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Scientific Research

# Modeling the effect of ultrasound on viscosity, consistency coefficient, and flow behavior index of different concentrations of xanthan gum

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**ABSTRACT**

The use of ultrasonic waves to change the structure of the gums leads to the modification and improvement of their functional characteristics and rheological properties. In this research, the effects of ultrasonic intensity and treatment time on apparent viscosity, consistency coefficient, and flow behavior index of different concentrations of xanthan gum were investigated and modeled. Genetic algorithm-artificial neural network method with three inputs (ultrasonic power, treatment time and gum concentration) and three outputs (viscosity, consistency coefficient, and flow behavior index) was used to model the process. The apparent viscosities of the xanthan gum control sample (untreated) at concentrations of 0.1, 0.15, and 0.2% were 21.0, 39.9, and 66.5 mPa.s, respectively. The results of this research showed that gum viscosity decreased with increasing intensity and duration of ultrasound application. Ultrasonic treatment for 20 min significantly reduced the apparent viscosity of xanthan gum from 39.9 to 23.2 mPa.s ($p< 0.05$). The genetic algorithm-artificial neural network modeling results showed that the network with 3-5-3 structure in a hidden layer and using the hyperbolic tangent activation function can predict the rheological parameters of xanthan gum with high correlation coefficient and low error value. Values of mean squared error (MSE), normalized mean squared error (NMSE), mean absolute error (MAE), and correlation coefficient (r) to predict the apparent viscosity of xanthan gum were 73.17, 0.20, 6.48, and 0.90, respectively. Based on the results of the sensitivity analysis test, ultrasonic treatment intensity was the most effective factor in changing the apparent viscosity, consistency coefficient, and flow behavior index of xanthan gum.

## 1. Introduction

Hydrocolloids (gums) are hydrophilic compounds that are used as thickeners to change the rheological properties of foods. One of the widely used gums in the food industry is xanthan gum. This gum is an anionic hydrocolloid and an extracellular polysaccharide produced by *Xanthomonas campestris* [1]. Xanthan gum is widely available and used in the food industry as a thickening, stabilizing, suspending, emulsifying and gelling agent. Aqueous solution of xanthan gum shows pseudoplastic behavior [2-4].

Currently, the modification and improvement of the quality of hydrocolloids using non-thermal processes has attracted the attention of many researchers and food processing companies [5, 6]. For example, the effect of high hydrostatic pressure on the rheological properties and foams/emulsions stability of *Alyssum homolocarpum* seed gum has been investigated by Ghaderi et al. (2020). These researchers reported that the use of this non-thermal method leads to an increase in the stability of the foam and emulsion prepared from *Alyssum homolocarpum* seed gum [5].

Today, ultrasound is used as a new green tool with unique effects in food preservation and processing. The effect of ultrasound waves is due to cavitation phenomenon, heating, increasing mobility and creating shear stress in the samples [7, 8]. One of the most recent applications of ultrasound is to change the composition and structural properties of polymers such as hydrocolloids [9-11].

The ability of xanthan gum to control solution properties (due to high viscosity at low concentration) has promoted its use as a rheology modifier in various industries [1]. The rheological properties of gum solution play an important role in the design of processes and the selection of processing and material transfer devices. In recent researches, ultrasound has been used for the controlled decomposition of gums and as a result changes in their viscosity and rheological properties [9-13]. The effect of ultrasound on the rheological behavior of sugar beet pectin was investigated by Yang et al. (2020). The results obtained by these researchers showed that the viscosity and consistency coefficient values of pectin decrease after applying ultrasound [14].

The artificial neural network model is a mathematical model with strong adaptability and excellent simulation ability to investigate unknown [15, 16]. Genetic algorithm is inspired by nature and was formed based on the fact that the best have the right to survive [16, 17]. The combined genetic algorithm-artificial neural network method is widely used to model processes and predict desired parameters in the design and development of systems. This method has a high ability to find the optimal value of a complex objective function [17, 18].

