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Characterization and Performance Evaluation of NADES-CAF in Ultrasound and Microwave Extraction of Phycocyanin from *Arthrospira platensis*

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ABSTRACT

Ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) were applied to accelerate the extraction of Phycocyanin (P), which is considered a safe natural antioxidant, from *Arthrospira platensis*. The applications were combined with natural deep eutectic solvent-citric acid fructose (NADES-CAF) as a safe green solvent for the product and environment in acceleration. This study evaluates the characteristics and performance of NADES-CAF at various concentrations (1, 2, and 3%) in UAE and MAE, which were analyzed based on Peleg's model. The results showed that the increased NADES-CAF concentrations enhanced the solvent properties (density, viscosity, EC, and TDS) under ultrasonic and microwave conditions, thereby improving extraction performance. The UAE achieved a higher extraction rate value (0.0316 - 0.0411 mg/mL.min) compared to MAE (0.0111–0.0193 mg/mL·min) and also a higher maximum capacity (1.4353–2.7389 mg/mL) than MAE (1.5243–1.9453 mg/mL). A peak maximum capacity of 2.7389 mg/mL was achieved with UAE using 3% NADES-CAF. It should be an efficient and sustainable method for extracting phycocyanin from *Arthrospira platensis.* Peleg's model successfully described extraction performance and accurately predicted the phycocyanin content during extraction. The study demonstrated that NADES-CAF concentrations improved solvent properties and extraction performance, with UAE achieving a higher extraction rate value and maximum capacity than MAE.

1. INTRODUCTION

Natural antioxidants like phycocyanin offer safer and more sustainable alternatives to synthetic compounds. Microalgae, single-celled organisms that thrive in diverse environments, produce various bioactive compounds, including antioxidants. However, microalgae have complex and robust cell walls, making it challenging to extract specific biomolecules. To overcome this problem, physical, chemical, and biological methods are needed to enhance the extraction and recovery of targeted compounds [1].

Arthrospira platensis is a type of cyanobacteria microalgae often used in the functional food and pharmaceutical industries because of its antioxidant, anti-inflammatory, and anticancer properties [2, 3]. This type of microalgae has a 60-70% protein content, making it a suitable vegetable protein source. Phycocyanin (P) is one of the pigments in *Arthrospira platensis* that can capture light energy during photosynthesis. Phycocyanin contains antioxidants that can prevent cancer and Alzheimer's [4]. In the food industry sector, phycocyanin is a natural dye that can improve food quality [3].

The exploration of antioxidant compounds is still being developed to achieve efficiency and optimization. Recent technological development is the application of techniques and solvents that are safe and non-toxic but capable of improving extraction performance. The success of collecting functional compounds in the material is greatly influenced by the ability of the solvent to diffuse into the material and release the functional compound from its position in the material. NADES is a new category in the ionic liquid family that inherits the characteristics of ionic liquid (IL) but with a more affordable and environmentally friendly approach and a more straightforward synthesis process. The application of NADES aligns with the principle of green chemistry and supports environmentally friendly extraction processes, making it a promising tool for advancing sustainability in scientific research [5]. In applying NADES as a solvent, it is crucial to consider its physical characteristics that favor penetration into the material's pores and the release of bioactive compounds [6]. Therefore, the characterization of NADES must be studied first before application to determine its potential application in the extraction process [7, 8]. NADES, which is composed of a solution of citric acid and fructose (NADES-CAF), can also act as a stabilizing agent in the extraction process of antioxidant compounds that are temperature sensitive. This is one of the main advantages that needs to be optimized to prevent structural degradation of P compounds when exposed to high temperatures during extraction [9, 10].

In this research, the NADES applied is NADES-CAF, which is made from natural ingredients that are environmentally friendly, relatively cheap, and do not have negative or toxic effects on the extract produced. The application of NADES is expected to support the solvent's character in facilitating the process of collecting bioactive compounds from the material and bringing them into the solvent. The success of the acceleration can be attributed to the character of the NADES applied.

