



Integration of PIGE, ANN, and MCNPX: From Accurate Detection of Microplastics to Global Standardization of Plastic Pollutant Monitoring

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ABSTRACT

Microplastic pollution in water sources poses a serious threat to human health and natural ecosystems. This research examines the efficiency of the proton-induced gamma emission (PIGE) method combined with bidirectional long short-term memory (Bi-LSTM) neural networks and MCNPX numerical simulations for the accurate detection of microplastics. Utilizing MCNPX simulations, the optimal proton energy (3 to 7 MeV) and predicted gamma spectra for environmental samples were determined. Results showed that the PIGE method is most effective at energies of 3 to 7 MeV for high concentrations and at higher energies for concentrations below 1%. The Bi-LSTM model, a subset of artificial neural networks with bidirectional architecture, was configured with a learning rate of 0.001 and trained over 100 epochs (with a batch size of 32). To prevent overfitting, Dropout and Batch Normalization layers were used, while Early Stopping and (ReduceLROnPlateau) mechanisms optimized the training process by monitoring the validation loss and dynamically adjusting the learning rate. This hybrid system achieved an accuracy of 95%, sensitivity of 93%, and an F1 score of 94%, indicating significant improvement over conventional methods. This approach offers a reliable solution for tracking microplastics and, due to its applicability in complex environments like oceans and groundwater, has the potential to become a global standard such as ISO. In the future, it can be integrated with the Internet of Things (IoT) for real-time monitoring and better environmental protection.

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INTRODUCTION

The issue of environmental pollution by microplastics (MPs) has become a global problem due to the increasing evidence of microplastics' presence in waters, soils (Guo et al., 2025), and even in the human body (Bexeitova et al., 2024; Miera-Domínguez et al., 2024). The origin of microplastics (MPs), defined as plastic fragments smaller than 5 mm (Randhawa, 2023), is porous to many industrial and consumer activities and poses serious health threats, such as respiratory ailments and cancer due to inhalation or accumulation within the body (Dai et al., 2024; Goswami et al., 2024). Microplastics can find their ways to the sub-cellular moiety via active and passive approaches (Goswami et al., 2024). The small size of MPs enables them to easily interact with environmental media as well as biological systems, serving as vectors for pollutants and microorganisms (Babuji et al., 2023; Khan et al., 2024). The

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environmental impacts of MP pollution span a spectrum of impacts on aquatic life, food webs, and biodiversity in general (Bexeitova et al., 2024). Many methods have been introduced to detect the concentration of these particles. Recently, extensive research is being conducted in the field of using nuclear analysis methods to detect the amount of microplastics in air and water (Berkel & Ozbek, 2024a; Günther & Imhof, 2024). Some detection methods are optical microscopy, scanning electron microscopy (SEM), transmission electron microscopy (TEM), Fourier-transform infrared (FTIR), and Raman spectroscopy, which although commonly used, have inherent limitations such as high costs, long procedures, accuracy challenges in complex matrices, lack of non-destructive testing capabilities, and inflexible approach (Berkel & Ozbek, 2024a; Ismail et al., 2024; Liu et al., 2023). Each of these previous methodologies has its own unique advantages and limitations. Table 1 summarizes the strengths and weaknesses of commonly used analytical techniques in microplastic identification. Unlike traditional optical and spectroscopic methods which consume time at sample preparation, the PIGE-ANN-MCNPX technique enables destructive-free, specific recognition and accuracy quantification of microplastics. Microplastics are commonly detected in human tissues and organs, with distinct characteristics and entry routes, and variable analytical techniques exist (Roslan et al., 2024). Detection methods employing these techniques are often too time-consuming and are not compatible with real-time or large-scale monitoring. The recent developments in nuclear analysis techniques, such as PIXE (Miwa et al., 2024), PIGE, RBS (Boussahoul, 2024), and STIM, demonstrate greater potential for resolving issues pertaining to the non-destructive, quantitative, elemental microplastic detection enabled by nuclear methods (Boussahoul, 2024; Miwa et al., 2024).