The use of ultrasound treatment has been recommended due to its many beneficial physicochemical effects [7, 10]. Therefore, in this research, the effect of ultrasonic power and treatment time on the apparent viscosity, consistency coefficient and flow behavior index of different concentrations of xanthan gum were investigated and modeled by genetic algorithm-artificial neural network method.

## 2- Materials and methods

### 2-1- Xanthan gum solution preparation

Xanthan gum powder was purchased from FuFeng Company (China). To prepare different concentrations of xanthan gum, solutions with concentrations of 0.1, 0.15 and 0.2% (w/v) were prepared by dissolving gum powder in distilled water. To complete the gum dehydration process, the solutions were kept at room temperature for 1 hour and then used for ultrasound treatment.

### 2-2- Ultrasound treatment

An ultrasonic bath (model vCLEAN1-L6, Backer, Iran) with a frequency of 40 kHz was used to apply ultrasound treatment on the xanthan gum. For this purpose, 2 liters of each solution prepared from xanthan gum was poured into the ultrasonic bath. Then, the effect of ultrasonic power (at two levels of 75 and 150 W) and treatment time (at five intervals of 0, 5, 10, 15 and 20 min) on the gum solution was investigated.

### 2-3- Measurement of apparent viscosity

The rheological properties of hydrocolloids are of great importance due to the structural and textural properties that hydrocolloids produce in food products [19]. A rotary viscometer (Brookfield, DV2T, RV, USA) was used to measure the apparent viscosity of the solutions treated with ultrasound. To measure the apparent viscosity of xanthan gum, the viscosity of the solutions was measured at a shear rate of 61/s using a UL adapter Kit at 25°C.

### 2-4- Calculation of consistency coefficient and flow behavior index

Different rheological models were used to calculate consistency coefficient and flow behavior index. Considering the nature of the gum, the low concentration of the solutions, the errors obtained from the review of different rheological models, as well as the articles published in this field [20, 21], the Power law model (Equation 1) was found to be suitable for investigating the rheological behavior of this gum solution. Therefore, in this study, to calculate the consistency coefficient and flow behavior index of the solutions prepared from xanthan gum, first the shear stress of the solutions at different shear speeds (12-134 $s^{-1}$) was recorded by a viscometer and then the Power law model was used for modeling.

$$\tau = k\dot{\gamma}^{n} \quad (1)$$

In this equation, $\dot{\gamma}$ is the shear rate ($s^{-1}$), τ is the shear stress (mPa), k is the consistency coefficient ($mPa.s^n$), and n is the flow behavior index (dimensionless) [22]. MATLAB software (R2012a) was used for fitting the power law model and calculation of consistency coefficient and flow behavior index.

### 2-5- Modeling by genetic algorithm-artificial neural network method

Artificial neural network is a deep learning technique inspired by the neurons of the human nervous system [16]. A common artificial neural network is a connected parallel structure consisting of an input layer consisting of neurons (corresponding to input variables), a hidden layer consisting of neurons, and an output layer consisting of neurons (corresponding to output variables) [23 ].

In this study, for modeling and predicting the rheological properties of ultrasonically treated xanthan gum, three inputs (ultrasonic power, treatment time and gum concentration) and three outputs (viscosity, consistency coefficient and flow behavior index) were considered for the network. Neurosolution software (version 5, NeuroDimension, Inc., USA) was used for genetic algorithm-artificial neural network modeling [24].

**2-6- Statistical analysis**

In this research, the effect of ultrasonic waves on the viscosity, consistency coefficient and flow behavior index of different concentrations of xanthan gum was investigated. This research was conducted in a factorial format based on completely randomized design and analyzed using SPSS 21 software. All the tests were performed in three repetitions and Duncan's multi-range test was used at the 95% probability level to compare the average of the observed responses.

## 3- Results and discussion

**3-1- Effect of ultrasound on apparent viscosity**

Ultrasound is able to break down complex hydrocolloids into smaller molecular components and thus reduce the viscosity of the solution prepared from them [10]. Figure 1 shows the effect of intensity and time of ultrasound treatment on the apparent viscosity of xanthan gum with a concentration of 0.15%. Similar behavior was observed in other concentrations. By increasing the power of the ultrasonic device, the intensity of treating the samples increased and caused the viscosity of the solutions to decrease. Statistically, this reduction was significant in most treatment times ($p<0.05$).