In addition to using NADES-CAF, ultrasonic-assisted extraction (UAE) and microwave-assisted extraction (MAE) were used to accelerate phycocyanin extraction. This offers several advantages from a green chemistry perspective, including reduced solvent usage, shorter extraction time, and lower energy consumption. UAE efficiently extracts targeted bioactive components by exploiting its characteristic cavitation effect [11]. Meanwhile, MAE utilizes microwave radiation to disrupt cell structures and extract bioactive compounds rapidly [12]. However, scaling up these techniques for industrial use requires further optimization.

The research aims to characterize various concentrations of NADES-CAF and its performance in UAE and MAE phycobiliprotein from *Arthrospira platensis.* NADES characterization was carried out under the presence of ultrasonic waves and microwaves. The extraction performance was tested by analyzing the change in phycocyanin content in the solvent by applying Peleg's model as a kinetic approach. The results of the NADES-CAF characterization produced in the research can be a reference for further application of NADES-CAF to extract various bioactive materials from natural materials. The success of accelerating the extraction process through wave treatment and its interaction with the NADES-CAF solvent can provide new insights into extraction technology.

2. METHOD

2.1 Materials and instrument

Arthrospira platensis powder was purchased from Spiruganik Polaris (Jakarta, Indonesia). Components of NADES-CAF used in the experiment are citric acid from Weifang Ensign Industri, Jakarta, Indonesia (purity of 99,5%), High Purity Fructose 99% Powder Crystalline CAS 57-48-7 for Sweeteners (purity 99%), and aquadest from Progo Mulyo, Yogyakarta, Indonesia. Meanwhile, the instruments used were UAE (Hangzhou type DW-SD20-1200H, China), MAE (Electrolux, type EMM2308X, Indonesia), centrifuge (Kokusan, type H-27A, Japan), UV-Vis Spectrophotometer (Mesulab, type N2S, China), and Viscometer Brookfield RTV (Ametec Inc, America). The electrical conductivity (EC) and total dissolved solid (TDS) of the NADES investigated in this work were measured using an E-1 Portable TDS and EC Meter. The density of NADES was measured using the ratio between the mass and volume of NADES using a pycnometer. Meanwhile, the viscosity was measured using a Brookfield Viscometer with rpm 20 and spindle 1.

2.2 The NADES preparation and property measurement

The NADES-CAF solvent was made from citric acid and fructose. Citric acid and fructose were mixed at a molar ratio of 1:1 and dissolved in distilled water, followed by ultrasonic probe treatment at 20 kHz for 30 minutes with 80% amplitude until the desired liquid was formed, based on the NADES preparation method with modification [13]. The NADES-CAF was diluted into 1, 2, and 3% concentrations.

The properties measured in NADES-CAF include density, viscosity, electrical conductivity (EC), and total dissolved solids (TDS). Measurements were carried out every 30 minutes for 150 minutes. In addition, the characteristics of NADES were also measured at six temperature points (30, 40, 50, 60, 70, and 80)°C to determine the effect of temperature on its characteristics. The evaluation was carried out using ultrasonic waves and microwaves.

2.3 The extraction of phycocyanin using UAE and MAE

In this study, the extraction used ultrasonic extraction equipment from Hangzhou Dowell Ultrasound Tech. Co., Ltd. has model number DW-SD20-1200H, a power of 1.2 kW, and a 220 V / 20 kHz voltage. The sample was placed in a beaker glass and placed under the probe. Extraction was carried out using an ultrasonic extractor with ultrasonic waves at a frequency of 20 kHz and set at an amplitude of 80%. An illustration of the ultrasound-assisted extraction can be seen in Figure 1.