Unlike conventional approaches, such as the ones discussed previously, these new methods enable precise elemental diagnostics without compromising the sample, making them especially useful in a variety of environmental and health-related studies. This study proposes an innovative approach that combines the Particle Induced Gamma Emission (PIGE) and Artificial Neural Network (ANN) with MCNPX simulation to exceed the current methods' boundaries and aid in universal standardization of monitoring plastic pollutants. Our goal is to establish a novel, precise, and affordable means of microplastic detection by employing PIGE spectroscopy alongside Artificial Neural Networks (ANN) and MCNPX simulations. The CRP project launched in Europe in 2024 aims at assessing the fate and environmental impact of plastics using isotopic techniques (Adu-Gyamfi & Meniailo, 2023). While this project focuses on soil and crop ecosystems, our study extends this methodology to water environments by incorporating nuclear simulations and AI-based detection. The increasing acceptance of the standardization of microplastic monitoring can be felt from the launch of the CRP project that took place in Europe in the year 2024 (Adu-Gyamfi & Meniailo, 2023). Our proposed

Table 1. Comparative summary of analytical techniques used in microplastic detection

Method	Application	Accuracy	Cost	Notes	Reference
Optical Microscopy	Visual inspection, particle size estimation	Low	Low	Simple setup, no chemical analysis	(Miwa et al., 2024)
SEM/TEM	Surface morphology, nanoplastic detection	High	Very High	Requires vacuum and sample preparation	(Ismail et al., 2024)
FTIR	Polymer identification	High	Moderate	Fast, non-destructive, limited by water interference	(Berkel & Ozbek, 2024a)
Raman Spectroscopy	Molecular composition	High	High	High specificity, sensitive to fluorescence	(Günther & Imhof, 2024)
PIGE	Elemental analysis	High	Moderate	Non-destructive, quantitative, needs accelerator	(Boussahoul, 2024)
MCNPX Simulation	Particle tracking, gamma prediction	High (with validation)	Low (after modeling)	Physics-based, requires experimental confirmation	(Nguyen & Chen, 2024)

framework furthers this aim by integrating nuclear analysis (PIGE), artificial neural networks (ANN), and the Monte Carlo method (MCNPX) with the basis of international standards, providing reproducible and scalable methodologies.

MATERIAL AND METHODS

This research utilized the MCNPX Monte Carlo simulation code to construct a PIGE-based system designed for microplastic detection in aquatic environments. The geometry was defined using the CELL card which encompassed the entire target material, as well as the detector parts. The target was modeled as a cubic volume with dimensions of $1 \times 0.1 \times 0.1 \text{ cm}^3$ (Rastgoo & Sadremomtaz, 2024). This volume was filled with a homogeneous mixture of water and polymethyl methacrylate (PMMA) which was chosen because of its structural strength, optical transparency, and environmental resistance. With MCNPX, a radiation source can be defined with the SDEF keyword, enabling the user to define numerous particle types such as protons, gamma and X rays, neutrons, and various other ions (Martínez-Fernández et al., 2024; Rastgoo & Sadremomtaz, 2024). In this case, the chosen form of radiation was a proton beam with energy spanning from 0–20 MeV; this preference was made considering the operational parameters of the Karaj cyclotron facility so the results could actually be useful. To resemble actual conditions, samples were homogenized with an ultrasonic device for 30 minutes, and confirmed through light microscopy before simulation. The experimental procedures which simulate the dissolving of the particles using ultrasonic devices for half an hour served as the basis for modeling the even distribution of PMMA particles in the water. In the MCNPX simulation, this condition is approximated through an uniform mixture model that is implemented with the FILL card and confirmed with consistent gamma-ray yield over many runs. but in real time MCNPX simulation, he hypothesized a fully controlled scenario where particles are evenly distributed in the water matrix within the environment. This guaranteed that PMMA particles were homogeneously distributed throughout the water matrix. The energy spectrum of emitted photons was calculated using the Sipm detector and the tally F8 configuration for gamma ray detection. Although the integrated approach of microplastic identification using PIGE, ANN and MCNPX demonstrates accuracy, certain drawbacks exist. For instance, one challenge of estimating elements' gamma rays in water matrices is the possible weakening of gamma rays. Even though a lot of detail is put into modeling how particles interact with the environment through MCNPX simulations, real-world samples of the environment can have obstrusive constituents of variable densities that can't be captured in controlled simulations (Nguyen & Chen, 2024). Although the impact of these factors is best captured with the aid of matrix correction methods and normalization procedures, further testing under other environmental conditions is recommended for better accuracy in models. Within the MCNPX framework, the PIGE process was assessed by detecting the emitted gamma-ray spectra using a Silicon Photomultiplier (SiPM) detector model. Characteristic peaks of PMMA's constituent elements such as carbon-12, oxygen-16, and hydrogen-1 were identified and spectrally interpreted and microplastic quantified using Genie 2000 software. Although high-purity germanium (HPGe) detectors provide unmatched energy resolution, the SiPM-based system was selected in this study due to its low size, weight, and cost, as well as the ease with which it can be integrated with portable or IoT monitoring devices. For dependable gamma-ray detection, the system was calibrated with a standard radioactive source (^{22}Na) which emits gamma rays at two specific energies 511 keV and 1275 keV. The calibration was conducted using a Sipm detector whose energy response was measured by checking if the position of the simulated peaks corresponded to the expected values. It was verified with several runs that the energy resolution was within $\pm 2\%$, which aids in proper spectrum analysis while reducing the precision error (Nguyen & Chen, 2024; Rastgoo & Sadremomtaz, 2024). This step was critical in preserving trust for

