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Artificial neural networks classification of s-band absorption performance in eco-friendly microwave absorbers

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ABSTRACT

Microwave absorbers are essential for applications such as radar stealth and electromagnetic compatibility. Nevertheless, traditional materials encounter obstacles related to cost and sustainability, which has led to the exploration of new options such as materials derived from agricultural waste. This study focuses on the classification challenge of evaluating the absorption performance of eco-friendly microwave absorbers in the S-band (2 to 4 GHz) frequency. Three multilayer perceptron (MLP) algorithms, namely levenberg marquardt (LM), resilient backpropagation (RBP) and scale conjugate gradient (SCG) are assessed for classification accuracy. The dataset consists of 135 absorption performance values of microwave absorbers that were taken from experimental measurements using the naval research laboratory (NRL) arch free. The MLP algorithms will be divided into three divisions, which are training, validation and testing, evaluating important criteria such as accuracy, precision, sensitivity and specificity. The performance of three types of algorithms will be compared using two basic inputs: the absorption values and the single slot sizes. The RBP algorithm achieved 100% accuracy, and a lower mean squared error (MSE) of 0.02500 compared to the LM and SCG. This study provides valuable insights for designing better microwave absorbers and highlights the commercial potential of agricultural waste materials in such applications.

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1. INTRODUCTION

The rapid evolution of industry 4.0, including advancements like 5G communication systems, has led to an increased concern about the radiation effects of these technologies on human health. Studies have shown that radio frequency radiation can have detrimental health impacts such as headaches, cellular damage, increased brain tumor risk, and cancer [1]–[3]. Consequently, the development of anti-microwave materials has become essential to ensure safe levels of electromagnetic exposure [4], [5].

Microwave absorbers play a crucial role in reducing unwanted radio frequency radiation that may disrupt electronic devices and machinery. These absorbers are used in various applications across several frequency ranges, such as telecommunications, military technologies, high-speed electronics, and the automotive industry [6]–[8]. The integration of biomass materials into microwave absorbers is a promising area of research, driven by the need for cost-effective and environmentally sustainable solutions [9].

Accurately predicting the absorption performance of microwave absorbers presents a significant challenge due to the complexity of the materials and their interactions with microwaves. Artificial neural networks (ANNs) have emerged as a powerful tool in microwave engineering for their ability to learn from extensive datasets and handle complex, nonlinear relationships. Among the various ANN architectures, the multilayer perceptron (MLP) is particularly popular due to its robustness and adaptability [10]–[12]. This study focuses on employing ANNs to classify the absorption performance of eco-friendly microwave absorbers in the S-band frequency range.

The S-band, ranging from 2 to 4 GHz is widely utilized in various applications. It is commonly used in radar systems, including weather radar, surface ship radar, and some communications satellites [13]. The S-band is favored for these applications due to its balance between range and resolution, as well as its ability to penetrate through atmospheric conditions like rain and fog. This makes it a critical frequency band for both civilian and military purposes, necessitating effective microwave absorption solutions to mitigate unwanted interference and enhance system performance [14].

MLPs are a popular choice in neural network applications due to their structure, which includes an input layer, one or more hidden layers, and an output layer. The hidden layers perform the main computational tasks, enabling the network to learn hierarchical representations of the input data. Each MLP algorithm has unique features and benefits, making it essential to evaluate its performance in this specific application [15]–[17]. The Levenberg Marquardt (LM), resilient backpropagation (RBP), and scaled conjugate gradient (SCG) algorithms each offer distinct advantages, making a comparative analysis essential to identify the most effective approach for this task. MLP networks are currently widely used by researchers in various fields of study, including military applications, telecommunication systems, essential oil grading, pattern recognition and the oil industry, among others. These applications demonstrate the versatility of MLP networks for different types of data and problem domains. For example, MLP was successfully implemented in studies for military applications, highlighting its effectiveness in handling complex and sensitive information [18]–[21].

The innovation in this research lies in the dual focus on utilizing eco-friendly-derived materials for microwave absorbers and applying different ANN algorithms to enhance classification accuracy. This approach not only contributes valuable insights for optimizing microwave absorber design but also highlights the commercial potential of eco-friendly-derived materials in microwave absorption applications. By employing the benefits of eco-friendly materials, this study addresses both environmental sustainability and technical performance. This study provides a comprehensive analysis of the classification performance of these MLP algorithms, demonstrating that RBP achieves superior results with 100% accuracy and a significantly lower mean squared error (MSE) compared to LM and SCG. The detailed evaluation of these algorithms provides a robust comparison, ensuring that the findings are well-supported. These findings offer important implications for the development and practical application of eco-friendly-based microwave absorbers, suggesting that they can be a viable and effective solution in various industries.

