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An Application of Ultrasonic Waves in the Pretreatment of Biological Sludge in Urban Sewage and Proposing an Artificial Neural Network Predictive Model of Concentration

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Abstract: This research examines whether ultrasonic waves can enhance the hydrolysis, stability, and dewatering of activated sludge from raw urban wastewater. Sampling and physical examination of the activated sludge that was returned to the aeration pond were carried out using ultrasonic waves that were guided at frequencies of 30 and 50 kHz for periods of 0.5, 1, 3, 5, 10, 15, and 30 min. Various tests, including volatile suspended solids, inorganic solids, volatile solids, sludge resistant time, capillary suction time, total suspended solids, total solids, and volatile soluble solids, were carried out to advance further the processes of hydrolysis, stabilization, and dehydration of samples. According to the observations, the volatile soluble solids at a frequency of 30 kHz and $t = 15$ min were raised by 72%. The capillary suction time of 30 and 50 kHz in 1 min demonstrated a drop of 29 and 22%, respectively. It is crucial to consider that, at 10 min and the frequency of 50 kHz, the greatest efficiency was found. The 30 kHz and 1 min yielded the optimum sludge dewatering conditions. Finally, artificial neural networks (ANN) are utilized to propose predictive models for concentration, and the results were also very accurate (MAE = 1.37%). Regarding the computational costs, the ANN took approximately 5% of the time spent on experiments.

Keywords: wastewater treatment; ultrasonic; sludge treatment; artificial neural network; dewatering

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Citation: El Jery, A.; Kosarirad, H.; Taheri, N.; Bagheri, M.; Aldrdery, M.; Elkhaleefa, A.; Wang, C.; Sammen, S.S. An Application of Ultrasonic Waves in the Pretreatment of Biological Sludge in Urban Sewage and Proposing an Artificial Neural Network Predictive Model of Concentration. *Sustainability* **2023**, *15*, 12875. https://doi.org/10.3390/su151712875

Academic Editor: Andrea G. Capodaglio

Received: 4 July 2023
Revised: 17 August 2023
Accepted: 20 August 2023
Published: 25 August 2023

1. Introduction

The municipal sewage sludge separated from sewage in the treatment process must be decontaminated and purified before reuse. Concentrating, settling, and dewatering are the most common sludge treatment processes [1]. These measures usually account for approximately half of the entire wastewater treatment expenses, requiring careful and specialized management. Stabilization is considered the most basic, expensive, and technical sludge treatment process [2–4]. Conventionally, stabilization is a procedure that dramatically decreases the sludge's microbiological threats and organic material that is decomposing [5–8]. If it is possible to reduce the percentage of sludge water with some measures and then transfer it to the ground, using the properties of fertilizers and valuable compounds in the sludge, it is feasible to employ land remediation technologies to continue their purification process [9–11]. To a considerable extent, this can lower the cost of sludge treatment [12–15]. Sludges from wastewater treatment plants are often used as fertilizers or soil texture modifiers. It is possible to transfer sludge to the ground in liquid, paste, and dry form. In transporting liquid sludge, due to the large volume of water and the need for significant transmission networks (pipe laying or the use of tankers), it is usually uneconomical and not cost-effective [16–19]. Accordingly, the dewatering operation before removing the sludge from the treatment plant is often inescapable [20–23]. Based on the kind of primary or activated sludge, the water content in the sludge texture ranges from 96% to 99%, and the proportion of perishable organic matter is very high [24,25]. Urban sewage sludge, significantly activated sludge, often composed of biomass and microbial bodies, is very resistant to dehydration and hardly loses its water [26,27]. The water in activated sludge or biological sludge includes free water, the water between clots, water attached to the surface of flocs, and water in the body of living microbes (transplanted water). To remove water from these sludges, it is of great importance to release the free water between the clots [28,29]. Sludge treatment is a set of operations performed before the dewatering or sludge concentration stage so that the sludge dewatering and concentration work can be conducted easily [30,31]. Sludge treatment may be conducted by one of the following methods:

Thermal pretreatment, application of chemicals, mechanical decomposition of sludge, and ultrasonic waves [32–34]. Among the advantages of sludge pretreatment methods with ultrasound waves, the following can be mentioned:

The advantages of this model are it is possible for it to be added to the existing facilities, low cost, and proper operation compared to other pretreatment methods. Moreover, on-site production of carbon source for denitrification facilities, full automation of bulking control process caused by filamentous bacteria and foam in digesters, better digester stability, together with the improvement of volatile solid destruction and biogas production, advancement of sludge dewatering ability, improvement of sludge quality, reduction in organic biologically degradable substances, and decline in the number of pathogens in sludge are advantages as well [35–37]. The new findings confirm the increase in its use in the full-scale decomposition of urban sludge, the increase in its hydrolysis efficiency, and the improvement of the ability of biological decomposition of organic compounds of various wastewaters, including dairy industries, and its employment in improving the anaerobic digestion of activated sludge [38]. Considering the long retention time in the anaerobic process and the problems of sludge dewatering in treatment plants, there is a need to utilize procedures to alleviate or even eliminate the limitations and consequently decrease the operating and maintenance costs. Since they have the ability to minimize sludge particle size and promote enzyme activity, ultrasonic waves can speed up the hydrolysis procedure, which is the limiting factor in digesters, leading to a reduction in retention time [39,40].