Table 2. Definition of the substance of water and microplastics with characteristics (Berkel & Ozbek, 2024b; Boran et al., 2024)

Sample No.	Microplastic Composition (PMMA %)	Water Composition (%)	Density (g/cm ³)	Standard Error (%)	Number of Replicates	Confirmatory Method
1	0	100	1.00	±0.2	10	N/A
2	0.1	99.9	1.001	±0.3	8	FTIR
3	0.2	99.8	1.002	±0.4	8	FTIR
4	0.3	99.7	1.003	±0.5	7	FTIR
5	0.5	99.5	1.006	±0.4	7	FTIR
6	1	99	1.012	±0.3	6	FTIR
7	2	98	1.024	±0.5	6	FTIR
8	5	95	1.059	±0.6	5	FTIR, Raman
9	10	90	1.118	±0.7	5	FTIR, Raman

spectral analyses and lowering spectral analysis uncertainty. For each scenario, a minimum of five independent replicates ($n = 5$) were conducted for each simulation to ensure reproducibility. These conditions allowed for the achievement of statistical reliability. RSD values were under 1% across the condition, demonstrating exceptional reliability across trials. In addition, paired t-tests assessing differences in concentration between the samples were performed with a significance threshold of $p < 0.05$, alongside 95% confidence interval computation for primary KPIs aimed at testing variability across unpaired observations. Setting 1×10^8 primary particles as the baseline for all simulations allowed error margin boundaries of less than 1%. The Bi-LSTM neural network was trained using the Adam optimizer with a 0.001 learning rate over 100 epochs with a set batch size of 32. Application of Dropout layers (0.2) alongside Batch Normalization enhanced convergence and reduced overfitting. The making of water-microplastic samples is given in Table 2 of this document. The microplastic portion is polymethyl methacrylate (PMMA) holding the following chemical formula $C_5O_2H_8$ (Boran et al., 2024). For this research work, PMMA was chosen because of its high environmental persistence and considerable structural strength which makes it an ideal candidate for model persistent microplastics in water bodies. Each sample had a set water (H_2O) matrix (Guo et al., 2025) while the amount of PMMA varied between 0.1% and 10%. To enhance reproducibility, each simulation scenario was performed no less than five times independently ($n=5$ to 10), with aggregate standard error values computed across iterative trials. Spectral precision was further verified through FTIR and Raman methods to make sure no divergence existed with experimental detection protocols and affirm consistency with established spectral frameworks (Berkel & Ozbek, 2024a; Ismail et al., 2024). To verify spectral fidelity, prominent peaks were juxtaposed with ex-situ detection processes employing FTIR and Raman spectroscopy (Berkel & Ozbek, 2024a; Ismail et al., 2024). These methods serve specific benchmarks in spectral fidelity and are not incorporated during the simulation process.

Figure 1 gives an illustrative overview of the integrated PIGE-Bi-LSTM-MCNPX framework for microplastics detection in the water. The workflow starts by irradiating a water-PMMA mixture with proton beams, followed by gamma ray emission modeling in MCNPX simulations. Obtained spectra are processed and input into a deep learning model for further classification and quantification.

Although high-purity germanium (HPGe) detectors provide unmatched energy resolution, the SiPM-based system was selected in this study due to its low size, weight, and cost, as well as the ease with which it can be integrated with portable or IoT monitoring devices. For dependable gamma-ray detection, the system was calibrated with a standard radioactive source

