SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage: https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Observation on the Electrical Conductivity of Agarwood Inoculant Using Electrical Impedance Spectroscopy Measurement for Pulsed Eddy Current Technology Application

Eza Elhanis Anuwar[1*], Nurmiza Othman[1], Balkis A. Talip[2], Fahmiruddin Esa[2], Mohamad Sidiq Mohd Basir[3], Nurul A'in Ahmad Latif[4], Ilham Mukriz Zainal Abidin[4]

[1] Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia
[2] Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Higher Education Hub, 86400 Panchor, Johor, Malaysia
[3] Pejabat Pengurusan Makmal, Universiti Tun Hussein Onn Malaysia, Pagoh Higher Education Hub, 86400 Panchor, Johor, Malaysia
[4] Leading Edge NDT Technology (LENDT) Group Industrial Technology Division, Malaysia Nuclear Agency, 43000 Kajang, Selangor, Malaysia

ARTICLE INFO

Article history:
Received 6 April 2026
Received in revised form 20 May 2026
Accepted 5 July 2026
Available online 18 July 2026

Keywords:
Agarwood inducer, electrochemical analysis, Electrical Impedance Spectroscopy, Pulsed Eddy Current

ABSTRACT

Using agarwood inducer involves applying a substance to Aquilaria trees to stimulate agarwood formation by replicating natural triggers that activate the tree's defensive response and resin production. Traditionally, the distribution of the inducer has been assessed through a time-consuming and destructive holing process. However, this technique can negatively impact the quality of agarwood formation. To address this issue, agarwood plantation workers must consider the correct injection dose to achieve optimal induction strength while controlling inducer usage to prevent wastage. Understanding the spread and distribution of the injected inducer within the Aquilaria tree is essential during the injection process. This study focuses on fundamental research on the electrical properties of the agarwood inducer towards applying a non-destructive detection method based on Pulsed Eddy Current (PEC) technology to enhance efficiency and economise the use of the inducer. The electrical properties of the inoculant were measured using Electrical Impedance Spectroscopy (EIS). Subsequently, the electrical properties obtained from the Nyquist plots were further analysed concerning the conductivity behaviour of the microbes in the inducer solution. A correlation between the electrical properties from the EIS measurement and the conductivity state of samples is crucial for future application of the PEC system to detect the inducer distribution. Implementing this detection method would reduce the injection process, enable more economical use of the inducer, and maintain the quality of agarwood formation.

1. Introduction

Agarwood is a fragrant black resinous wood used in incense, perfume, and miniature sculptures [1][2]. It develops in the heartwood of Aquilaria trees when the Aquilaria Tree contracts

* *Corresponding author.*
E-mail address: ge220045@student.uthm.edu.my

https://doi.org/10.37934/araset.61.5.322332

Phialophora parasitica, a type of mould, and secretes a resin to fight the mould [3]. Inducing agarwood formation can be approached through conventional, natural, and artificial methods [4]. Naturally, the physical injury or harm that thunder, animals grazing, insect and disease infestations give to Aquilaria trees is frequently associated with the conventional method of agarwood creation [5].

In the artificial method, people actively create conditions that induce the Aquilaria tree to produce Agarwood. The goal is to trigger the tree's natural defence mechanism, leading to the accumulation of resin and the eventual formation of Agarwood. The correct dose of inoculant injection is crucial to trigger the formation of artificial Agarwood in the Aquilaria tree. It is usually repeated so that the artificial Agarwood has a similar quality as the Agarwood formed naturally. Therefore, monitoring the distribution of post- injection inoculants is very important. The tree-holing technique is currently used to monitor its distribution [5]. It is time-consuming and destructive as it removes part of the damaged Agarwood from the Aquilaria tree [6]. This has triggered the formation of unwanted Agarwood due to the defence mechanism of the Aquilaria tree towards the holing process.

Therefore, this research proposed a new method based on Pulsed Eddy Current (PEC) to monitor the post-injection microbial inoculant distribution for Agarwood formation non-destructively. However, the initial focus will be on identifying the electromagnetic behaviour of microbes within the inoculant, specifically their electrical conductivity levels. Multiple approaches are available to explore the electrical conductivity of agarwood inoculants, and among these options is Electrical Impedance Spectroscopy (EIS).