This study presents a novel approach to enhance the hydrolysis, stability, and dewatering of activated sludge obtained from raw urban wastewater treatment processes. Unlike conventional methods such as thermal pretreatment, chemical application, and mechanical decomposition, our research explores the application of ultrasonic waves as an innovative and cost-effective technique. Ultrasonic waves offer several distinct advantages that set our approach apart. They can be seamlessly integrated into existing wastewater treatment facilities, requiring minimal modifications, and present a lower overall cost compared to more complex and resource-intensive methods. Moreover, our study addresses the limitations often encountered with other techniques, such as long retention times, by expediting the hydrolysis process, a critical factor in sludge stabilization. Through a series of experiments and comprehensive tests, we demonstrate that ultrasonic waves effectively improve the dewatering ability of activated sludge, contributing to the reduction in water content and enhancing overall sludge quality. These findings pave the way for more efficient and sustainable wastewater treatment processes.

A thorough comparison between our proposed approach and existing methods in sludge treatment reveals the distinctive attributes that make our study significant. While chemical applications and mechanical decomposition methods require the addition of costly agents or substantial mechanical energy, ultrasonic waves operate as a nonintrusive and energy-efficient alternative [41]. Thermal pretreatment, often characterized by high energy consumption, is replaced by our ultrasonic method that achieves comparable or even superior results [42]. Unlike other pretreatment techniques, ultrasonic waves exhibit the unique capability to reduce particle size, enhance enzyme activity, and improve sludge stability [43]. Moreover, our research addresses challenges related to the dewatering process, a crucial step in sludge management, by achieving optimal conditions for dewatering through controlled ultrasonic exposure. This aspect distinguishes our study from traditional approaches and underlines the potential of ultrasonic technology in revolutionizing the field of wastewater treatment. Through explicit comparisons and comprehensive analyses, we establish the originality and relevance of our study, contributing to the advancement of sustainable and efficient sludge treatment practices.

Research shows few studies have been conducted on the hydrolysis of raw biological sludge in ultrasonic reactors in sewage treatment facilities. Improving the conditions of stabilizing and dewatering sludge under the influence of ultrasonic waves in a short time while being innovative can make sludge control in sewage treatment facilities easier. The primary objective of the current study is to clarify how well ultrasonic waves may improve the stability and dewatering operations of activated sludge from municipal sewage. The utilization of machine-learning-based predictive models has become prevalent in many engineering problems [44–47]. However, this has not yet been happening in wastewater treatment research, so the present study also puts forward a predictive model using artificial neural networks (ANN), and the concentration is predicted using the ANN model.

2. Materials and Methods

This study is indeed operational research with the goal of determining how well ultrasonic waves function to improve the dewatering properties of raw urban sewage sludge under various frequency-related circumstances and residence time. The whole process was conducted in a laboratory environment using an ultrasonic device. In this research, at first, by applying ultrasonic waves, the water in the activated sludge was released. The state of hydrolysis and stabilization was determined, respectively, by conducting experiments evaluating volatile solids (VS), volatile soluble solids (VS_{SOL}), and volatile suspended solids (VS_{SS}); additionally, sludge dewatering property by conducting tests of total solids (TS), total suspended solids (TSS), capillary suction time (CST), and sludge resistant time (SRT) was elucidated. In order to obtain reasonable results, the experiments were repeated three times. Finally, the results were analyzed employing SPSS software. The optimal ultrasonic option was determined regarding the frequency and time required for hydrolysis, stabilization, and dewatering of raw biological sludge. TS, TSS, organic solids (VS), inorganic solids (nVS), VS, and VS_{SOL} tests were performed based on procedures presented in the standard method book [48] and, to determine the CST of sludge samples, 5 mL of sludge was taken from a funnel with a diameter of 5 mm and poured onto filter paper. The time taken to wet the filter paper, which ranged from 1 to 3 cm, was measured and reported in seconds [49]. The CST values for untreated municipal sewage sludge are around 200 s or more; for treated sludge, the mentioned value reaches 10 s or less [50]. The dewatering rate of treated sludge was evaluated using a vacuum filtering process. The sample was held under a consistent vacuum pressure of 34 kPa for 20 min using this approach, which involved pouring 100 mL of the treated sludge sample into a typical Buchner funnel outfitted with wet filter paper. In order to determine the specific resistance of sludge (SRF), the volume of filtered water and the filtration time are recorded. With a related volume–time diagram, the value of SRF is determined [51]. SRF values of municipal sewage sludge for treated and digested sludge are between 3×10^{11} and 40×10^{11} m/kg and, for primary sludge, the values are 1.5×10^{14} to 5×10^{14} m/kg [52]. The specific resistance of sludge is calculated from the following equation:

$$SRF = \frac{2PbA^2}{\mu C} \tag{1}$$

in which *SRF* is the specific resistance of sludge (m/kg), *C* is the mass of solids per unit volume of filtered water (kg/m^3), *A* is the filter surface (m^2), *P* is the test pressure (N/m^2), μ is the dynamic viscosity (N·s/m^2), *V* is the volume of water collected in time (t), (m^3), *t* is the time from the start of the test and application of suction (s), and *b* is the slope (s/m^6). *b* is the slope of a line whose horizontal axis is the volume of water collected per time unit (t) in cubic meters, and its vertical axis is the result of division (t/V). At the same pressure and temperature and equal filter surface, the higher the slope of this line indicates that the time required to filter a certain amount of water from the sludge is more prolonged. Therefore, it is more difficult to extract water from the sludge. In this case, the specific resistance of the sludge is higher. In various conditions, the increase in this parameter means that either a higher pressure is needed to filter the sludge or a larger surface is required for this purpose, both of which suggest that the sludge's resistance is more elevated and dewatering from the sludge becomes harder [53].

3. Results

The effect of ultrasonic waves on the appearance and structure of sludge under normal conditions and after the application of ultrasonic waves for 1.5 min and 2 min is shown in Figure 1. As can be seen, the stability circumstances, distribution, and balance of suspended materials in the sludge have been altered by the utilization of ultrasonic waves. Likewise, it has affected the ability to settle and concentrate the sludge.