Ultrasonic energy is known to induce a number of physicochemical reactions that lead to changes in the functional properties of hydrocolloids in liquid food systems [25]. In this study, the apparent viscosity of xanthan gum decreased with the increase of ultrasound treatment time. At a constant power of 75 W, increasing the time of ultrasound treatment up to 20 min caused a significant decrease in the apparent viscosity of xanthan gum from 39.9 to 23.2 mPa.s (cp) ($p<0.05$). The decrease in viscosity of gums when exposed to ultrasound can be attributed to the breakdown of their large molecular structures into smaller forms due to the cavitation effect [11, 25]. Li et al. (2017) reported that ultrasonication within 10 to 20 min rapidly caused a high decrease in the viscosity of konjac glucomannan gum solution (at a concentration of 1%) [10].

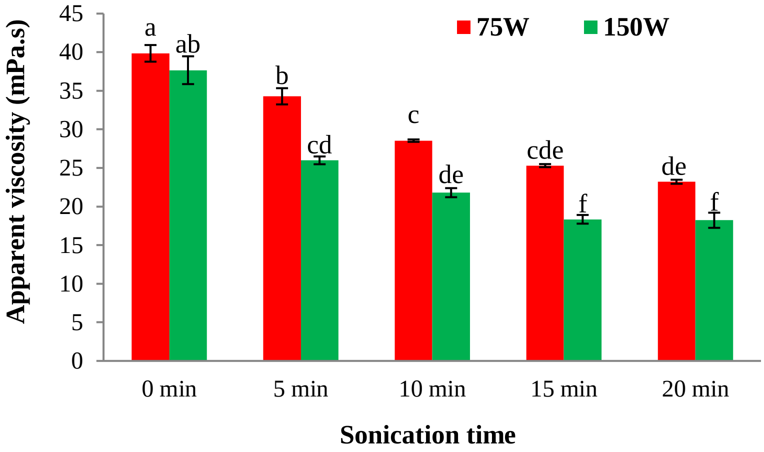


**Figure 1- Effect of sonication power and durations on the apparent viscosity of xanthan gum (concentration=0.15%)**

Different letters above the columns indicate a significant differences ($p<0.05$)

Figure 2 shows the effect of ultrasound treatment time on the apparent viscosity of different concentrations of xanthan gum. This figure corresponds to the power of 75 W of the ultrasonic device, and the data obtained from the power of 150 W also showed a similar behavior. In all concentrations, the apparent viscosity decreased with increasing sonication time, and the highest decrease was related to the time of 20 min. In this research, the highest apparent viscosity of xanthan gum was related to the control sample with a concentration of 0.2% and the lowest apparent viscosity was related to the sample with a concentration of 0.1% and treated with ultrasound for 20 min. The effect of ultrasonic waves on the rheological properties of locust bean gum solution has been investigated by Farizadeh and Abbasi (2023). Their results showed that the viscosity of locust bean gum solution was decreased with increasing ultrasound treatment time (0-90 min) [13].

Figure 2 also shows the effect of xanthan gum concentration on apparent viscosity. Similar to other gums, with increasing gum concentration, the apparent viscosity of xanthan gum also increased. The apparent viscosity of the control sample of xanthan gum (untreated) with concentrations of 0.1, 0.15 and 0.2% was 21.0, 39.9 and 66.5 cp, respectively. In the control sample and the samples treated with ultrasound, statistically, there was a significant difference between the apparent viscosity of different gum concentrations ($p<0.05$).