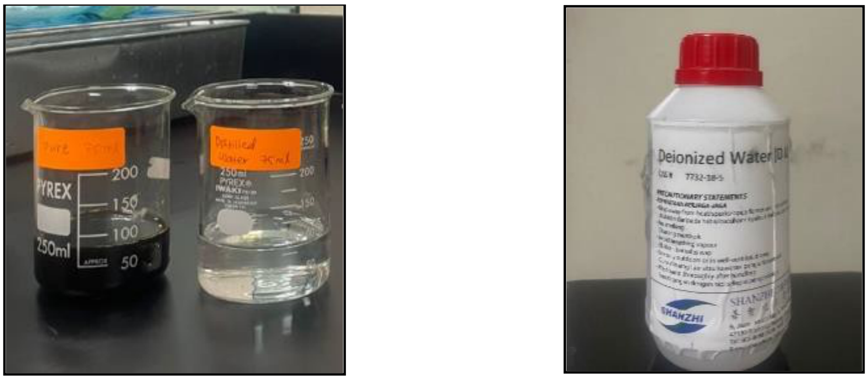
2. Methodology

2.1 Research Activities

To ensure the research project is conducted systematically, manageable, and efficiently, it is essential to carry out the necessary actions appropriately. This study will adhere to the correct procedures and progress through various stages. The research procedure utilized for this study includes the preparation of Agarwood inoculant samples and the application of techniques to measure electrical behaviours in microbes.

2.2 Sample Preparation of Agarwood Inoculant

Sample preparation of Agarwood inoculant in liquid form was done in the Food Microbiology Laboratory of the University Tun Hussein Onn Malaysia, Pagoh [7]. In this initial study, a mere three samples suffice to examine the presence of electrical conductivity. These three samples encompass pure inoculant, distilled water, and deionized water, intending to demonstrate the survival of microbes under low-frequency conditions. Subsequently, the testing protocol has been divided into two distinct phases, denoted as Test A and Test B. Test B is slated for execution two weeks later and will involve varying frequencies for assessment. Fig. 1, shows the pure inoculant sample, distilled water, and deionized water intended for use in this experiment.



(a) Pure inoculant and distilled water (b) Deionized water

Fig. 1. Three different types of samples

Table 1 displays the three types of samples used in the study. The first sample comprises a 75 ml volume of pure inoculant. The second type involves 75 ml of distilled water, while the final type encompasses 75 ml of deionized water.

Table 1
Three Different Types of Samples

Sample	Volume (ml)
Pure Inoculant	75
Distilled Water	75
Deionized Water	75

2.3 Techniques to Measure the Electrical Behaviors in Microbes

Electrical Impedance Spectroscopy (EIS) was used to measure the electrical properties of the inoculant because this technique can accurately evaluate the electrical behavior of the prepared inoculant sample. EIS is a potent method for examining the electrical characteristics of a wide range of materials [8]. EIS stands out as a crucial electrochemical technique that involves measuring impedance in a circuit using ohms as the unit of resistance [9]. This project utilized the EIS approach for liquid inoculants. EIS is typically operated in a three-electrode mode [10].

In electrochemical investigations, the interaction between the cathode and anode was analyzed, focusing on their interactions with the inoculants, referred to as solution X, at specific contact points, as shown in Fig. 4. During EIS analysis, these electrochemical interactions were assessed under dynamic conditions. Under dynamic conditions, oxidation and reduction processes occur, leading to concentration shifts and current flows [11]. Similarly, analogous processes are observed in electrochemical methods. EIS analysis involves measuring ionic and electronic conductivities and electrochemical interactions and processes.

During EIS investigations, the potentiostat or galvanostat regulates the voltage difference between a reference electrode and a working electrode. Both electrodes are the components of an electrochemical cell. The potentiostat achieves this control by introducing current into the cell through a platinum electrode. Simultaneously, the potentiostat or galvanostat measures the current flow between the counter and the working electrodes. This setup applies to both field probes and laboratory cells and involves an electrochemical cell with three electrodes.

In this setup, the first electrode serves as the conductor (counter) electrode, fulfilling the role of completing the cell circuit and aiding in the current flow. In this work, the counter electrode will consist of platinum because commonly counter electrode is constructed from platinum or another appropriate material [12]. Subsequently, the following electrode is referred to as the reference electrode, which maintains a consistent potential over an extended period. The exact potential of the working electrode is determined with precision using the reference electrode made of silver/silver chloride. Finally, the last electrode, composed of copper, serves as the working electrode. The working electrode also can be made of steel, aluminium, or copper. However, in this experiment, the working electrode is made explicitly from copper [13]. Notably, the working electrode is the point of interest where the electrochemical reaction under investigation occurs.