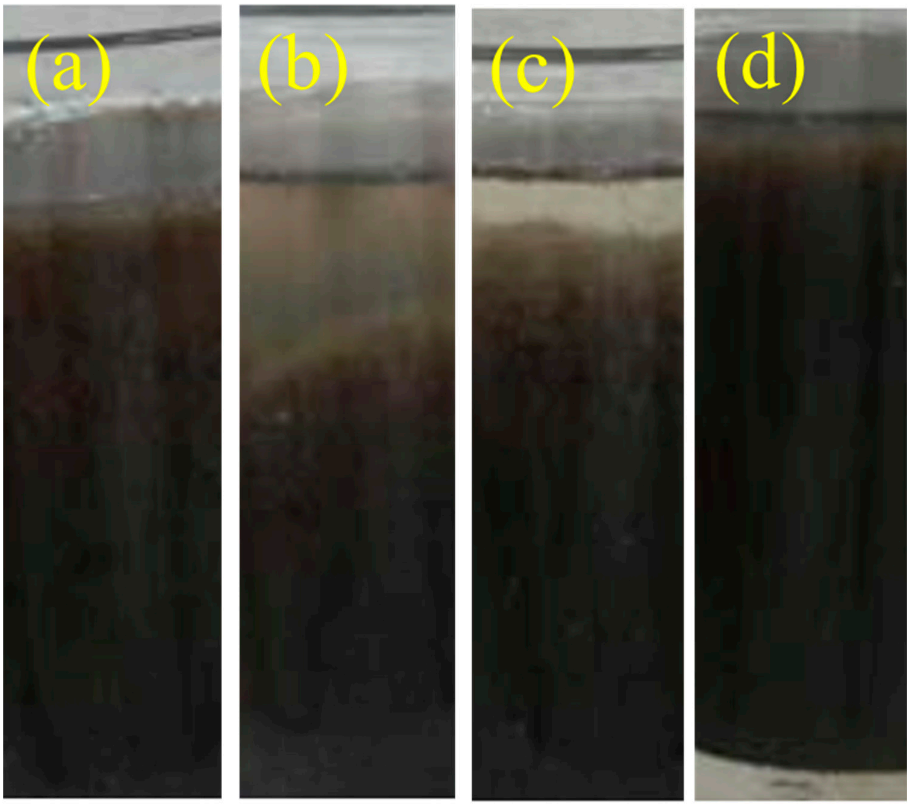

Figure 1. The difference in the appearance of the sludge prepared at the frequency of 30 kHz during (**a**) 2 min, (**b**) 1 min, (**c**) 30 s, and (**d**) 0 s contact time with ultrasonic waves after half an hour of settling time.

3.1. The Solubilization of Organic Solids under the Influence of Ultrasonic Waves

The trend of changes in total solids, organic solids, dissolved organic solids, and suspended organic solids at the frequency of 30 kHz is shown in Figure 2. The results indicate a comprehensive view of how these components evolve over time. Specifically, the dissolved organic solids exhibit noteworthy behavior. They demonstrated an initial rapid increase of 72% from the commencement of the experiment until the 15 min mark. However, intriguingly, with the prolongation of ultrasonic exposure to 30 min, there was a substantial decline of 37% in comparison to the levels observed at the 15 min interval. This pattern of behavior in dissolved organic solids is consistent with findings from [54], which similarly exhibited a comparable trend in response to varying ultrasonic exposure durations. This alignment across studies lends further credibility to the observed dynamics in the dissolved organic solids component.

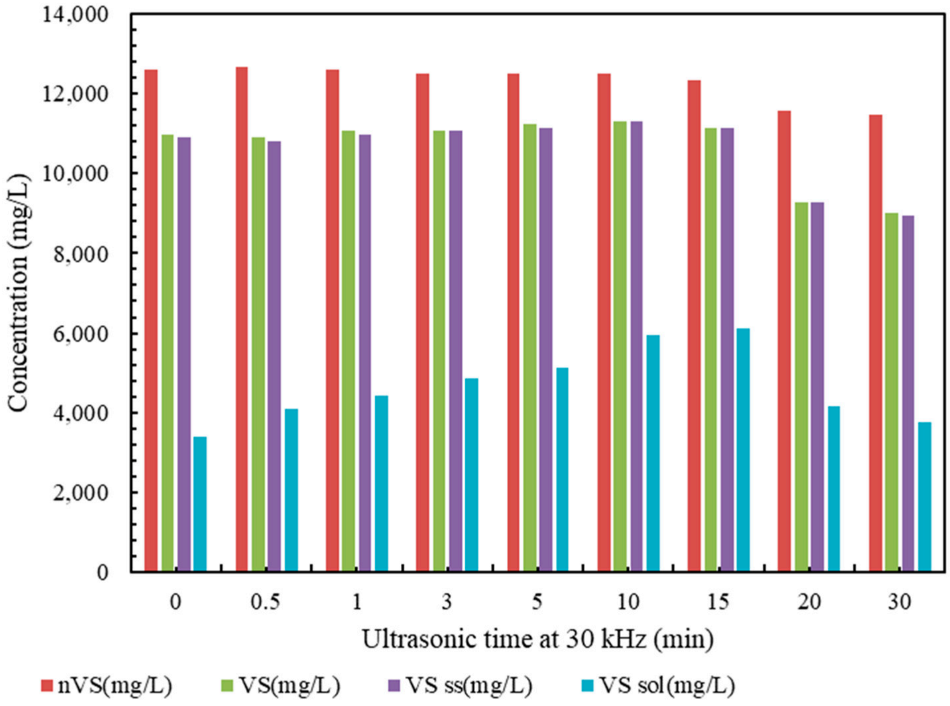

Figure 2. Concentration changes of total solids, organic solids, dissolved organic solids, and suspended organic solids over time at the frequency of 30 kHz.