2. METHODOLOGY

The dataset consists of 135 absorption performance values of microwave absorbers taken from the experimental measurements using the NRL Arch Free [22]. This dataset focuses exclusively on the single-slot S-band, which operates within the frequency range of 2 to 4 GHz. The single-slot rectangular is categorized into three sizes, which are small, medium, and big.

2.1. Data collection and preprocessing

The absorption performance values were measured using the NRL Arch Free method, which ensures accurate and consistent data collection. The data was then preprocessed by normalizing the values to ensure uniformity, randomizing the dataset to prevent any bias and dividing it into three phases: 70% for training, 15% for testing and 15% for validation. This division is important for assessing the model's performance across different stages of learning and evaluation.

2.2. ANN model and algorithms

The data is classified using the ANN approach, specifically the MLP. Three MLP methods, namely LM, RBP, and SCG are utilized for this analysis. These algorithms are used to classify the S-band absorption values for the three single-slot sizes. These algorithms were chosen for their effectiveness in handling classification tasks. The MLP network structure included an input layer, a hidden layer with 10 neurons and an output layer corresponding to the three size classes.

2.3. Implementation

The ANN model was implemented using MATLAB version R2021a. The pattern recognition neural network (patternet) function in MATLAB was utilized for training and evaluating the network. The training process involved adjusting the weights and biases of the network to minimize the error in classification.

2.4. Performance evaluation

The performance of the ANN was evaluated using several criteria, including the confusion matrix, accuracy, sensitivity, precision and MSE. The confusion matrix, shown in Table 1, provides a detailed breakdown of the model's classification performance across the three size categories which are small, medium and big. It provides insights into how well the model distinguishes between these categories presenting the number of correct and incorrect classifications.

In Table 1, BP indicates the number that is correctly classified as small, medium, or large. SN is a number that is incorrectly classified as not small, not medium, or not big. SP indicates instances incorrectly classified as small, medium, or big. BN represents that it is correctly classified as not small, not medium, or not big. The performance of the ANN classification technique is evaluated by calculating the accuracy, precision, sensitivity, and specificity [23]–[25], as indicated in (1) to (4).

a) Accuracy is a quantitative statistic that evaluates the overall correctness [19] of an S-Band microwave absorber absorption for each group of size classification model.

$$Accuracy = \frac{BP}{BP+BN+SP+SN} \quad (1)$$

b) Sensitivity is the ability of a classifier to identify positive occurrences among all actual groups of size correctly.

$$Sesitivity = \frac{BP}{BP + SN} \quad (2)$$

c) Specificity measures the ability of the model to detect negative cases accurately.

$$Specificity = \frac{BN}{BN + SP} \quad (3)$$

d) Precision is a measure of how closely the data label aligns with the positive labels assigned by the classifier.

$$Precision = \frac{BP}{BP + SP} \quad (4)$$

Table 1. The confusion matrix of a three-class classification

Group (size)	Predicted small	Predicted medium	Predicted big
Actual small	BP	SN	SN
Actual medium	SP	BP	SN
Actual big	SP	SN	BP

3. RESULTS AND DISCUSSION

This section presents the results of implementing the ANN technique using three different datasets. The results encompass comparisons between ANN architectures, accuracy, MSE values, and confusion matrix comparisons. Finally, the ANN with the best performance was selected as the optimal model for classifying the S-band absorption performance of eco-friendly microwave absorbers. Figure 1 shows the architecture of a neural network using the patternet function in MATLAB. In this figure, there are two parameters, which are the absorption value and the size number set as an input, ten hidden neurons, and three outputs. The output in this context is three class sizes of rectangular slot arrays in binary values (0 and 1).

3.1. Data classification for a single slot S-band using the MLP algorithm in ANN technique

Table 2 shows the training dataset used to train the network LM algorithm. The minimum accuracy of the training dataset is 78.9%, while the maximum is 100%. The minimum accuracy of the validation dataset is 65%, while the maximum is 100%. The minimum accuracy of the testing dataset is 70%, while the maximum is 100%. Hidden neuron number 1 outperformed others, with all datasets achieving 100% and the lowest mean-squared error of 0.03333.