Once the experiment is completed, the data will be displayed on the Bode and Nyquist plots. This technique will introduce the impedance, Z, for measuring the equivalent permeability of particle mixtures like the agarwood inoculant. Typically, the sample resistance or impedance is calculated to determine the resistivity or its reciprocal value (conductivity). A lower impedance indicates a higher conductivity value in the inoculant [14]. Fig. 2 shows a diagram of Electrical Impedance Spectroscopy (EIS) and Fig. 3 demonstrates the fundamental experimental procedures for electrochemical analysis using EIS. The counter electrode is abbreviated as CE; WE represent the working electrode and the reference electrode is denoted as RE.

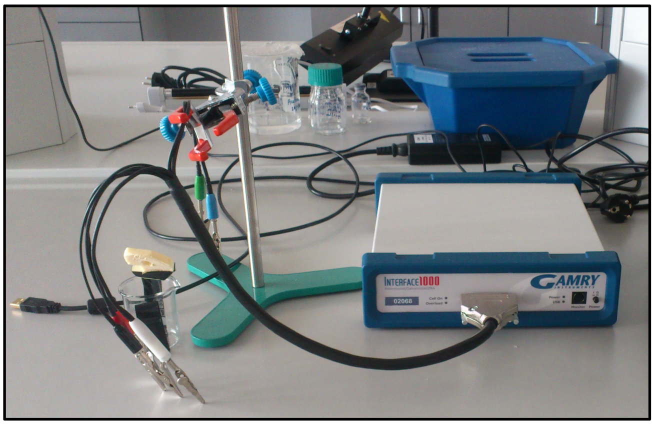


Fig. 2. Electrical Impedance Spectroscopy (EIS)

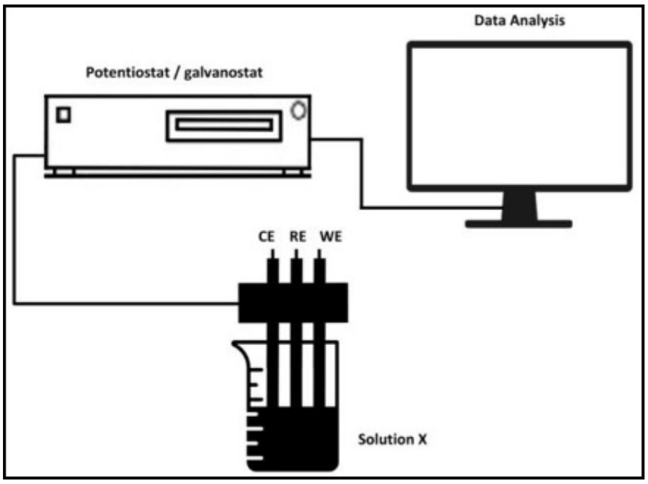


Fig. 3. Final Setup of Electrical Impedance Spectroscopy

3. Results

3.1 Measurement of Inoculant's Characteristics

The primary objective of this project is to identify electrical signals generated by the in-situ electrochemical activities of microbes within the inoculant sample. The electrical conductivity of the inducer will be used to determine if it meets a specified threshold.

This project was divided into two parts: Test 1 and Test 2. Both tests utilize the same sample volume, 75 ml. However, they operate at different frequency ranges. Test 1 covers frequencies from 0.1 Hz to 10 Hz, while Test 2 spans from 0.1 Hz to 1 kHz. Test 2 was conducted two weeks after Test 1 completion. Test 1 involves the analysis of two samples, while Test 2 expands to include three samples due to the inclusion of deionized water. The results are presented through Bode plot graphs and Nyquist plots for each sample.

3.1.1 Test 1 (0.1 Hz – 10 Hz)

To investigate the electrical properties of the inoculant samples, the data obtained by Electrical Impedance Spectroscopy (EIS) is expressed graphically in a Bode plot and a Nyquist plot, as shown in Fig. 4, Fig. 5, Fig. 6 and Fig. 7. Fig. 4 and Fig. 5 represent the impedance measurement from the pure inducer sample without dilution to any other substances, while Fig. 6 and Fig. 7 display the results obtained from the distilled water sample.