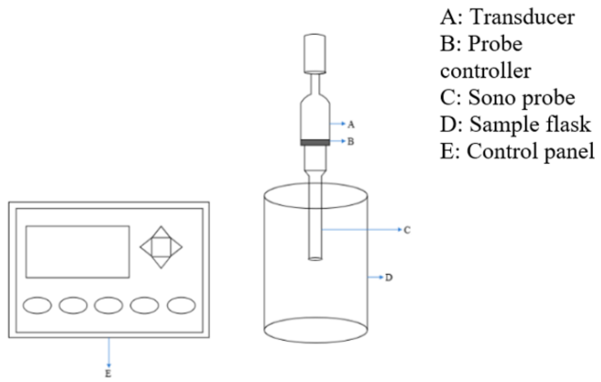
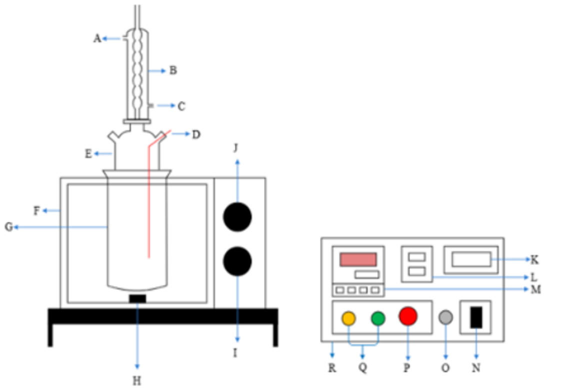


Figure 1. The schematic of UAE

The MAE was also conducted using a microwave modified into an Electrolux EMM2308X with a capacity of 23 L, a microwave power of 1200 W, and a voltage of 220-240 V/ 50 Hz for MAE processes. The system has a stirrer speed controller, microwave power, temperature controller, and extraction time on the control panel, as shown in Figure 2. The stirrer speed is controlled at 180 rpm. This process uses 800 W of power. Then, the flask containing the solution is put into the microwave.

The UAE and MAE extraction processes are carried out by placing 10 grams of *Arthrospira platensis* powder in 300 mL of solvent. The UAE and MAE extraction processes are performed by placing 10 grams of *Arthrospira platensis* powder in 300 ml of solvent. The extraction process was carried out for 150 minutes due to the preliminary research, which showed that within 150 minutes, the P concentration in a solvent tended to be in an equilibrium condition.



A: Water in
B: Condensor
C: Water out
D: Temperature recorder
E: Connecting flask
F: Microwave cavity
G: Sample flask
H: : Magnetic stirrer
I: Microwave timer
J: Microwave power
K: Rpm screen
L: Time controller
M: Temperature & Power controller
N: Switch button
O: Rpm controller
P: Timer button
Q: Indicator lamp
R: Control panel

Figure 2. The schematic of MAE

2.4 The correlation between TDS and EC

The correlation between TDS and EC is explored as the effect of the activity of specific dissolved ions that influences the EC value, as well as the average activity of all ions in the liquid and ionic strength [14, 15]. The correlation between TDS and EC is estimated using Eq. (1), where the k will increase along with the increase of ions in water.

$$TDS\ (mg/L) = k.\mathrm{EC}\ (\mu s/cm) \tag{1}$$

2.5 The determination of phycocyanin content

The P extraction process was carried out by mixing 10 grams of *Arthrospira platensis* powder with 300 mL of solvent and treated with NADES concentrations of 1, 2, and 3% for 150 minutes in a flask. The extraction performance was evaluated by observing the concentration of P in the solvent every 30 minutes during the 150-minute UAE and MAE. The levels of P were measured every 30 minutes using a spectrophotometer. The sample was transferred to a 15 mL centrifuge tube and centrifuged at 4000 rpm for 10 minutes to separate the pellet from the supernatant. The P content in the supernatant was analyzed using a UV-Vis Spectrophotometer at 620 nm and 652 nm wavelengths. The use of UV-Vis spectrophotometry to analyze compounds in extracts has been widely used, for example to analyze the tannin content of kirinyuh extract [16], and the curcumin content in turmeric [17]. The calculation formula for P content uses the following equation [18].

$$P\ (mg/mL) = \frac{A_{620\,nm} - 0.474\,(A_{652\,nm})}{5.34} \tag{2}$$

2.6 The kinetics approach of phycocyanin content during UAE and MAE

This study used Peleg's model to describe the P change from *Arthrospira platensis* using UAE and MAE. Peleg's model is a model that explains the rate of sorption of mass components to other components [19]. The change in P in the extract was then calculated by Peleg's model using the following formula [20]:

$$C_t = C_0 + \frac{t}{K_1 + K_2.t} \tag{3}$$

where, C_t (mg/mL) is the concentration of P in solvent at t time of extraction; C_0 (mg/mL) is the P concentration in the solvent at t = 0; K_1 (mL.min/mg) is the Peleg's model constant value; K_2 (mL/mg) is the constant capacity value of Peleg's model, and t (min) is the time. The C_0 value was zero at the beginning of extraction so that the equation can be written in Eq. (4).