The trend of total solids, organic solids, dissolved organic solids, and suspended organic solids at 50 kHz frequency is shown in Figure 3. The results show that the dissolved organic solids increased from the beginning of the experiment to 10 min (99%). With the increment of ultrasonic time up to 30 min, it decreased by 49% compared to 10 min. Investigations show that the increase in dissolved organic solids from the beginning to 15 and 10 min at frequencies of 30 and 50 kHz, respectively, is a result of sludge floc disintegration and particle size reduction, which raises the number of dissolved solids [55]. A similar trend is observed in the research of Yang et al. [56].

3.2. Stability of Organic Solids under the Impact of Ultrasonic Waves

The changing trend of total solids, organic solids, and mineral solids at 30 kHz frequency is shown in Figure 4. The results show that the total and organic solids remained constant from the beginning of the experiment for 15 min. With the increase in ultrasonic time up to 30 min, TS and VS decreased by 9.4 and 17.9%, respectively.

The trend of changes in total solids, organic solids, and mineral solids at 50 kHz frequency is shown in Figure 5. The results show that the total and organic solids are constant from the beginning of the experiment up to 10 min. With the increment of ultrasonic time up to 30 min, the TS and VS have declined by 14 and 24%, respectively.

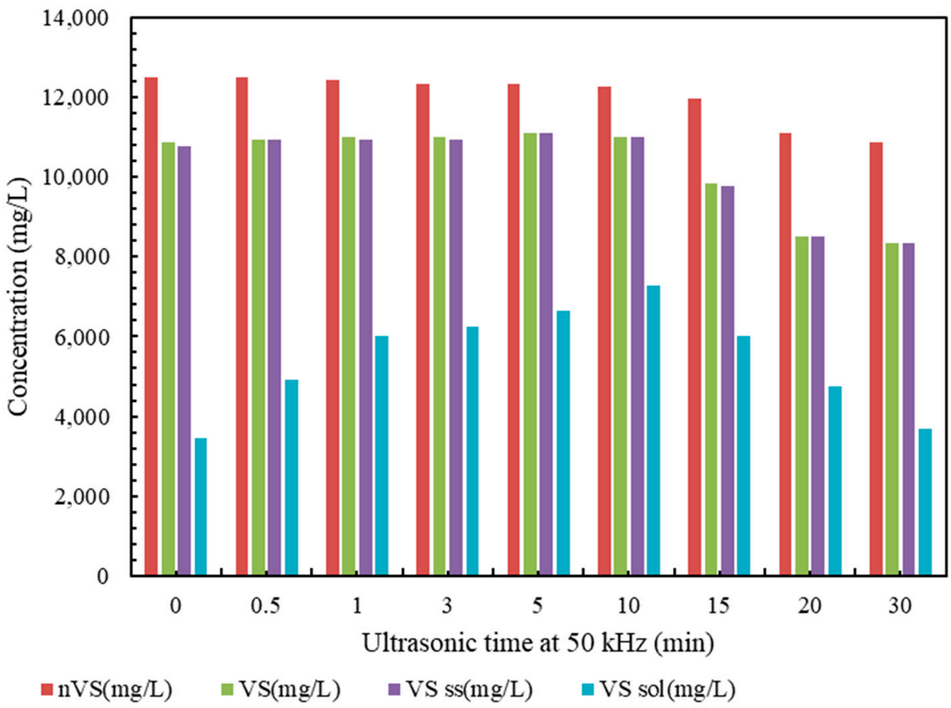

Figure 3. Concentration changes of total solids, organic solids, dissolved organic solids, and suspended organic solids over time at the frequency of 50 kHz.

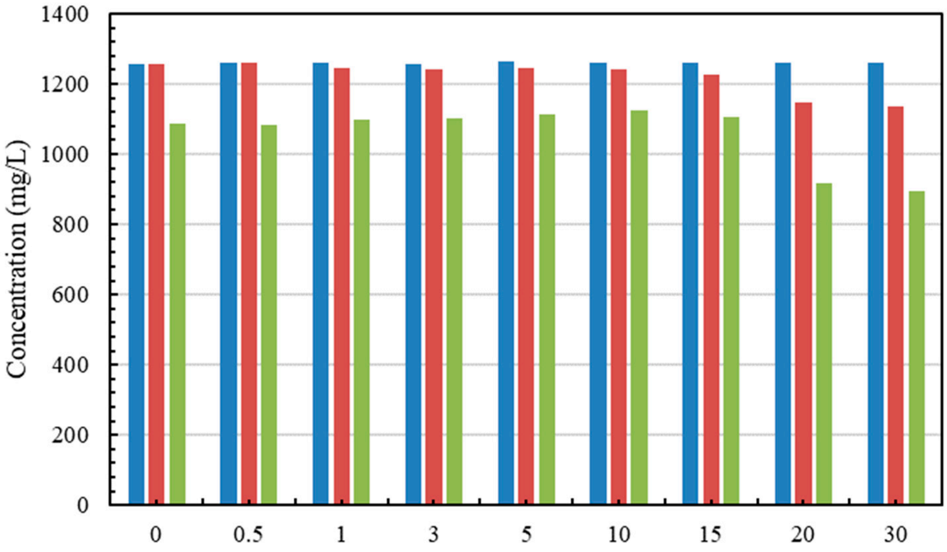

Figure 4. The trend of changes in total solids, organic solids, and inorganic solids over time at the frequency of 30 kHz.