Subsequently, Table 2 presents the impedance values obtained from the EIS measurements at a frequency of 10 Hz. These values, recorded in an Excel file, are derived from the Bode and Nyquist plots. These values serve as crucial indicators of the electrical behavior of the samples under study. To facilitate further analysis, the impedance values are converted using the following formula:

$$\sigma = \frac{1}{Z}$$

where σ represents the conductivity and Z represents the impedance.

When analyzing Sample A, the pure inoculant sample, the Nyquist plot reveals that this sample exhibits lower impedance at the analyte concentration. This indicates that the sample has higher conductivity, with a measured value of $7.84 \times 10^{-3} Sm^{-1}$. This could be associated with the electrochemical activities of the microbes in the inoculant sample. In the bode plot, although specific values are not shown on the graph, the intercept at this frequency represents a peak in the electrochemical response, and its position on the graph is consistent with theoretical expectations for a peak in impedance magnitude.

Regarding Sample B, the distilled water sample, the graph in Fig. 6 and Fig. 7 displays a disordered pattern and a significantly high impedance value, indicating that distilled water lacks electrical conductivity. This aligns with the expected behavior of distilled water, which is not a good conductor of electricity. The changes in the electrode and solution during oxidation and reduction processes influence the impedance of the electrochemical system, and these changes are reflected in the Nyquist plot and the Bode plot obtained through EIS. The specific characteristics of the Nyquist plot can be analyzed to gain insights into the electrochemical reactions occurring at the electrodes.

Table 2
Electrical Conductivity Measurements for Two Samples

Sample	Bode Plot (Ω)	Nyquist Plot (Ω)	Conductivity, σ (Sm^{-1})
Pure Inoculant	Z = 127.52	Z' = 124.42 -Z" = 27.96	7.84×10^{-3}
Distilled Water	Z = 61088.97	Z' = 61084.05 -Z" = 775.19	1.64×10^{-5}