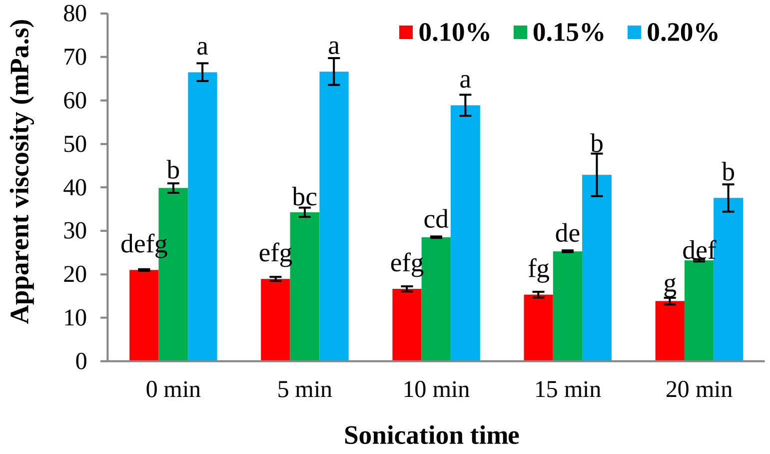


**Figure 2- Effect of sonication durations on the apparent viscosity of different concentrations of xanthan gum (power=0.75W)**

Different letters above the columns indicate a significant differences (p<0.05)

### 3-2- Results of genetic algorithm-artificial neural network modeling

In this research, due to the lower error value obtained by using the hyperbolic tangent activation function, this type of function was selected as the activation function in the hidden and output layer. Based on the trial and error method, it was determined that if 50% of the data is used for training, the network is well able to learn the relationships between inputs and outputs. 10% of the data was used for validating the trained network. In order to evaluate the network, the remaining data (40%) was used. The results of this research showed that the artificial neural network with 5 neurons in the hidden layer can well predict the apparent viscosity, consistency coefficient and flow behavior index of different concentrations of xanthan gum.

Recently, artificial neural networks have been widely used to model nonlinear biological systems due to their accuracy and high generalization ability in modeling [23]. The error values (mean squared error, normalized mean squared error, mean absolute error, minimum absolute error and maximum absolute error) and correlation coefficient for predicting apparent viscosity, consistency coefficient and flow behavior index are reported in Table 1. The normalized mean squared error for predicting the apparent viscosity, consistency coefficient and flow behavior index of different concentrations of xanthan gum by the optimal neural network was equal to 0.20, 0.20, and 0.30, respectively, which shows the power of the network in reducing the error during modeling. Also, correlation coefficient calculated for predicting the apparent viscosity, consistency coefficient and flow behavior index of different concentrations of xanthan gum by the optimal neural network was equal to 0.90, 0.90, and 0.85, respectively.

**Table 1- The error values in prediction of apparent viscosity, consistency coefficient, and flow behavior index of different concentrations of xanthan gum**

| Error | Apparent viscosity | Consistency coefficient | Flow behavior index |
|---|---|---|---|
| **Mean squared error** | 73.17 | 28420.77 | 0.00 |
| **Normalized Mean squared error** | 0.20 | 0.20 | 0.30 |
| **Mean absolute error** | 6.48 | 122.07 | 0.03 |
| **Minimum absolute error** | 0.23 | 0.48 | 0.00 |
| **Maximum absolute error** | 20.81 | 487.67 | 0.12 |
| **Correlation coefficient (r)** | 0.90 | 0.90 | 0.85 |

The mean square error values against the number of formed generations is shown in Figure 3. As can be seen, the amount of error decreases in the first generations, and after about 16 generations, the amount of error reaches a constant value, which shows the ability of the genetic algorithm method to optimize the parameters of the artificial neural network. In this modeling, the minimum value of the mean square error calculated for the rheological parameters of xanthan gum was 0.019.