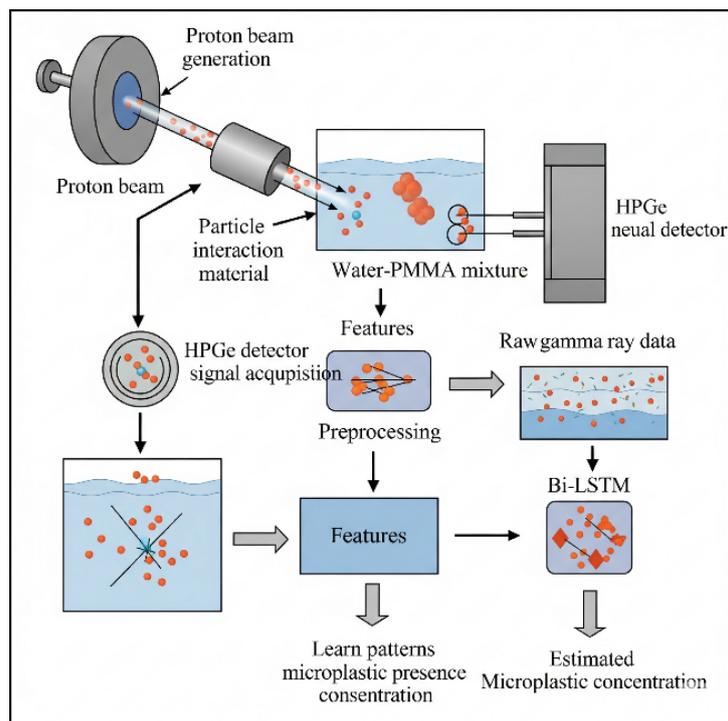


Fig. 1. Schematic representation of the PIGE-Bi-LSTM-MCNPX framework for microplastic detection in water environments

(^{22}Na) which emits gamma rays at two specific energies 511 keV and 1275 keV. The calibration was conducted using a Simp detector whose energy response was measured by checking if the position of the simulated peaks corresponded to the expected values. It was verified with several runs that the energy resolution was within $\pm 2\%$, which aids in proper spectrum analysis while reducing the precision error. For each scenario, a minimum of five independent replicates ($n = 5$) were conducted for each simulation to ensure reproducibility, and RSD values were under 1% across the condition, demonstrating exceptional reliability across trials.

Neural Network Architecture and Training Hybrid CNN-RNN Model Architecture

The deep learning model was designed as a hybrid architecture to leverage the distinct advantages of both Convolutional Neural Networks (CNN) and Recurrent Neural Networks (RNN) for spectral data analysis. The architecture initiates with a one-dimensional convolutional layer (Conv1D) that acts as a hierarchical feature extractor. This layer is adept at identifying localized, low-level patterns within the gamma-ray spectra, such as the initial rise or decay of characteristic peaks, which serve as foundational features for subsequent layers. The feature maps generated by the convolutional layer are then passed to the core of the model: a multi-layered Bidirectional Long Short-Term Memory (Bi-LSTM) network. This recurrent structure was specifically chosen for its proficiency in modeling sequential data. The bidirectional nature of the network allows it to process the spectral data in both forward (increasing energy) and backward (decreasing energy) directions. This is critical for capturing the complete context of spectral features, as the significance of a peak can be influenced by both preceding background noise and succeeding Compton scattering edges. To enhance model robustness and prevent overfitting on the training dataset, two key regularization techniques were employed. Dropout layers were strategically placed to randomly deactivate a fraction of neurons during training, forcing the network to learn more distributed and resilient feature representations. Furthermore, Batch Normalization was applied to stabilize the learning process and reduce internal covariate

shift by normalizing the activations of each layer. The model was trained for 100 epochs with a batch size of 32.

LSTM Cell Mechanism

The fundamental component of the Bi-LSTM is the LSTM cell, a sophisticated unit designed to overcome the vanishing gradient problem inherent in simple RNNs. Its efficacy lies in the cell state, which acts as a conveyor belt for information, allowing long-term dependencies to persist through the sequence. This memory flow is meticulously regulated by three gating mechanisms. The forget gate employs a sigmoid activation to selectively prune irrelevant information from the cell state, retaining only dependencies that are deemed useful for the final classification. The input gate then determines which new information from the current spectral data point is salient and should be stored in the cell state. Finally, the output gate generates the hidden state for the current time step, which is a filtered version of the cell state that represents the network's working memory and is passed to the next layer. This precise, learned control over information retention and flow enables the LSTM to model the complex and long-range structural dependencies present in the spectral data.

Training Protocol and Performance Evaluation

The model was trained following a defined protocol using the Adam optimizer, an adaptive learning rate optimization algorithm that is well-suited for noisy objective functions typical of spectral data. To ensure optimal convergence, two callbacks were utilized. The ReduceLROnPlateau callback adaptively reduced the learning rate whenever the validation loss stagnated, allowing for finer-grained optimization in later training stages. Concurrently, Early Stopping was implemented to terminate the training process if no improvement in validation loss was observed over a set number of epochs, thereby preventing overfitting and preserving the best-performing model weights. To ensure a comprehensive and unbiased validation of the model's classification performance, a suite of standard metrics was derived from the confusion matrix. Accuracy provided a global measure of the model's correctness across all classes. However, given the potential for class imbalance in environmental samples, other metrics were deemed more informative. Sensitivity (Recall) was crucial for evaluating the model's ability to correctly identify all true microplastic-containing samples, thus minimizing false negatives. Precision measured the reliability of a positive prediction, indicating the proportion of samples classified as containing microplastics that truly did. Finally, the F1 Score was calculated as the harmonic mean of precision and recall, offering a single, robust metric that balances the trade-off between false positives and false negatives, which is particularly important in environmental monitoring applications.