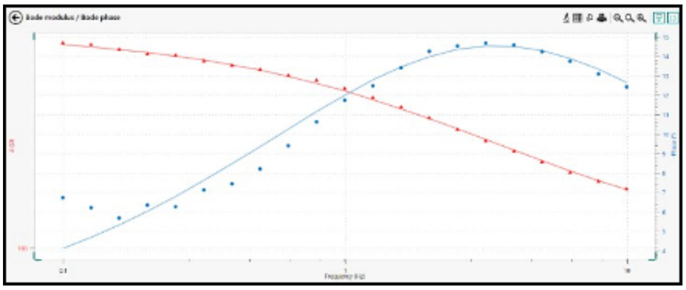


Fig. 4. Bode plot graph for pure inoculant sample

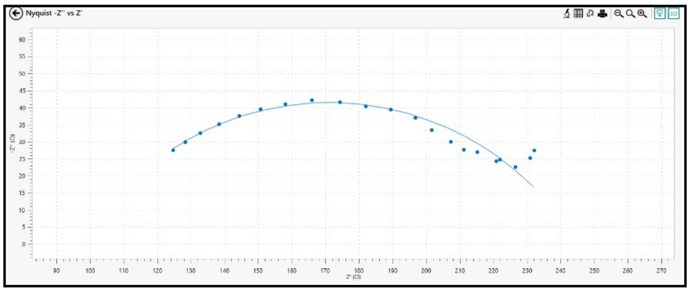


Fig. 5. Nyquist plot graph for pure inoculant sample

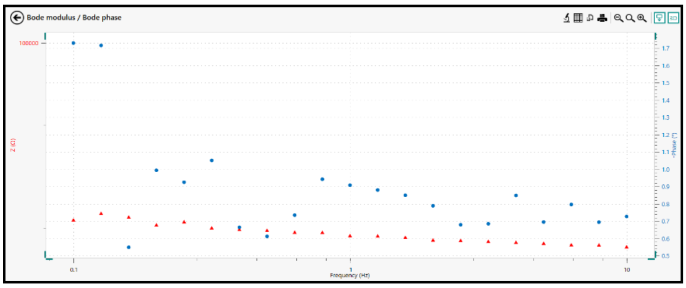


Fig. 6. Bode plot graph for a distilled water sample

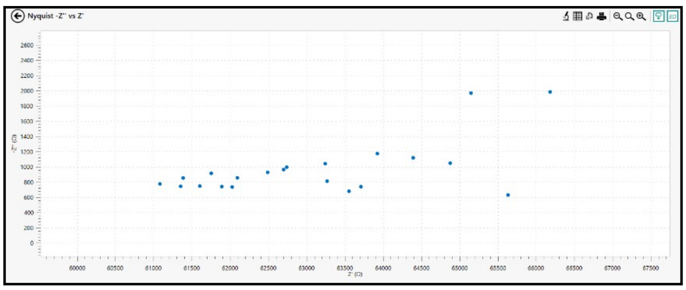


Fig. 7. Nyquist plot graph for a distilled water sample

3.1.2 Test 2 (0.1 Hz – 1 kHz)

Test 2 was conducted to measure the electrical properties of the inoculant samples across a frequency range from 0.1 Hz to 1000 Hz. Table 3 displays the impedance and conductivity values for three different samples. These measurements were specifically taken at a frequency of 100 Hz, providing a detailed view of the samples behavior at this particular frequency.

According to the results shown in Fig. 8 and Fig. 9, the pure inoculant sample exhibits a graph with low impedance, and its conductivity value is $7.76 \times 10^{-3} Sm^{-1}$. This graph closely resembles the one observed in Fig. 4 and Fig. 5 from Test 1, even though the frequency range has shifted to a broader range. Furthermore, the impedance behaviour observed from Sample B in Fig. 10 and Fig. 11 presents a chaotic pattern and demonstrates a notably elevated impedance value. This observation strongly suggests that distilled water hardly possesses electrical conductivity [16]. The chaotic pattern observed in the electrochemical response of distilled water can be attributed to the unique properties of water as well as the conditions of the experimental setup.

Despite its classification as a non-conductive substance, distilled water undergoes autoionization, resulting in the formation of small amounts of hydrogen ions (H^+) and hydroxide ions (OH^-). These ions, even at low concentrations, contribute to unexpected electrochemical behaviours. Additionally, the presence of dissolved gases, such as oxygen and carbon dioxide, in the water can influence its electrochemical characteristics. The interactions between water molecules and the electrode surfaces lead to surface absorption and changes in the electrode interface [17]. The irregularities or impurities on the electrode surface may further contribute to non-uniform reactions, introducing complexity to the electrochemical processes. The chaotic pattern may, therefore, emerge from the interplay of ionization, dissolved gases, and electrode interfaces, highlighting the intricate nature of water's electrochemical behaviour in the experimental context. Variability in impedance, influenced by these factors, contributes to the observed irregularities, highlighting the complex nature of distilled water's electrochemical behaviour in the experimental context.

Table 3
Electrical Conductivity Measurements for Three Samples

Sample	Bode Plot (Ω)	Nyquist Plot (Ω)	Conductivity, σ (Sm^{-1})
Pure Inoculant	Z = 128.81	Z’ = 127.38 -Z” = 19.11	7.76×10^{-3}
Distilled Water	Z = 43528.10	Z’ = 43524.34 -Z” = 572.01	2.30×10^{-5}
Deionized Water	Z = 35434.57	Z’ = 35420.71 -Z” = 990.73	2.82×10^{-5}