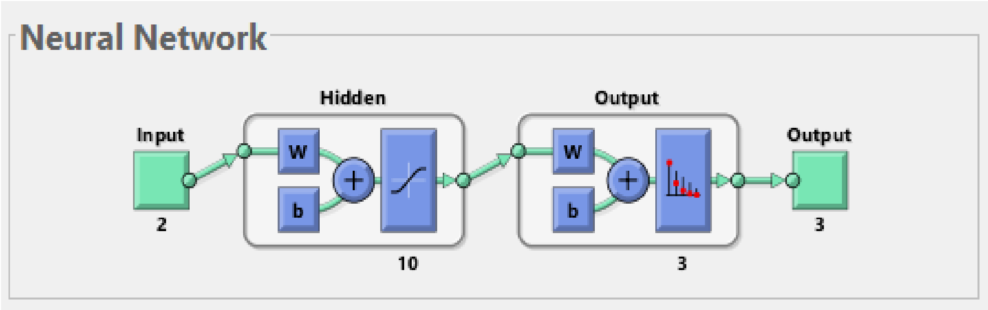

Figure. 1. The architecture of a neural network for three sizes of rectangular slot

Similarly, Table 3 tabulates the training dataset used to train the network RBP algorithm. The minimum accuracy of the training dataset is 82.1%, while the maximum is 100%. The minimum accuracy of the validation dataset is 70%, while the maximum is 100%. The minimum accuracy of the testing dataset is 75%, while the maximum is 100%. Hidden neuron number 4 is the best, with all datasets reaching 100% with the lowest mean squared error of 0.02500.

Table 1. Training data set using the LM algorithm

Hidden neuron	Accuracy (%)			MSE value
	Training	validation	Testing	
*1	100	100	100	0.03333
2	80	65	95	0.08333
3	91.6	80	90	0.06667
4	78.9	95	90	0.04167
5	82.1	85	80	0.05000
6	91.6	95	90	0.04165
7	84.2	85	90	0.06667
8	91.6	85	90	0.06676
9	83.2	80	70	0.04157
10	93.7	95	95	0.05100

**best hidden neuron in LM*

Table 3. Training data set using the RB algorithm

Hidden neuron	Accuracy (%)			MSE value
	Training	validation	Testing	
1	100	100	100	0.15000
2	100	100	100	0.05834
3	84.2	85	90	0.05000
*4	100	100	100	0.02500
5	89.5	70	100	0.09167
6	100	100	100	0.05834
7	84.2	80	85	0.05833
8	86.3	85	90	0.04167
9	82.1	100	75	0.03334
10	84.2	85	75	0.05834

**best hidden neuron in RB*

Table 4 shows the training dataset used to train the network SCG algorithm. From this table, the minimum accuracy of the training dataset is 78.9%, while the maximum is 100%. The minimum accuracy of the validation dataset is 75%, while the maximum is 100%. The minimum accuracy of the testing dataset is 70%, while the maximum is 100%. Hidden neuron number 3 outperformed others, with all datasets achieving 100% and the lowest mean-squared error of 0.03331.

Table 4. Training data set using the SCG algorithm

Hidden neuron	Accuracy (%)			MSE value
	Training	Validation	Testing	
1	100	100	100	0.11667
2	100	100	100	0.10000
*3	100	100	100	0.03331
4	90.5	90	100	0.05000
5	78.9	90	90	0.05833
6	88.4	80	80	0.06723
7	87.4	80	85	0.06671
8	84.2	75	80	0.05001
9	86.3	80	70	0.07500
10	92.6	85	95	0.07241

**best hidden neuron in SCG*

3.2. Comparison of the MLP algorithms in the ANN technique

From Table 5, it was found that LM, RBP and SCG achieved 100% accuracy for all parameters but were different in MSE. In this result, taking MSE as one of the considerations, the RBP obtained the lowest MSE, which is 0.02500 in hidden neurons 4, and concluded that the RB performs the best among training algorithms. Figure 2 shows the confusion matrix for the ANN model using resilient backpropagation with 135 absorption performance values. It illustrates perfect classification performance, with all 45 values of small, medium and big sizes correctly classified, resulting in no misclassifications. This is reflected in the confusion matrix, where the diagonal values represent the correct classifications and the off-diagonal values are zero.