RESULTS AND DISCUSSION

This research utilized the PIGE method for the detection of microplastics in water environment using a proton beam with an energy range between 0 to 20 MeV. The gamma ray spectrum emitted from samples with different concentrations of PMMA dissolved in water was compared to the blank measurements that had no microplastics. The results of emitted gamma spectrum of water samples containing microplastics and samples without microplastics have been compiled in figures 2 and 3. The findings show that at energies of 7.3 MeV and below 5 MeV, there are differences between pure water and water-microplastic mixtures. In particular, changes in the maximum value of backscattered photons in the region of energies less than 3MeV indicate that the height of gamma-ray peaks diminishes with an increase in microplastic concentration. The lowest peak corresponds to the sample containing 10% PMMA, which indicates what the amplitude of the microplastic power is to the spectrum response.

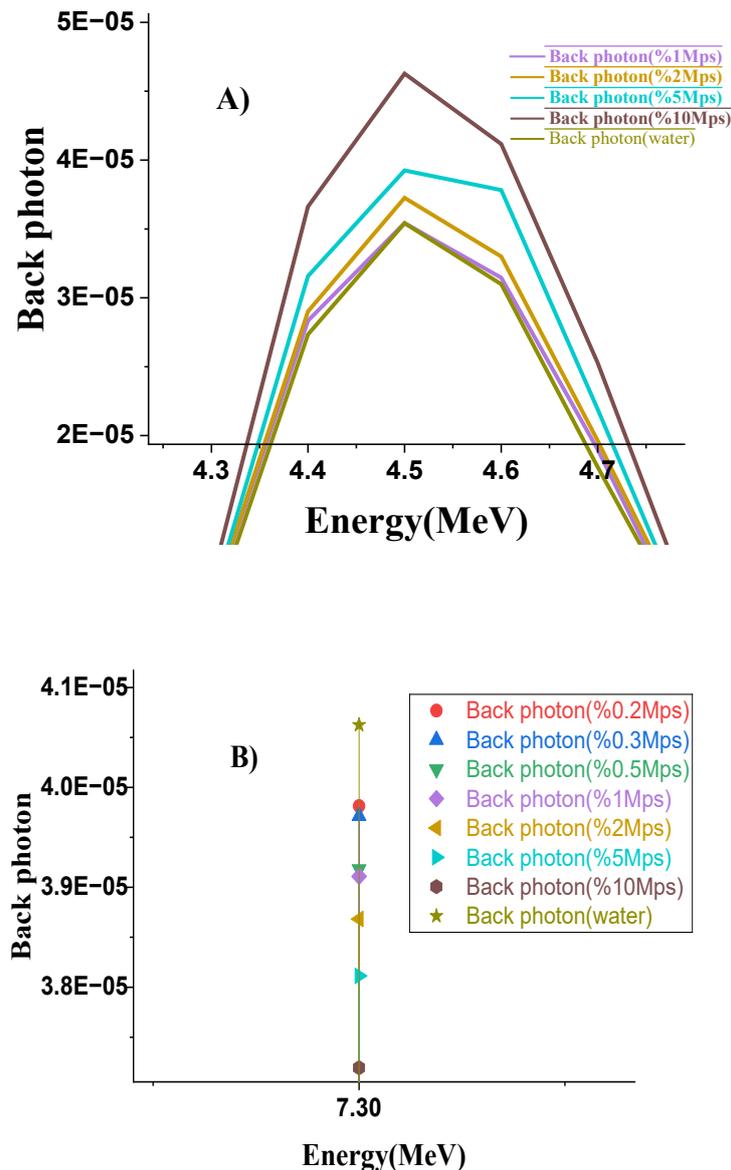


Fig. 2. Variation in the peak of backscattered photons at energies below 5 MeV and detection in water with and without 1%-10% microplastics (A), variation in the height of backscattered photons at 7.30 MeV energy and detection in water with and without 0.2%-10% microplastics (B).

Comparative Analysis of Optimization Algorithms

To improve transparency in model selection, we compare the performance of three gradient descent algorithms used in this study: Adam, RMSProp, and AdaGrad. Each algorithm has distinct characteristics affecting convergence, stability, and final accuracy. Adam optimizer integrates adaptive learning rates and momentum, enabling fast convergence and high precision in non-linear and noisy environments such as gamma-ray spectra analysis. RMSProp adjusts learning rates per parameter but lacks momentum and is less stable in early epochs. AdaGrad effectively handles sparse gradients but suffers from rapidly decaying learning rates, which limits long-term learning capability. To corroborate these conclusions, spectral data were analyzed using a Bi-LSTM neural network model. The model was first optimized using three gradient descent algorithms — namely, Adam, RMSProp (~89%), and AdaGrad (~87%) — to assess which method performed best in minimizing detection error, particularly in scenarios