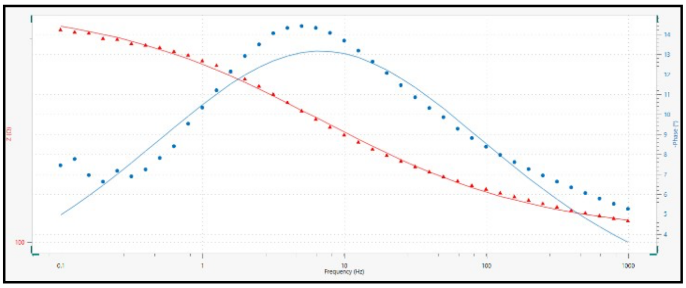


Fig. 8. Bode plot graph for a pure inoculant sample

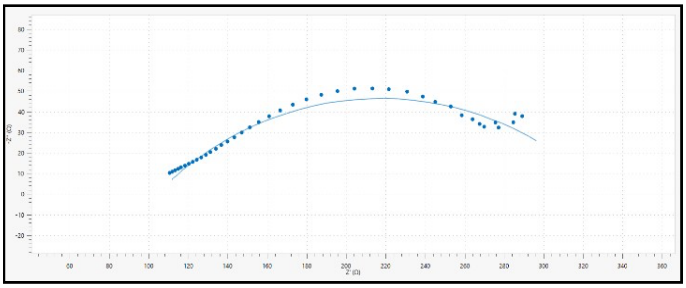


Fig. 9. Nyquist plot graph for a pure inoculant sample

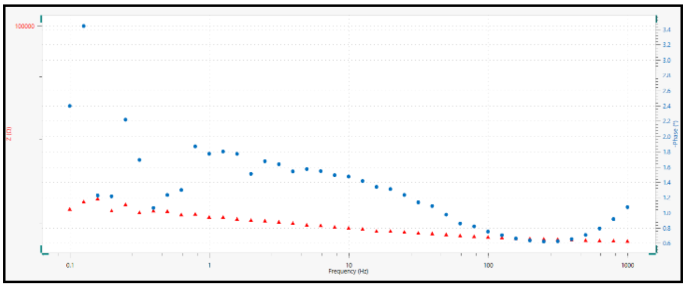


Fig. 10. Bode plot graph for a distilled water sample

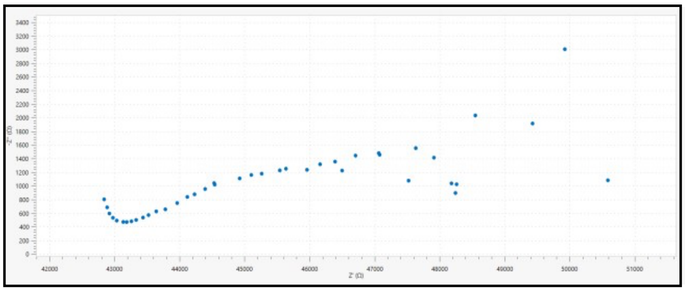


Fig. 11. Nyquist plot graph for a distilled water sample

Regarding the results from the deionized water sample depicted in Fig. 12 and Fig. 13, the Bode plot and Nyquist plot reveal impedance characteristics that indicate the presence of electrical conductivity in the deionized water which the value is $2.82 \times 10^{-5}\ Sm^{-1}$. This value is higher than the conductivity of distilled water. Furthermore, the impedance value is very high when compared to the impedance level from the pure inoculant sample, indicating the presence of conductivity at a very low level. Distilled water and deionized water are characterized by low conductivity due to their minimal ion content [18]. Distilled water, produced through distillation, possesses extremely low ion concentrations, as the distillation process effectively removes most mineral ions [19]. Despite this, it may retain small amounts of dissolved gases. Deionized water, on the other hand, undergoes ion exchange or similar processes designed to selectively remove ions, resulting in even lower ion concentrations compared to distilled water. Both types of water exhibit high impedance due to their low ion content, with the choice between them often dependent on specific experimental or application requirements related to desired purity levels and processing methods. For this study, distilled water has been selected to be used during the dilution process of the pure inoculant sample when further investigation is needed on the conductivity characteristics of the sample.

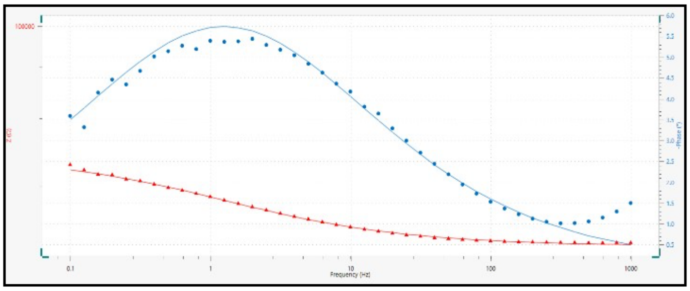


Fig. 12. Bode plot graph for deionized water sample

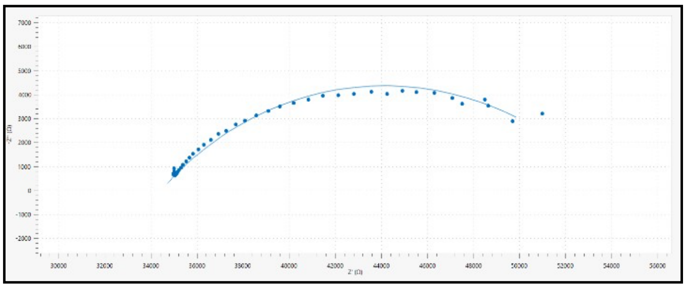


Fig. 13. Nyquist plot graph for a deionized water sample

3.2 Discussion and Analysis

During the experimentation, the frequency range was adjusted to span from 0.1 Hz to 1 kHz to see the electrical behaviours during the broad range of frequency sweeps.