Investigations show that the reduction in dissolved organic solids in the ultrasonic time of 10 min and 15 min until the end of the experiment at the frequency of 30 kHz, respectively, indicates the beginning of the stabilization phase, which has also led to the reduction in organic solids. Corroborating these findings, the study referenced as [57] also observed a comparable trend regarding the influence of frequency and ultrasonic exposure time on the reduction in dissolved organic solids.

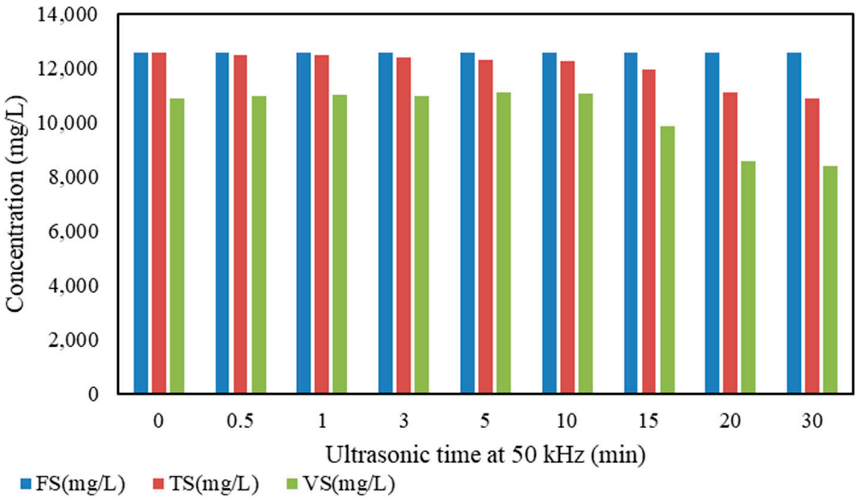

Figure 5. Trend of changes in total solids, organic solids, and mineral solids over time at a frequency of 50 kHz.

3.3. The Effect of Ultrasonic Waves on Sludge-Specific Resistance and Capillary Suction Time

The trend of changes in sludge-specific resistance at frequencies of 30 and 50 kHz is shown in Figure 6. The results show that the specific resistance of the sludge at two different frequency values of 30 and 50 kHz has a downward trend at the beginning and reaches the lowest value at the time of 1 min (26% and 21% reduction in comparison with the initial sample, respectively). With the increment of ultrasonic time, an upward trend for sludge-specific resistance was observed and, at the time of 15 min, reached the highest value (an increase of 66% and 49%, respectively), which will continue to reduce the specific resistance of the sludge until 30 min. However, the corresponding value did not reach the initial value until the end of the experiment.

The trend of capillary suction time changes at frequency values of 30 and 50 kHz is depicted in Figure 7. The results show that the time related to the capillary suction at two frequency values of 30 and 50 kHz has a downward trend at the beginning and reaches the lowest value at the time of 1 min (29% and 22% decline compared to the initial sample, respectively). With the increment of ultrasonic time, the trend of increasing the sludge-specific resistance is observed and, at the time of 15 min, it reached the highest value of enhancement of 33% and 29%. Continuing again, we will have the process of reducing capillary suction time; however, the corresponding value did not reach the initial value until the end of the experiment. Studies show that, when ultrasound waves propagate between water, gas, and steam, they produce bubbles and fall with great intensity and speed [58]. This phenomenon, known as acoustic cavitation, creates a unique chemical environment with a temperature higher than 5000 K and pressure exceeding 10^8 Pa [53,58]; reactive hydroxyl radicals are generated due to the thermal decomposition of water molecules in the bubbles. High-frequency treatments have been implicated in the potential hydrolysis of water molecules, leading to the generation of hydroxyl radicals (·OH). This intriguing phenomenon involves the disruption of water molecules by the high-frequency energy, which can break apart the molecular bonds, resulting in the release of hydroxyl radicals [59]. These hydroxyl radicals are highly reactive and possess potent oxidative capabilities. The process starts with the energy from the high-frequency waves being absorbed by the water molecules present in the system. This energy absorption can cause the water molecules to undergo dissociation, leading to the formation of hydroxyl radicals and hydrogen ions [60]. The hydroxyl radicals generated in this manner are known for their strong oxidizing nature, making them capable of initiating various chemical reactions, including the degradation of organic compounds. Hydroxyl radicals (·OH) are considered highly reactive because they have an unpaired electron, which makes them extremely eager to react with other molecules in their vicinity [61]. These radicals can oxidize organic molecules by abstracting hydrogen atoms from them, ultimately leading to the breakdown of complex organic compounds into simpler, more soluble forms. This feature of ultrasonic waves can change the dewatering properties of sludge and, as a result, increase the decomposition rate of organic pollutants [62]. The generation of hydroxyl radicals (·OH) through high-frequency treatments can enhance the dewatering properties of sludge by breaking down complex organic compounds, reducing viscosity, improving water separation, lowering surface tension, promoting efficient settling, and forming more porous solid cakes. These effects can lead to improved water drainage, faster solid–liquid separation, and enhanced cake formation. However, careful consideration is needed to avoid excessive oxidation that could negatively impact the desired treatment outcomes [63].