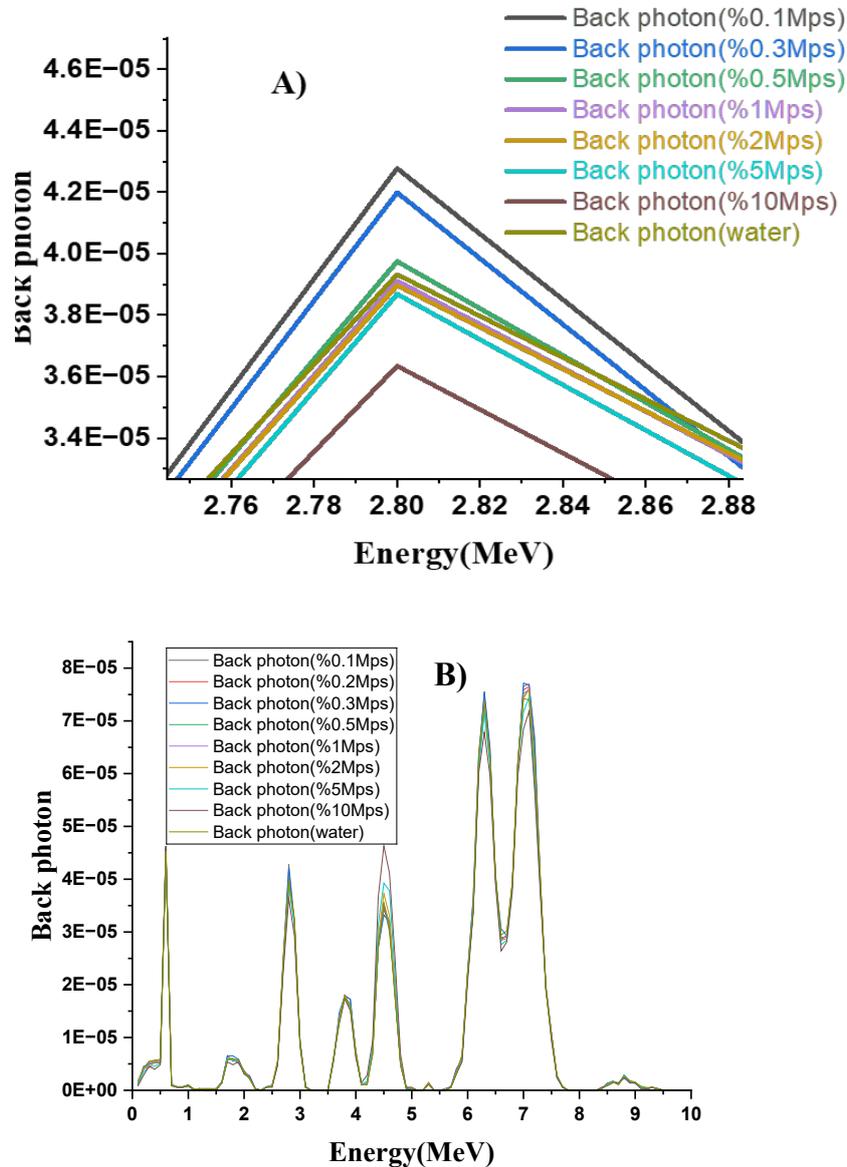


Fig. 3. Variation in the peak of backscattered photons at energies below 3 MeV and detection of water with and without 0.1%-10% microplastics (A), and the energy of backscattered photons at 0-20 MeV energy (B).

involving overlapping gamma-ray peaks and water matrix effects. As shown in Figure 4, the results indicate that Adam demonstrated superior performance compared to both RMSProp and AdaGrad in terms of convergence speed and classification accuracy, achieving a test accuracy of 95%, an F1 score of 94%, and a sensitivity of 93%.

Figure 5 illustrates the training and validation loss curves of the Bi-LSTM model using the Adam optimization algorithm. After 100 epochs, both losses reached roughly 0.07, demonstrating effective learning with minimal overfitting. The addition of Dropout layers as well as Batch Normalization proved beneficial in ensuring consistent performance during training, and Early Stopping and ReduceLRonPlateau optimally lowered the learning rate to enhance generalization. Their reproducibility across simulation trials was statistically evaluated and found to be high. For all tested conditions, relative standard deviation (RSD) metrics were under 1%, demonstrating low variability. In addition, paired t-tests were performed to assess differences between sample concentrations across a given measurement ($p < 0.05$). To help