$$C_t = \frac{t}{K_1 + K_2.t} \tag{4}$$

The K_1 value is related to the B_0 value as the initial extraction rate (mg/mL.min). Meanwhile, the K_2 value is used to identify the C_e as the maximum capacity (mg/mL). Then, the value of B_0 and C_e can be seen in Eqs. (5) and (6). Therefore, the final equation for Peleg's model can be written in Eq. (7).

$$B_0 = \frac{1}{K_1} \tag{5}$$

$$C_e = \frac{1}{K_2} \tag{6}$$

$$C_t = \frac{t}{\frac{1}{B_0} + \frac{t}{C_e}} \tag{7}$$

After obtaining the Peleg's model value, the next step is to prove the accuracy of the model in predicting the P concentration during the extraction. The evidence is based on the value of the sum of squares of errors (SSE) in Eq. (8), the root mean square error (RSME) in Eq. (9), chi-squared (χ^2) in Eq. (10), and coefficient of determination (R^2) in Eq. (11) [21-23].

$$SSE = \sum_{i=1}^{N} \left(C_{obs,i} - C_{pred,i}\right)^2 \tag{8}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(C_{obs,i} - C_{pred,i}\right)^2} \tag{9}$$

$$\chi 2 = \frac{\sum_{i=1}^{N}\left(C_{obs,i} - C_{pred,i}\right)^2}{N - n} \tag{10}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(C_{obs,i} - C_{pred,i})^2}{\sum_{i=1}^{N}(C_{obs,i} - \bar{C}_{obs})^2} \tag{11}$$

3. RESULTS AND DISCUSSION

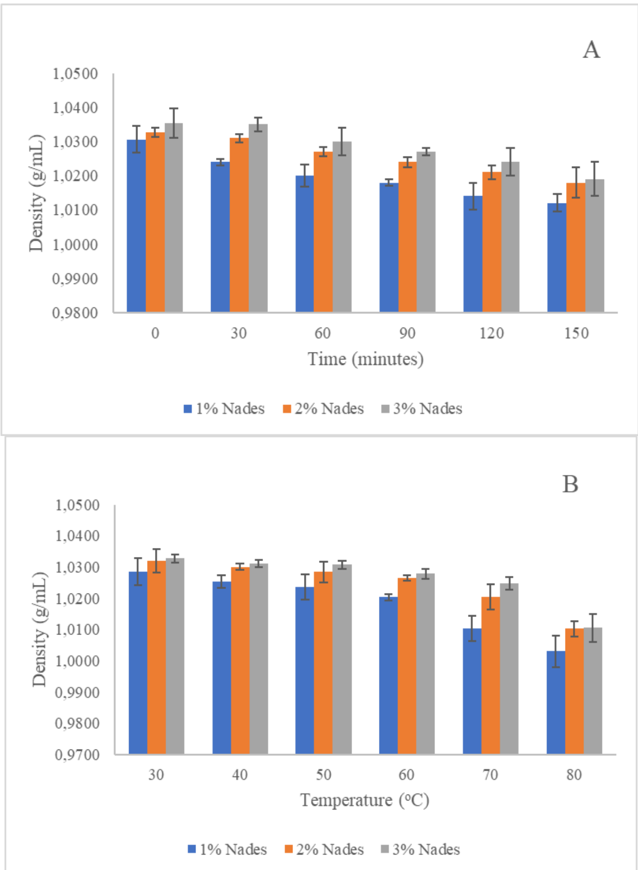
3.1 The characteristics of NADES-CAF under ultrasound wave and microwave wave