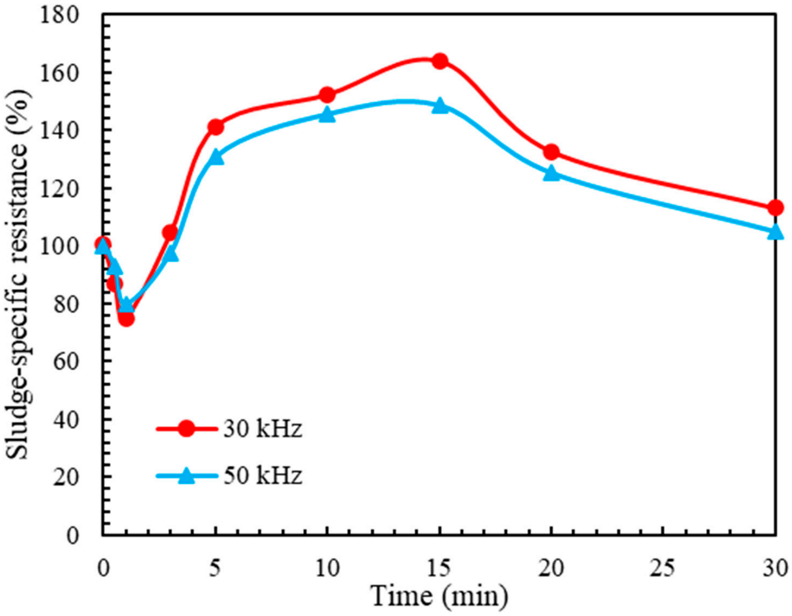

Figure 6. Percent of changes in sludge-specific resistance over time and ultrasonic frequency shift compared to the control sample.

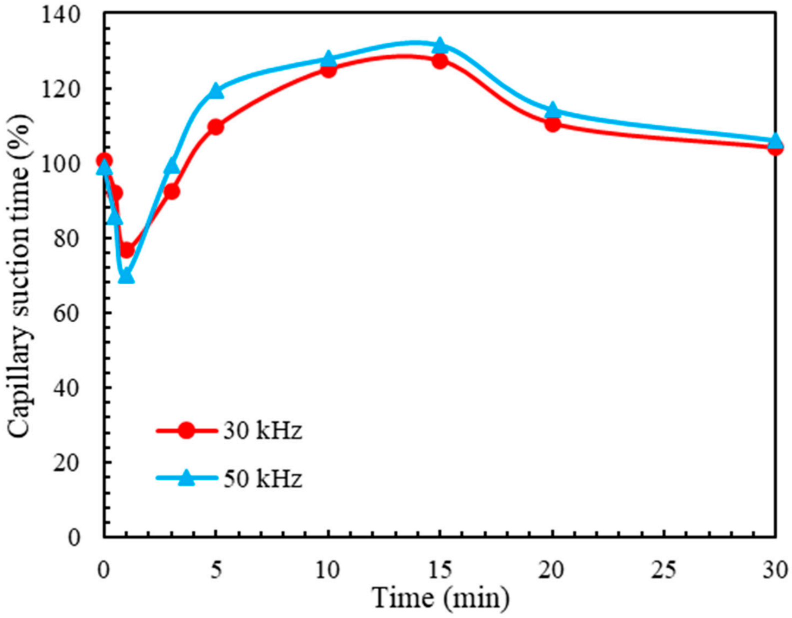

Figure 7. Percent of capillary suction time changes over time and ultrasonic frequency change compared to the control sample.

3.4. Investigating the Effectiveness of Ultrasonic Waves in Changing the Appearance and Structure of Sludge

Contact with ultrasonic waves for up to 30 s destroys larger flocs. Increasing the contact time by up to 1 min improves water separation from the raw activated sludge tissue and makes the sludge more biphasic [64]. In the continuation of the application of waves, it destroys the cellular tissue of microorganisms, which destroys the membrane cells, and increased turbidity in the supernatant and monophasic sludge can be seen. Ultrasonic waves increase the dewatering ability of sludge by creating ruptures in the sludge [65]. Figure 8 shows the SEM, which illustrates how ultrasonic vibrations impact the structure of sludge flocs at contact times of 2, 10, and 30 min compared to the sample at 0 s. The results demonstrate how ultrasonic time influences the separation of the sludge flocs, which leads the particle size to decrease [12]. The changes in the appearance of the sludge flakes in this study are consistent with the SEM images of the ultrasonically treated sludge presented in Paul et al.'s research [12].

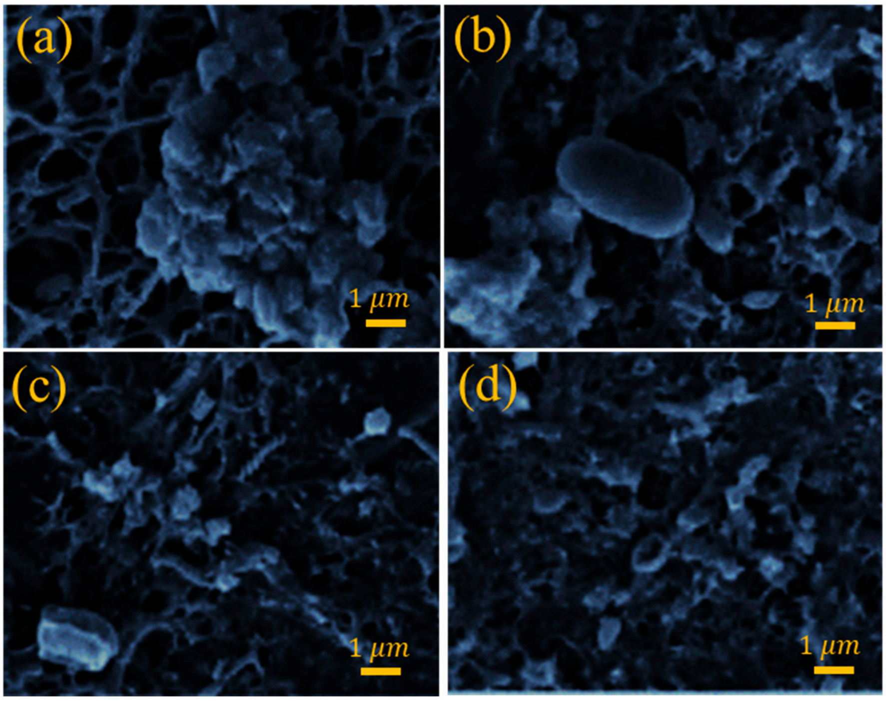

Figure 8. SEM image of raw activated sludge in ultrasonic time: (**a**) zero (control), (**b**) 2 min, (**c**) 10 min, and (**d**) 30 min.