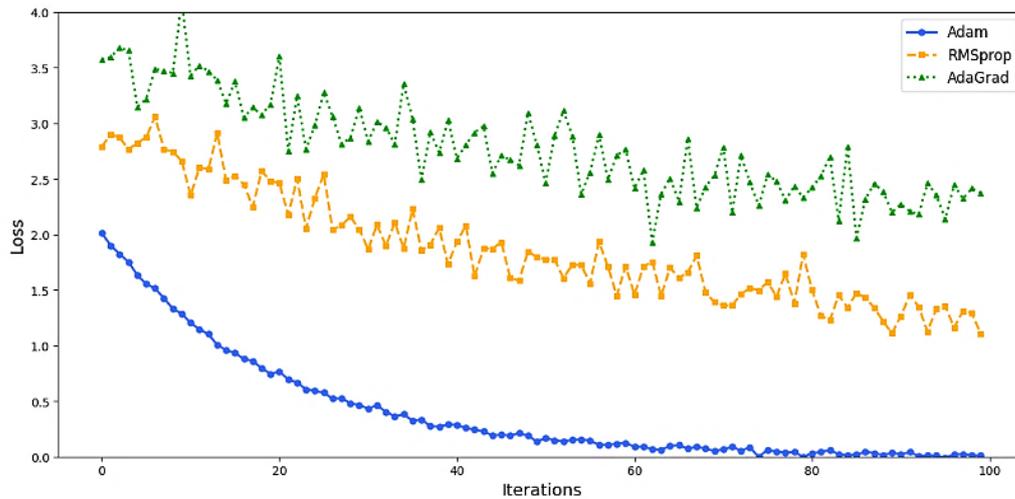


Fig. 4. Performance of Adam Optimizer Compared to RMSProp and AdaGrad Optimizers

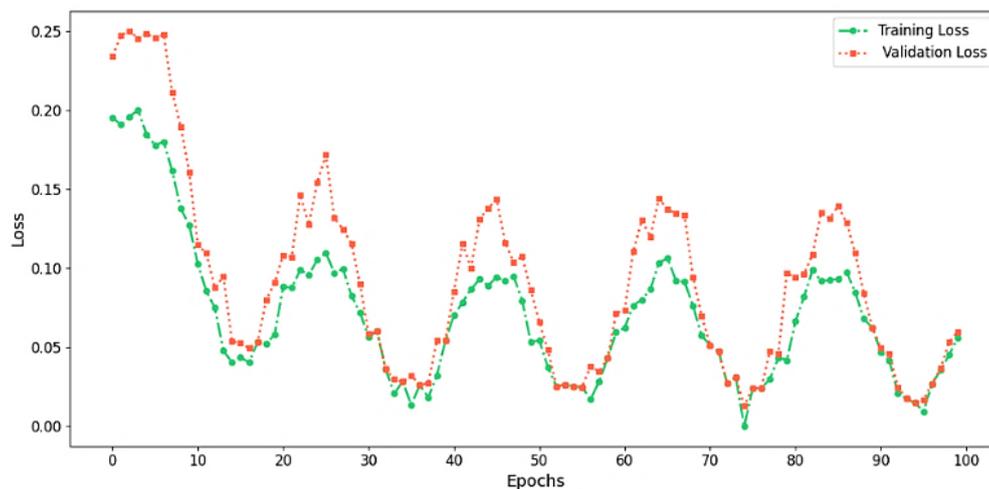


Fig. 5. Training and Validation Loss of the Bi-LSTM Neural Network Optimized with the Adam Algorithm

understand the meaning of these tests, we state the following hypotheses: Null Hypothesis (H_0): No significant difference exists in the peak intensity value and also the classification accuracy for microplastic in water and those with different PMMA concentrations. Alternative Hypothesis (H_1): Peak intensities and classification values change significantly with increase in microplastic concentration, which indicates stronger response from the system as measured by PIGE-ANN-MCNPX. Since we observed p-values < 0.05 for a number of important energies, we reject H_0 and accept H_1 which is the claimed method strongly detects microplastics with statistically verifiable accuracy. In addition, paired tests on selected key energy peaks showed p-values < 0.05 , hence affirming marked differences between samples with microplastics and without. These aligned results corroborated earlier work employing Bi-LSTM models for time series data (Hussain & Naseer, 2024). However, unlike those works which relied on textual data or sensor data and focused mainly on Bi-LSTM's applications, this study aimed at extending the applicability of the Bi-LSTM model to spectroscopic data using nuclear spectroscopy – a domain where there are complex and convoluted overlapping peaks and matrix effects. The unexpected superiority of our model is likely linked to tailored preprocessing techniques