Table 5. Summarizing of the best hidden neuron from each training algorithms

Training algorithm	Hidden neuron	Accuracy (%)			MSE value
		Training	validation	Testing	
Levenberg-Marquardt (LM)	1	100	100	100	0.03333
*resilient backpropagation (RB)	*4	100	100	100	0.02500
Scaled-Conjugate Gradient (SCG)	3	100	100	100	0.03331

**best hidden neuron*

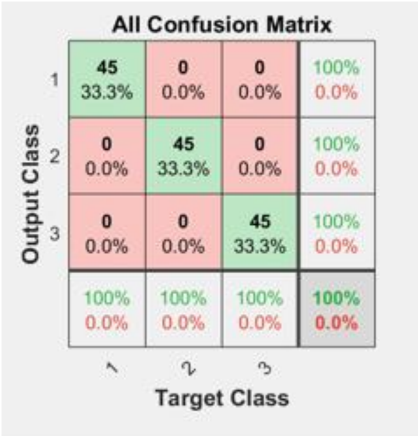

Figure 2. Overall confusion matrix for ANN technique using RB algorithm

3.3. The performance of the ANN classification technique

The performance of the ANN model was evaluated using four-parameter metrics which are accuracy, precision, sensitivity and specificity. These metrics provide a comprehensive assessment of the model's ability to classify the absorption performance of the single-slot S-band eco-friendly microwave absorbers. The findings of the best performance evaluation are summarized in Table 6.

Table 6. Performance evaluation of ANN

Performance parameter of ANN	Performance evaluation (%)
Accuracy	100
Precision	100
Sensitivity	100
Specificity	100

Figure 3 shows the performance evaluation graph of the ANN using 135 absorption performance values with resilient backpropagation when the number of hidden neurons is four. It highlights the effectiveness of the model by achieving 100% accuracy, precision, sensitivity and specificity. This high level of performance indicates that the ANN-resilient backpropagation model is highly reliable for classifying the absorption performance of microwave absorbers, demonstrating its potential for practical applications in various industries. The study's findings show that the ANN classification technique is effective in predicting the S-band absorption performance of eco-friendly microwave absorbers. The resilient backpropagation (RB) algorithm, particularly with hidden neuron 4 showed the best performance with a mean squared error of 0.02500. This high performance indicates the model's capability to accurately classify the absorption characteristics of different slot sizes. When compared to previous studies, this model's accuracy, precision and specificity are significantly higher, indicating an improvement in classification performance.

The strengths of this study include the high accuracy, precision, sensitivity and specificity of the ANN model, which highlights its reliability in predicting S-band absorption performance. Additionally, the study is limited by the use of a single-slot type of absorber shape. Future research should focus on exploring different slots of absorber shapes to provide a broader understanding of the model's applicability.

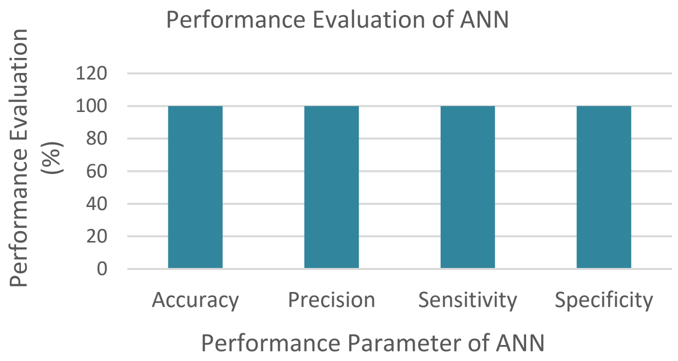

Figure 3. The performance evaluation of ANN- resilient backpropagation

4. CONCLUSION

This study has successfully demonstrated the classification of the absorption performance of single-slot S-band eco-friendly microwave absorbers using ANN. The ANN model utilizes two input features, absorption value and slot size, and evaluates the performance of three algorithms, which are LM, RBP and SCG. Based on the analysis of 135 data points, the RBP algorithm outperformed the others, achieving perfect classification performance. The RBP algorithm attained an accuracy, precision, sensitivity and specificity of 100%, indicating that all data points were correctly classified with no false positives or negatives. Additionally, RBP achieved a lower MSE value of 0.02500, demonstrating its excellent performance. The excellent performance of the RBP algorithm highlights its effectiveness and reliability in classifying the S-band absorption performance of eco-friendly microwave absorbers. This method will benefit the telecommunications industry by facilitating the production of high-quality eco-friendly microwave absorbers, enhancing efficiency and quality in the field.

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