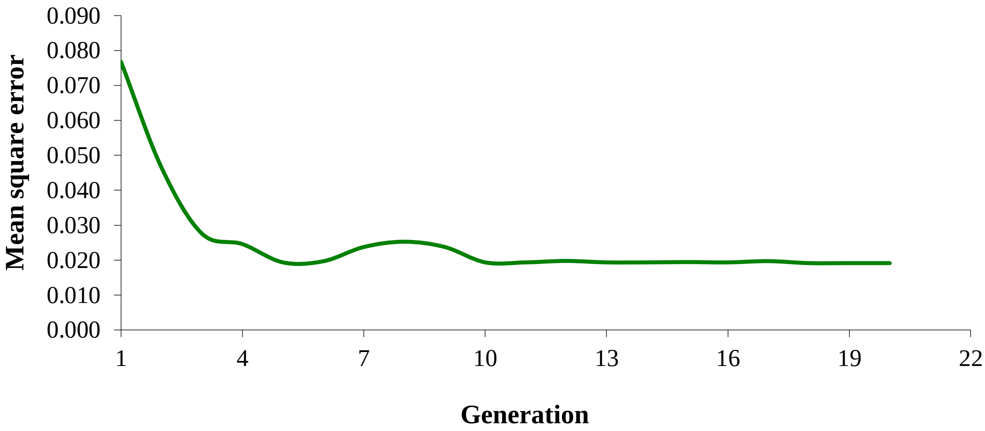


**Figure 3- Mean square error versus generation during training of network**

The actual values of the testing data for apparent viscosity, consistency coefficient and flow behavior index of different concentrations of xanthan gum and predicted by the genetic algorithm-optimal artificial neural network (3-5-3) are shown in Figure 4. The high value of the correlation coefficient indicates the high efficiency of the genetic algorithm-artificial neural network method for modeling the rheological parameters of xanthan gum.

