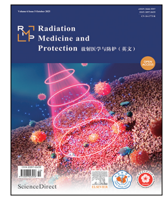

Review

Machine learning application in NaI(Tl) gamma-ray spectroscopy for radionuclide identification: A systematic review

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ABSTRACT

Radionuclide identification using NaI(Tl) gamma-ray spectroscopy is critical in nuclear security, environmental monitoring, and medicine. While cost-effective and efficient, NaI(Tl) detectors are limited by low energy resolution, spectral noise, and environmental variability. This systematic review evaluates how machine learning (ML) advancements address these limitations. Our analysis reveals that deep learning models—particularly convolutional neural networks (CNNs), hybrid architectures, and other advanced Deep Networks—excel in analyzing low-resolution spectra, achieving over 95% accuracy even under complex conditions (e.g., shielding effects, low-count spectra). Hybrid models which integrate CNNs with traditional algorithms demonstrate superior robustness and explainability. Nevertheless, traditional ML methods (e.g., SVMs) remain valuable for limited datasets or real-time applications. Despite these methodological advances, the field continues to face overarching challenges including data scarcity, model generalization, and explainability, necessitating standardized datasets and physics-informed ML frameworks. ML bridges the performance gap between NaI(Tl) and high-resolution detectors, enabling portable, automated solutions. Future research should prioritize hybrid models, dataset standardization, and optimization for field deployment, enhancing nuclear safety and environmental monitoring capabilities.

1. Introduction

Radionuclide identification is crucial across various fields, including nuclear security, environmental monitoring, and medical radiology.[1,2] In nuclear security, it is essential for preventing nuclear terrorism and monitoring radioactive materials in scenarios such as radiation portal monitoring or arms control verification. Environmental monitoring relies on the accurate identification of isotopes in contaminated samples, where the analysis often involves complex mixtures and low-count spectra under fluctuating background conditions.[3–5] In medical applications, isotopes such as ^{131}I and $^{99}Tc^{m}$ require precise identification for diagnostic and therapeutic purposes.[6,7]

One of the major challenges in these fields is the limitations of traditional gamma-ray detectors, such as NaI(Tl) crystals.[8] While NaI(Tl) detectors are widely used due to their cost-effectiveness, portability, and high detection efficiency, their low energy resolution and sensitivity to environmental fluctuations restrict their ability to distinguish closely spaced energy peaks or analyze low-count spectra with high noise.[9] These limitations are particularly problematic in complex scenarios, where isotopes like ^{134}Cs and ^{137}Cs overlap in the gamma-ray spectrum, or in field applications under fluctuating environmental conditions.[10]

Machine learning (ML) offers a promising solution to these challenges. ML models—including traditional algorithms such as logistic regression (LR), Bayesian classification, k-nearest neighbours (kNN), support vector machines (SVM), decision trees (DT), and gradient-boosted decision trees (GBDT), and neural-network-based approaches such as artificial neural networks (ANNs)—have shown strong potential to overcome the limitations of conventional analysis methods (e.g., peak-search algorithms, template matching), which often struggle with low-resolution spectra and spectral deformations (e.g., Compton scattering, attenuation).[11–13] ML techniques excel at parsing overlapping spectral features and adapting to the variability in environmental conditions, offering enhanced accuracy and efficiency, even in noisy,

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