4. Discussion

4.1. Examining How Well Ultrasonic Vibrations Function in the Hydrolysis of Organic Solids

The reduction in soluble organic solids in different ultrasonic times of 10 and 15 min until the end of the experiment, respectively, at the frequency of 30 and 50 kHz demonstrates the increase in the hydrolysis of organic solids and the beginning and stabilization stage, which further leads to the reduction in organic solids. The study conducted by Bougrier et al. [66] on the solubilization of biologically active sludge by ultrasonication showed that solid solubilization could be achieved with a contact time of more than 7 min. The study by Nickel et al. [67] indicated that treatment of raw activated sludge led to the hydrolysis of organic solids by 20 to 45%, which is inconsistent with the results obtained in the present research. In general, the findings of this investigation revealed that the ultrasonic times of 10 and 15 min at the frequency of 30 and 50 kHz, respectively, caused a portion of the sludge's organic constituents to become soluble, but the ultrasonic waves with the frequency of 50 kHz in a short time of 10 min in addition to higher efficiency, 93% compared to 72%, is a suitable option for the degradation of organic solids in untreated biological sludge. Kargar et al.'s [68] study showed that ultrasonic waves reduce the volatile solids of the sludge exiting the anaerobic digester by 39.7% at a frequency of 35 kHz. Reducing the total solids and increasing the nonbiodegradable part at two frequencies of 30 and 50 kHz confirms the sludge stabilization process and the production of carbon dioxide and water [69]. The study conducted by Zhang et al. [70] indicated that ultrasonic waves with higher frequency are more effective in removing organic solids from sludge, which is in remarkable agreement with the results obtained in the current study. The present study's findings demonstrated that ultrasonic waves at a frequency of 50 kHz with an irradiation duration of more than 10 min are a good option for stabilizing organic solids in raw biological sludge. However, achieving the standard of 38% of organic solids removal requires more ultrasonic times [71].

4.2. Investigating the Effectiveness of Ultrasonic Waves in Improving the Dewatering Properties of Sludge

Studies show that sludge treatment with ultrasonic waves initially separates the interstitial water of the sludge. However, with an excessive decomposition of the sludge, the sludge flocs are destroyed to a large extent and very fine particles with a high negative surface charge are produced [72,73]. As a result, a large number of extracellular polymers are released into the sludge supernatant, boosting viscosity. An excessive increment in extracellular polymeric substances (EPS) destroys sludge dewatering, which increases CST and SRF until 15 min has been reached [74]. Feng et al.'s study [75] shows that the effect of ultrasonic waves on activated sludge includes two stages. In the first stage of the ultrasonic device, in specific energy conditions, up to 1000 kJ/kg TS provided at the time of 10 s, a small amount of the floc structure has been destroyed [76]. However, sludge settling improves in the second stage of degradation and solubilization at doses higher than 5000 kJ/kg TS and a time longer than 50 s. This leads to a decrease in sludge settling ability because of a reduction in particle size and an increase in EPS content. The results of the research conducted at the Hamburg University of Technology [77] accepted the minimum optimal contact time for the pretreatment of raw activated sludge with ultrasonic waves from 30 to 90 s, which is consistent with current research results. The results of Heidari et al.'s [39] research also showed that increasing the ultrasonic frequency and time by more than 3 min raises the amount of SRF in untreated activated sludge, which is consistent with the changes in the specific resistance of the sludge in the present study. Capillary suction time in contact time greater than 15 min is attributed to the completion of the solubilization process of all suspended solids and the beginning of sludge stabilization [78]. Lifka et al.'s [79] study of using ultrasonics to destroy water pollution shows that increasing the ultrasonic time leads to stabilizing organic sludge materials.

4.3. Artificial Neural Network

Using artificial neural networks (ANN), it is possible to predict important parameters in problems. Since this method can understand the complexity of physical issues, they are used in predicting complex flows. For instance, the present research predicts concentration in different situations using the ANN algorithm. Using the experimental results, we have trained a model. The performance of the model is evaluated using two widely used parameters, namely mean absolute error and R^2. In order to adjust the model, the contributing factors in the ANN model are tuned using a procedure called hyperparameter tuning [46,80–83]. Table 1 presents the model specifications. The model includes three kinds of layers, and the inputs are SRF, frequency, and time. The desired parameter, which is predicted, is concentration. The number of data points is 126, so 88 data points are used for training the model. The rest of the data points (38) are used for testing the model's performance. The employed ratio for splitting the dataset is 0.7–0.3. Based on the results of Table 1, the number of epochs is 35,000 and the batch size is 4. To prevent overfitting, regularization techniques and dropouts were integrated into the ANN architecture. Regularization involves adding a penalty term to the loss function during training, discouraging the model from assigning excessive importance to specific features. In the present study, we utilized L2 regularization, which imposes constraints on squared values of the model's weights. Also, in order to further prevent overfitting, dropouts were utilized in some hidden layers. These techniques help prevent the model from overfitting on certain features and enhance its ability to generalize to new data [84–91].