Facts also prove that the electrical conductivity of distilled water is typically very low, close to zero [4]. Distilled water is considered a poor conductor of electricity because it contains minimal ions or dissolved salts that can carry electrical charges. However, it is essential to note that even though distilled water has low conductivity, it is not a perfect insulator and can still conduct electricity to a limited extent due to the presence of trace impurities and the absorption of carbon dioxide from the air [20]. The exact conductivity value of distilled water may vary based on its purity and environmental conditions.

Furthermore, deionized water typically has very low electrical conductivity because it has had most of its ions, which are responsible for electrical conductivity, removed during deionization. However, it's important to note that achieving ideally "zero" electrical conductivity is practically impossible, as there may still be trace amounts of impurities of gases dissolved in the water that can contribute to very minimal conductivity. Electrolytic conductivity is determined by the number of free ions in water and their ability to move [5]. Hence, in Test 2, the Nyquist plot illustrates a significantly elevated impedance value.

The survival of the inoculant over two weeks between Test 1 and Test 2 is a critical aspect of the experimental investigation, as evidenced by the consistent results observed in Test 2, which took place after Test 1. The sustained presence and discernible patterns on the Bode plot and Nyquist plot during Test 2 indicate the viability and persistence of the inoculant. The ability of the inoculant to maintain its electrochemical characteristics over the specified duration underscores its stability and suggests potential resilience against external factors or changes in the experimental conditions. This continuity in the electrochemical response contributes valuable insights into the long-term survivability of the inoculant, enhancing the robustness and reliability of the experimental findings.

4. Conclusions

In summary, this study has successfully demonstrated that the inoculant remains viable even after extended storage periods. Furthermore, it has effectively extracted conductivity values through Bode plot graphs and Nyquist plots. With the conductivity data, the subsequent phase will investigate and analyse the relationship between these acquired electrical properties and the magnetic distribution of the sample within the Pulse Eddy Current (PEC) system, employing electromagnetic modelling and simulation techniques.

Acknowledgement
This research was supported by Ministry of Higher Education (MOHE) through Fundamental Research Grant Scheme (FRGS/1/2022/TK07/UTHM/03/1)

References

[1] Tan, Cheng Seng, Nurulhikma Md Isa, Ismanizan Ismail, and Zamri Zainal. "Agarwood induction: current developments and future perspectives." *Frontiers in plant science* 10 (2019): 122. https://doi.org/10.3389/fpls.2019.00122

[2] Hou, Wencheng, Peiwei Liu, Yangyang Liu, Yong Kang, Yun Yang, Yuxiu Zhang, Zhihui Gao et al. "Chi-Nan agarwood germplasms constitute a new chemotype of Aquilaria sinensis (Lour.) Spreng." *Industrial Crops and Products* 187 (2022): 115494. https://doi.org/10.1016/j.indcrop.2022.115494

[3] Van Beek, H. H. Report, T. N. Blanchette, B. B. Patrika, and Richardson, P.C. "(12) United States Patent," vol. 2, no. 12 (2005): 10265–10276

[4] Ngadiran, Sulaiman, Sayang Baba, Nor Farahiyah Aman Nor, Maizatulakmal Yahayu, Mohd Faizal Muhamad, Ahmad Kamil Ahmad Kushairi, Dayang Norulfairuz Abang Zaidel, and Ida Idayu Muhamad. "The induction techniques of resinous agarwood formation: A review." *Bioresource Technology Reports* (2023): 101337. https://doi.org/10.1016/j.biteb.2023.101337

[5] Azren, Putra Desa, Shiou Yih Lee, Diana Emang, and Rozi Mohamed. "History and perspectives of induction technology for agarwood production from cultivated Aquilaria in Asia: a review." *Journal of Forestry Research* 30 (2019): 1-11. https://doi.org/10.1007/s11676-018-0627-4