3.1.1 The density

The density of NADES-CAF in each concentration using

UAE and MAE has been depicted in Figure 3. Figure 3(A) explains the function of time and Figure 3(B) explains the function of temperature in the density as the under the effect of ultrasound waves. It can be seen that the density value decreases slightly along with the duration of ultrasonic wave exposure due to changes in the physical structure distance due to cavitation. Cavitation causes bubbles to burst, disrupting intermolecular interactions in the solvent so that the volume increases while the mass remains the same [24]. Figure 3(B) shows the result of observing density versus temperature. Density will also decrease when the NADES-CAF temperature increases. With increasing temperature, the particles of a substance will experience an increase in kinetic energy so that the volume value also increases [25]. The lower physical distance between solvent particles is expected to support the permeate of solvent into the *Arthrospira platensis* to accelerate the extraction. In this study, the density of NADES-CAF under ultrasonic waves was 1.0030 g/mL to 1.0353 mg/mL, which is higher than pure water (1.0000 mg/mL) [26].

As discussed before, the effect of ultrasound waves shows that the density of NADES-CAF under MAE also decreases over time and with rising temperature, as shown in Figure 3(C) and (D). Lower density enhances solvent penetration during extraction, facilitating bioactive compound release. This reduction also occurs due to increased molecular kinetic energy, which causes the molecules to move more rapidly, thereby reducing density. This graph also shows that the higher the concentration of NADES, the higher the density value. This occurs because the number of molecules in a given volume increase. From Figure 3, the density value of solvent is slightly lower under ultrasound wave treatment than a microwave. It can be correlated with their cavity in the bulk of the solvent and significantly affects the distance between solvent particles.



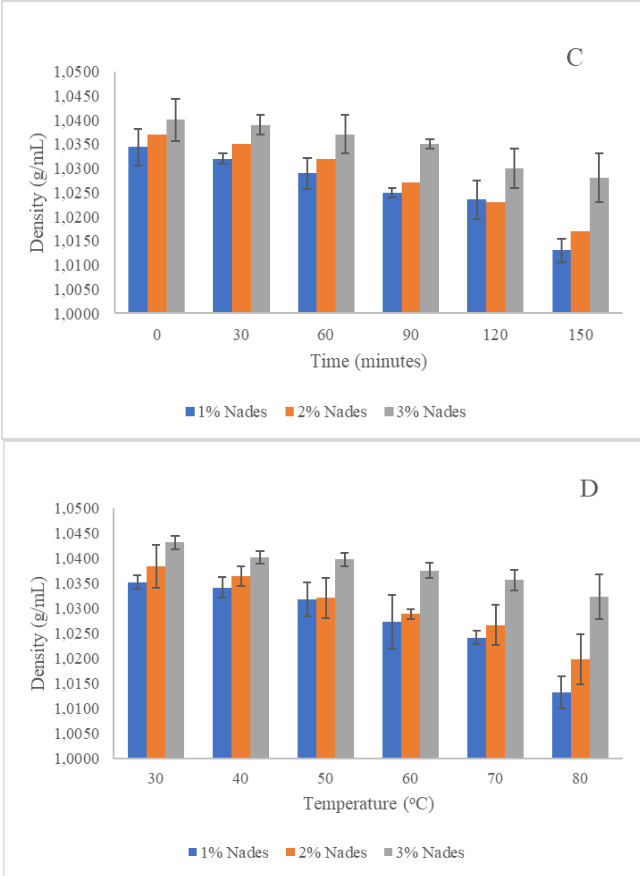


Figure 3. (A) Density of NADES-CAF in UAE during time; (B) Density of NADES-CAF in UAE during temperature; (C) Density of NADES-CAF in MAE during time; (D) Density of NADES-CAF in MAE during temperature

3.1.2 The viscosity

In this study, the viscosity of NADES-CAF affected by ultrasonic waves is depicted in Figure 4. Figure 4(A) illustrates the viscosity profile against time under the ultrasound wave. The viscosity decreases slightly with the duration of ultrasonic wave exposure. During 150 minutes of UAE, the viscosity values decreased from 15 cP to 1 cP (1% NADES); 15 cP to 2 cP (2% NADES); 17.5 cP to 2.5 cP (3% NADES).