Table 1. ANN model specifications.

Parameter	Values
Model input	SRF, Frequency, Time
ANN hidden layer structure	(32, 64, 128, 256, 128, 64, 32)
The activation function of the output layer	ReLU
Batch size	4
Epochs	35,000
Learning rate	0.01
Output parameter	Concentration

Figure 9 shows the results of the prediction of the ANN model. As can be seen, the results of the model are very accurate. The MAE of the model is 1.37% and the R-squared of the model is 0.98. It should be noted that comparing the required time for the experiments and the ANN model shows how advanced and accurate the machine-learning-based models are. It is concluded that the required time for the simulation of the model in Python is 5% of the experiments. Considering the accuracy of the models, the new proposed model could be used in various cases to avoid abundant experiments. For the simulation of the ANN model, a high-performance CPU (Intel-Core i7-10700k) equipped with 8 cores and a clock speed of 3.8 GHz, paired with 64 GB of RAM, is used.

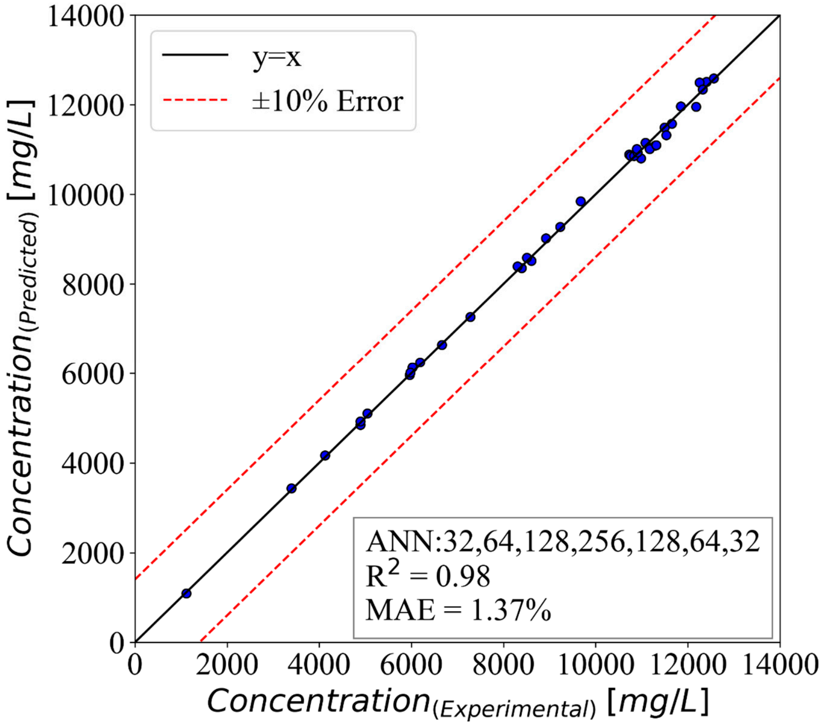

Figure 9. The ANN model predictions for concentration.

To add more insight on the selection of the ANN model, a comparison between the predictive capabilities of the ANN and random forest (RF) is performed. The RF model is optimized to achieve its highest accuracy. However, the results showed that the ANN model is superior to this model as well. The MAE of the RF model is 4.87% and the R^2 is

0.94. This shows the superiority of the ANN model over other machine learning models. The reason for this is the complex and deep structure of ANN models, which enables them to predict more complicated problems.

5. Conclusions

In this study, we determined optimal ultrasonic conditions for the hydrolysis of organic solids in raw biological sludge, revealing that a frequency of 50 kHz for 10 min provides effective results. While the highest sludge stabilization efficiency occurred at 50 kHz frequency in 40 min, achieving the 38% organic solid removal standard necessitated more time. Moreover, we established that the optimal conditions for sludge dewatering were at a frequency of 30 kHz with a contact time of 1 min. We also introduced a machine-learning-based model for concentration prediction, meticulously calibrated through hyperparameter tuning, revealing outstanding accuracy, with an R-squared (R^2) value of 0.98 and a mean absolute error (MAE) of 1.37%. To counter overfitting, the model incorporated L2 regularization and dropouts in specific hidden layers. Additionally, a comparison between our ANN model and the random forest algorithm showcased the ANN model's superiority, with a lower MAE of 1.37% and an R^2 of 0.98, outperforming the RF model with an MAE of 4.87% and an R^2 of 0.94. Simulating the ANN model required a high-performance CPU (Intel Core i7-10700k) featuring 8 cores and a 3.8 GHz clock speed, coupled with 64 GB of RAM, thereby ensuring rapid training and precise predictions. These findings not only enhance our understanding of sludge treatment, but also underscore the potential of machine-learning-based models for precise predictions in various research domains.

Author Contributions: Conceptualization, A.E.J. and C.W.; Methodology, A.E.J., H.K. and A.E.; Software, H.K., M.A., A.E. and S.S.S.; Validation, A.E.J., H.K. and M.A.; Formal analysis, N.T. and M.A.; Investigation, A.E.J., H.K., M.A., A.E. and S.S.S.; Resources, N.T. and M.B.; Data curation, H.K., N.T., M.B. and A.E.; Writing—original draft, A.E.J.; Writing—review and editing, H.K., M.B. and C.W.; Visualization, N.T., M.B., A.E. and S.S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Deanship of Scientific Research at King Khalid University under grant number RGP.2/57/44.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: The authors give their consent for publication.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: This work was supported by the King Khalid University, Abha, Saudi Arabia. The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through Large Groups Project under grant number (R.G.P. 2/57/44).

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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