[6] Zhang, Yan, Hui Meng, Feifei Lyu, Xiaohong Fan, Peiwei Liu, Xin He, Ying Huang, Bo Chen, Yun Yang, and Jianhe Wei. "Temporal characteristics of agarwood formation in Aquilaria sinensis after applying whole-tree agarwood-inducing technique." *Chinese Herbal Medicines* 15, no. 1 (2023): 37-44. https://doi.org/10.1016/j.chmed.2022.07.003

[7] Chen, Xuyu, Chun Sui, Yangyang Liu, Yun Yang, Peiwei Liu, Zheng Zhang, and Jianhe Wei. "Agarwood formation induced by fermentation liquid of Lasiodiplodia theobromae, the dominating fungus in wounded wood of Aquilaria sinensis." *Current microbiology* 74 (2017): 460-468. https://doi.org/10.1007/s00284-016-1193-7

[8] Grossi, Marco, and Bruno Riccò. "Electrical impedance spectroscopy (EIS) for biological analysis and food characterization: A review." *Journal of sensors and sensor systems* 6, no. 2 (2017): 303-325. https://doi.org/10.5194/jsss-6-303-2017

[9] Magar, Hend S., Rabeay YA Hassan, and Ashok Mulchandani. "Electrochemical impedance spectroscopy (EIS): Principles, construction, and biosensing applications." *Sensors* 21, no. 19 (2021): 6578. https://doi.org/10.3390/s21196578

[10] M. Grossi and B. Riccò, "Electrical impedance spectroscopy (EIS) for biological analysis and food characterization: A review," J. Sensors Sens. Syst., vol. 6, no. 2, pp. 303–325, 2017, doi: 10.5194/jsss-6-303-2017.

[11] E. Berdimurodov et al., Electrochemical impedance (EIS) and noise analyses for corrosion measurements. Elsevier Inc., 2023. doi: 10.1016/B978-0-443-15783-7.00017-7.

[12] Abdelwedoud, B. Ould, M. Damej, K. Tassaoui, A. Berisha, H. Tachallait, K. Bougrin, V. Mehmeti, and M. Benmessaoud. "Inhibition effect of N-propargyl saccharin as corrosion inhibitor of C38 steel in 1 M HCl, experimental and theoretical study." *Journal of Molecular Liquids* 354 (2022): 118784. https://doi.org/10.1016/j.molliq.2022.118784

[13] Berdimurodov, Elyor, Ilyos Eliboyev, Khasan Berdimuradov, Abduvali Kholikov, Khamdam Akbarov, Omar Dagdag, Mohamed Rbaa et al. "Electrochemical impedance (EIS) and noise analyses for corrosion measurements." In *Electrochemical and Analytical Techniques for Sustainable Corrosion Monitoring*, pp. 39-58. Elsevier, 2023. https://doi.org/10.1016/B978-0-443-15783-7.00017-7

[14] Kustyanto, Deny, Chomsin S. Widodo, and Didik R. Santoso. "Analysis of the Effect of NaCl Solution Concentration on the Properties of Impedance Solutions and Different Phases with a Gold Electrode Impedance Measurement System." Available: http://www.irjaes.com/pdf/V4N2Y19- IRJAES/IRJAES-V4N2P581Y19.pdf

[15] Zhang, Wang, and Ono, "Electrochemical Impedance Spectroscopy," *Microsc. Microanal. Lithium-Ion Batter.*, no. Dc, pp. 301–350, 2023, https://doi.org/10.1201/9781003299295-11

[16] Golnabi, H., M. R. Matloob, M. Bahar, and M. Sharifian. "Investigation of electrical conductivity of different water liquids and electrolyte solutions." (2009): 24-28.

[17] Zhao, Jinfeng, Georg Gorbatovski, Ove Oll, Erik Anderson, and Enn Lust. "Influence of water on the electrochemical characteristics and nanostructure of Bi (hkl)| Ionic liquid interface." *Electrochimica Acta* 415 (2022): 140263. https://doi.org/10.1016/j.electacta.2022.140263

[18] R. B. Darling, "Application Bulletin Deionized Water," no. Dl, pp. 1–5, 2013.

[19] H. Golnabi, M. R. Matloob, M. Bahar, and M. Sharifian, "Investigation of electrical conductivity of different water liquids and electrolyte solutions," *Iran. Phys. J.*, vol. 3, no. November 2014, pp. 24–28, 2009.

[20] K. Words, "Measuring pH of Pure Water and Other Low Conductivity Waters Water Analysis Instruments, Thermo Fisher Scientific", [Online]. Available: www.astm.org