The decrease in viscosity also occurs as the effect of the increase in temperature that is affected by the ultrasound wave, as seen in Figure 4(B). Viscosity decreased 17.5 cP to 0.5 cP (1%NADES); 21.5 cP to 2 cP (2% NADES); 25 cP to 2.5 cP (3% NADES) at 80°C under UAE. The ultrasound wave increases the kinetic energy of solvent particle barriers that weaken the hydrogen bonds between molecules so that the movement of molecules can flow easily [25]. This phenomenon caused a decrease in viscosity as long as the ultrasound treatment. The reduction in viscosity is also affected by the increase in temperature. The decreasing viscosity is required to support the extraction and lower the obstacle when the solvent is diffused into the material.

The effect of microwave on the viscosity profile is illustrated in Figure 4(C) and (D). The viscosity decreases over time and with increasing temperature. During 150 minutes of MAE, the viscosity values decreased from 15 cP to 1 cP (1% NADES); 20 cP to 1.5 cP (2% NADES); 22.5 cP to 2.5 cP (3% NADES). Viscosity decreased from 17.5 cP to 1 cP (1%NADES); 23 cP to 2 cP (2% NADES); 27.5 cP to 7.5 cP (3% NADES) at 80°C. This decrease occurs because heat weakens the intermolecular attraction forces, reducing the solution's viscosity. This graph also shows that the higher the concentration of NADES, the higher the viscosity value. This occurs because, at higher concentrations, the solution structure becomes denser, making it more viscous. Overall, as the previous discussion, the solvents' viscosity value under the microwave is higher than under ultrasound. The lower viscosity is expected to enhance solvent penetration during extraction, facilitating bioactive compound release and impacting the extraction.