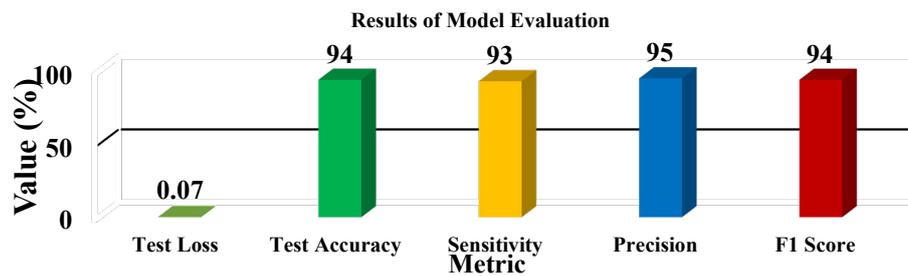


Fig. 6. Performance Evaluation of Bi-LSTM Recurrent Neural Network Using In-Network Evaluation Metrics

specific to the problem domain and extensive MCNPX simulation integration, which provided accurate predictions of expected gamma emissions under varying environmental conditions.

The unexpected superiority of our model is likely linked to tailored preprocessing techniques specific to the problem domain and extensive MCNPX simulation integration, which provided accurate predictions of expected gamma emissions under varying environmental conditions, ultimately leading to the model achieving 95% accuracy, 93% sensitivity, and a 94% F1-score in microplastic detection. The statistical significance of these results was confirmed with paired t-tests ($p < 0.05$), which rejected the null hypothesis that the model offered no improvement over baseline conditions. This high performance is attributed to the synergistic integration of three technologies: the nuclear-based detection of PIGE, the physics-driven simulation of MCNPX, and the advanced pattern recognition of the Bi-LSTM neural network. Unlike methods that rely on a single technique, our approach combines physics-informed modeling with data-driven analysis, leading to improved generalization and a reduction in false positives. In Figure 6 comparison to conventional methods like FTIR and Raman, the PIGE-ANN-MCNPX system outperforms them in accuracy, sensitivity, and F1 score metrics with values of 94%, 93%, and 94% respectively. The reasons for these improvements include:

- Accurate modeling of proton interactions via MCNPX simulations
- Learning rate adjustments through the Adam optimizer
- Strong Dropout and Batch Normalization regularization
- AI pattern recognition integration with nuclear detection

To evaluate the statistical significance of the differences between microplastic detection using PIGE-ANN-MCNPX and conventional methods, a paired t-test was performed at $\alpha = 0.05$. The null hypothesis (H_0) assumed that there is no significant difference in peak intensity or classification accuracy between samples with varying PMMA concentrations. The alternative hypothesis (H_1) stated that the proposed method would yield significantly better results due to its integration of nuclear simulation and deep learning-based pattern recognition.

Energy Considerations

The energy dependence of the PIGE method microplastic monitoring system dictates the practical usability and long-term sustainability of the technique. In this work, the optimal value of proton beam energy was found to be 3–7 MeV based on the simulations performed with MCNPX. This region of operations has lower power requirements for the accelerator and shielding, which is favorable for the global safety standards for ionizing radiation. Higher energies (>7 MeV) could enhance the signals, but would increase the background radiation, making the detector more complex, which is unfavorable for portable or semi-portable monitoring systems. At lower energies (<3 MeV), the gamma-ray yield becomes insufficient and the time needed to be efficient becomes longer.

Limitations of the Study

While the integrated PIGE-ANN-MCNPX approach demonstrates remarkable accuracy, some limitations remain. A primary challenge is the potential attenuation of gamma rays within the water matrix, which could affect the precision of quantification. Furthermore, the model assumes a homogeneous distribution of microplastics, whereas in real-world environmental samples, particulates are often found in non-uniform distributions. Another limitation concerns the proton irradiation energy range (0–20 MeV). While suitable for the Karaj cyclotron facility, this range may not be optimal for detecting microplastics at extremely low concentrations (less than 0.1%), where the signal-to-noise ratio becomes problematic. Future work could address these issues by validating the model with heterogeneous field samples and employing advanced noise filtering or ensemble learning techniques to enhance sensitivity under such conditions.

CONCLUSION

This study successfully demonstrated the high efficiency of an integrated PIGE, Bi-LSTM, and MCNPX framework for the accurate detection and quantification of microplastics in water. By combining nuclear analysis with physics-informed simulations and deep learning, the proposed system achieved 95% accuracy, outperforming conventional methods that are often limited by complex sample matrices and lower sensitivity. The MCNPX simulations were crucial in determining the optimal proton energy range (3–7 MeV) for effective detection. The developed model provides a robust, scalable, and non-destructive solution for environmental monitoring. Future integration with IoT technologies has the potential to establish this method as a global standard for real-time tracking of microplastic pollution, thereby offering a significant tool for environmental protection.

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The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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