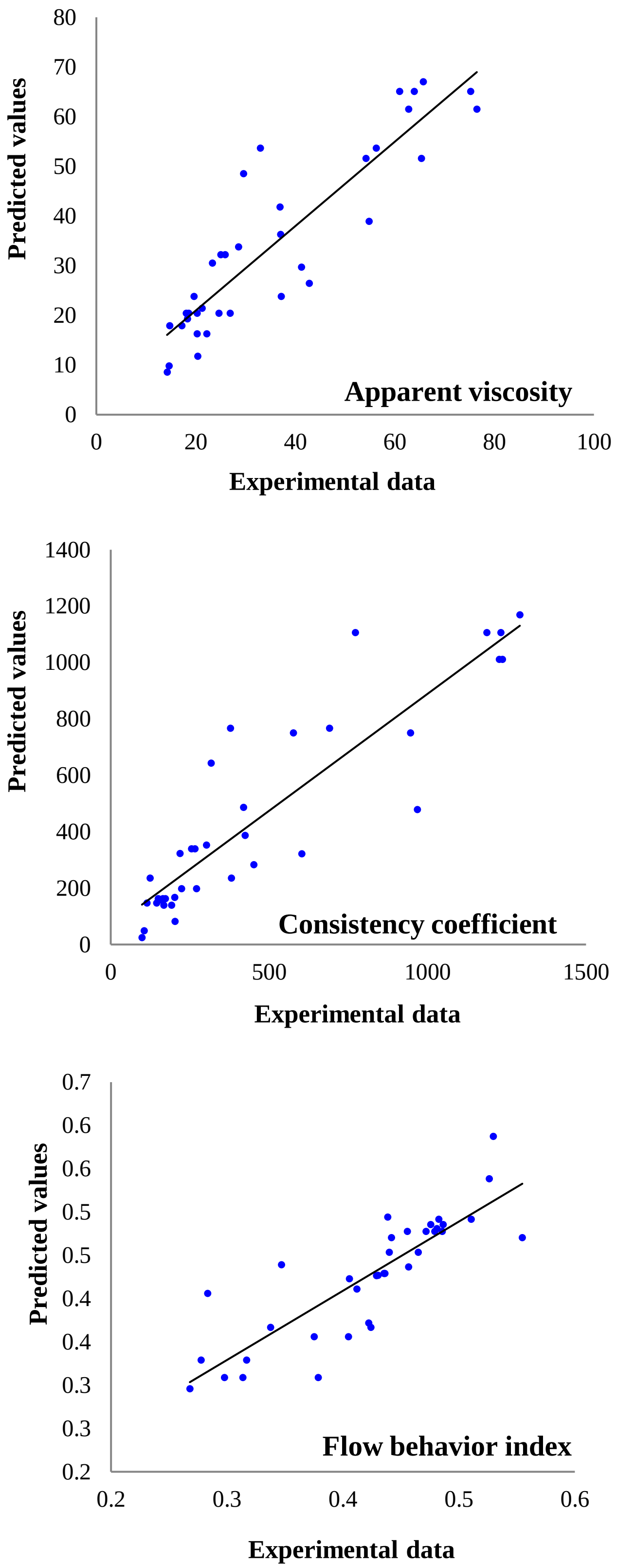


**Figure 4- Experimental data vs predicted values of apparent viscosity, consistency coefficient, and flow behavior index of different concentrations of xanthan gum**

The goal of the genetic algorithm-artificial neural network training process is to obtain optimal neural network weight and bias values. In Table 2, the values of weights and biases corresponding to each neuron for the network with 5 neurons in the hidden layer are reported.

**Table 2- Weight values and bias of the optimal network**

| Hidden neurons | Bias | Input neurons | | | Output neurons | | |
|---|---|---|---|---|---|---|---|
| | | Power (W) | Ultrasound time (min) | Concentration (%) | Apparent viscosity (mPa.s) | Consistency coefficient (mPa.s$^n$) | Flow behavior index |
| **1** | 1.1923 | -0.4902 | -0.4739 | 0.5210 | -0.0363 | 0.6134 | -0.5375 |
| **2** | 0.7321 | 1.3188 | -0.2686 | 0.5462 | -1.3554 | -0.7177 | 0.3747 |
| **3** | 0.6648 | 0.8298 | -0.4303 | -0.0068 | 0.5840 | -0.5938 | -0.8181 |
| **4** | -0.6641 | 0.6159 | 0.3397 | -0.5484 | -0.7956 | -1.3767 | -0.2871 |
| **5** | 2.1337 | 0.3350 | 1.2036 | -1.8546 | 0.3598 | -0.1854 | 0.2876 |
| **Bias** | | | | | -0.3314 | -0.5098 | 0.6223 |

Sensitivity analysis is a method in which the amount and distribution of input data with the greatest impact on the output of the model is determined. In fact, the sensitivity analysis of the input parameters reduces the trial and error steps and identifies the most important parameters affecting the desired phenomenon [26]. In order to check the influence of the input parameters and identify the most influential factor, a sensitivity analysis test was performed on the optimal network created by the genetic algorithm-artificial neural network method. As seen in Figure 5, among the input variables, ultrasonic power and ultrasonic treatment time are the most effective factors in changing the rheological parameters of Xanthan gum, respectively.

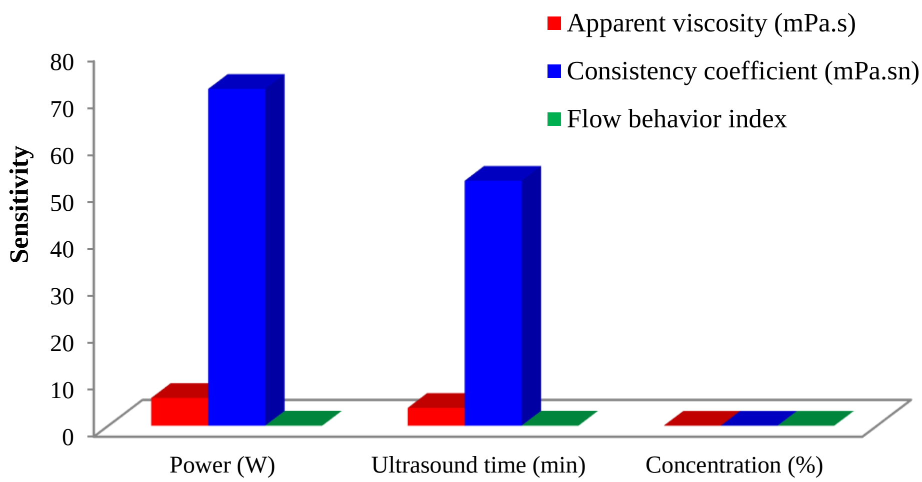


**Figure 5- Sensitivity analysis results for prediction of apparent viscosity, consistency coefficient, and flow behavior index of different concentrations of xanthan gum**

## 4- Conclusion

In this study, the intensity and time of ultrasound treatment on the viscosity, consistency coefficient and flow behavior index of different concentrations of xanthan gum were investigated. With increasing the ultrasonic power, the intensity of treating the samples increased and the viscosity of the solutions decreased. As the time of treatment with ultrasound waves increased, the apparent viscosity of xanthan gum decreased. With increasing gum concentration, the apparent viscosity of xanthan gum increased. In this research, genetic algorithm-artificial neural network modeling was used to predict the apparent viscosity, consistency coefficient and flow behavior index of different concentrations of xanthan gum. The research results showed that the genetic algorithm-artificial neural network method is suitable for predicting the rheological parameters of xanthan gum and this method can be used to predict the rheological behavior of different gums. The results of sensitivity analysis also showed that the intensity of ultrasound treatment is the most effective parameter in changing rheological parameters of xanthan gum.

**5- Acknowledgments**

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مقاله علمی_پژوهشی

# مدل‌سازی اثر فراصوت بر ویسکوزیته، ضریب قوام و شاخص رفتار جریان غلظت‌های مختلف صمغ گزانتان

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**چکیده**

استفاده از امواج فراصوت برای تغییر ساختار صمغ‌ها، منجر به اصلاح و بهبود ویژگی‌های عملکردی و خواص رئولوژیکی آنها می‌شود. در این پژوهش اثرات شدت فراصوت و زمان تیماردهی بر ویسکوزیته ظاهری، ضریب قوام و شاخص رفتار جریان غلظت‌های مختلف صمغ گزانتان بررسی و مدل‌سازی شد. برای مدل‌سازی فرآیند نیز از روش الگوریتم ژنتیک-شبکه عصبی مصنوعی با سه ورودی (توان فراصوت، زمان تیماردهی و غلظت صمغ) و سه خروجی (ویسکوزیته، ضریب قوام و شاخص رفتار جریان) استفاده گردید. ویسکوزیته ظاهری نمونه شاهد صمغ گزانتان (تیمار نشده) با غلظت‌های ۰/۱، ۰/۱۵ و ۰/۲ درصد به ترتیب برابر ۲۱/۰، ۳۹/۹ و ٦٦/۵ میلی‌پاسکال ثانیه بود. نتایج این پژوهش نشان داد که با افزایش شدت و زمان اعمال فراصوت، ویسکوزیته صمغ کاهش می‌یابد. تیماردهی با امواج فراصوت به مدت ۲۰ دقیقه باعث کاهش معنی‌دار ویسکوزیته ظاهری صمغ گزانتان از ۳۹/۹ به ۲۳/۲ میلی‌پاسکال ثانیه گردید ($p<0.05$). نتایج مدل‌سازی به روش الگوریتم ژنتیک-شبکه عصبی مصنوعی نشان داد شبکه‌ای با ساختار ۳-۵-۳ در یک لایه پنهان و با استفاده از تابع فعال‌سازی تانژانت هیپربولیک می‌تواند پارامترهای رئولوژیکی صمغ گزانتان را با ضریب همبستگی بالا و مقدار خطا پایین پیش‌بینی نماید. مقادیر میانگین مربعات خطا (MSE)، میانگین مربعات خطا نرمالیزه شده (NMSE)، میانگین خطا مطلق (MAE) و ضریب همبستگی (r) برای پیش‌بینی ویسکوزیته ظاهری صمغ گزانتان به ترتیب برابر ۷۳/۱۷، ۰/۲۰، ٦/٤۸ و ۰/۹۰ بود. بر اساس نتایج آزمون آنالیز حساسیت، شدت تیماردهی با فراصوت به‌عنوان مؤثرترین عوامل در تغییر ویسکوزیته ظاهری، ضریب قوام و شاخص رفتار جریان صمغ گزانتان بود.