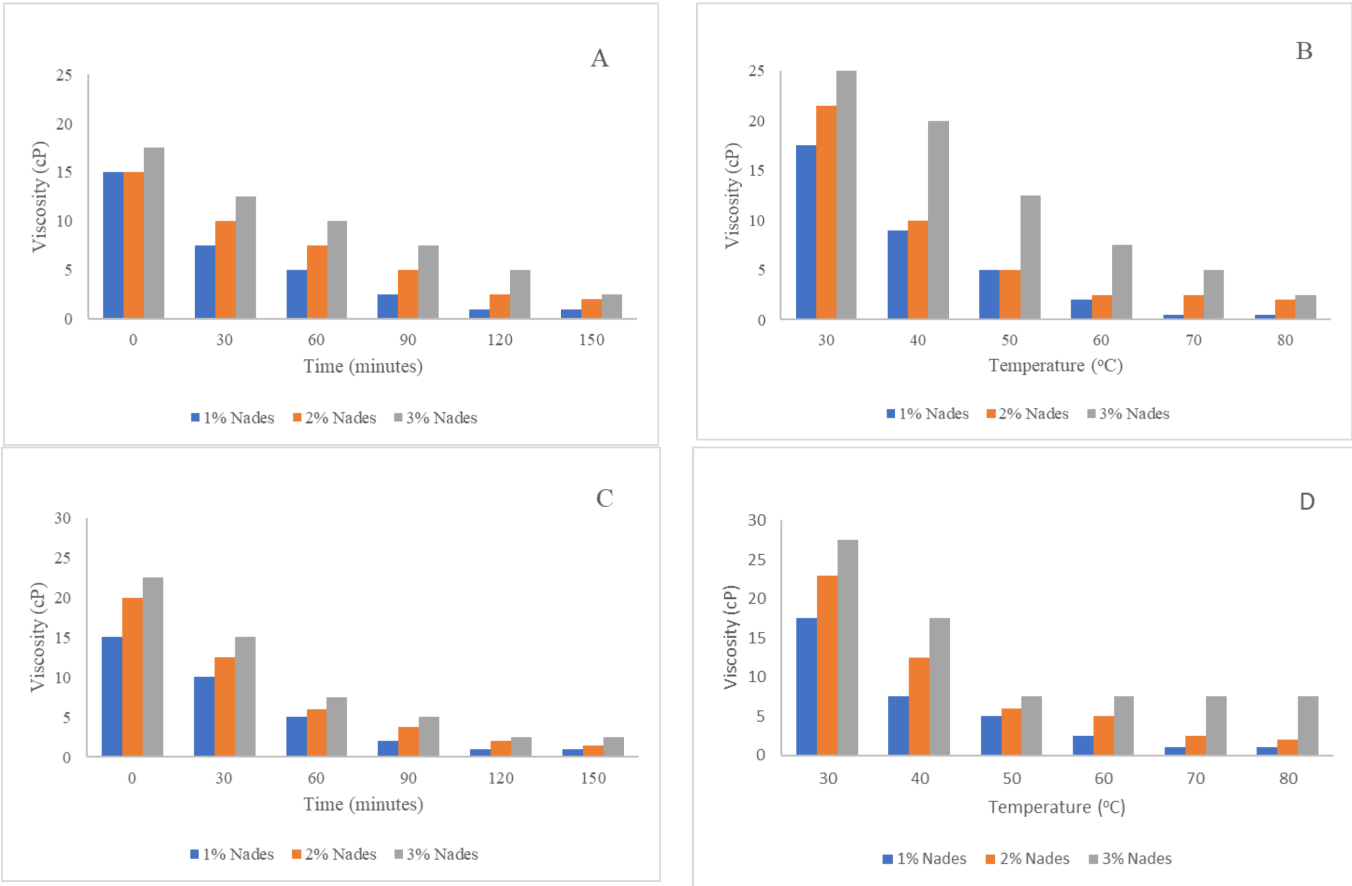


Figure 4. Viscosity of NADES-CAF during time (A) and temperature (B) in UAE as well as MAE during time (C) and temperature (D)

3.1.3 The TDS and EC

The TDS and EC values of NADES-CAF using UAE can be seen in Figure 5(A) and (B). The TDS value increases with the longer solvent contact time with ultrasonic waves. The longer the solvent is exposed to ultrasonic waves, the higher the heat generated, which causes evaporation. So, the TDS value increases. Ultrasonic waves can reduce the boundary layer surrounding solid particles. In this study, the highest density value was found at a NADES concentration of 3%, which was 1888 ppm, higher than the TDS value of fresh water, which was < 500 ppm [27].

The EC value of each solvent is measured as the effect of ultrasound treatment. The value of EC shows the capability of the solvent to conduct the electric current, which facilitates the dissolution of the functional compound into the solvent. This capability is supposed to play an important role in extracting a polar compound. EC was measured every 30 minutes for 150 minutes at 80% amplitude, as shown in Figure 5(A) and (B). The profile of EC value is between 1011 and 3894 (μS/cm), which is higher than pure water (0.555 (μS/cm)) [15]. Adding NADES-CAF increases the polarity and current as ions, which help extract P from *Arthrospira platensis*, thereby assisting the process of releasing bioactive compounds. Meanwhile, Figure 5(B) shows that the EC value increases with increasing temperature. The NADES concentration also influences the EC value. The higher the concentration value, the higher the material added, so the EC is high. This shows that the NADES entered affect the EC. This information can be used to support the extraction of the P compound.

The TDS and EC value of NADES-CAF using MAE is shown in Figure 5(C) and (D), where it can be seen that the TDS increases over time and with rising temperature. This increase occurs because higher temperatures elevate the kinetic energy of the molecules, making solids more readily dissolve in the solvent. When kinetic energy increases, the solvent molecules move more rapidly, promoting stronger interactions with the solute molecules, accelerating the dissolution process, and raising the TDS concentration [28]. This graph also shows that the higher the concentration of NADES, the higher the TDS value. This occurs because the amount of dissolved substances in the solution increases.

Figure 5(C) and (D) also show the EC of NADES-CAF using MAE. The EC values in this study increase with rising time and temperature. This increase is due to the kinetic energy generated by heating, which enhances the frequency of molecular collisions. As a result, the intermolecular forces weaken, and the EC increases [29]. This graph also shows that the higher the concentration of NADES, the higher the EC value. This occurs because the number of charged particles in the solution increases.

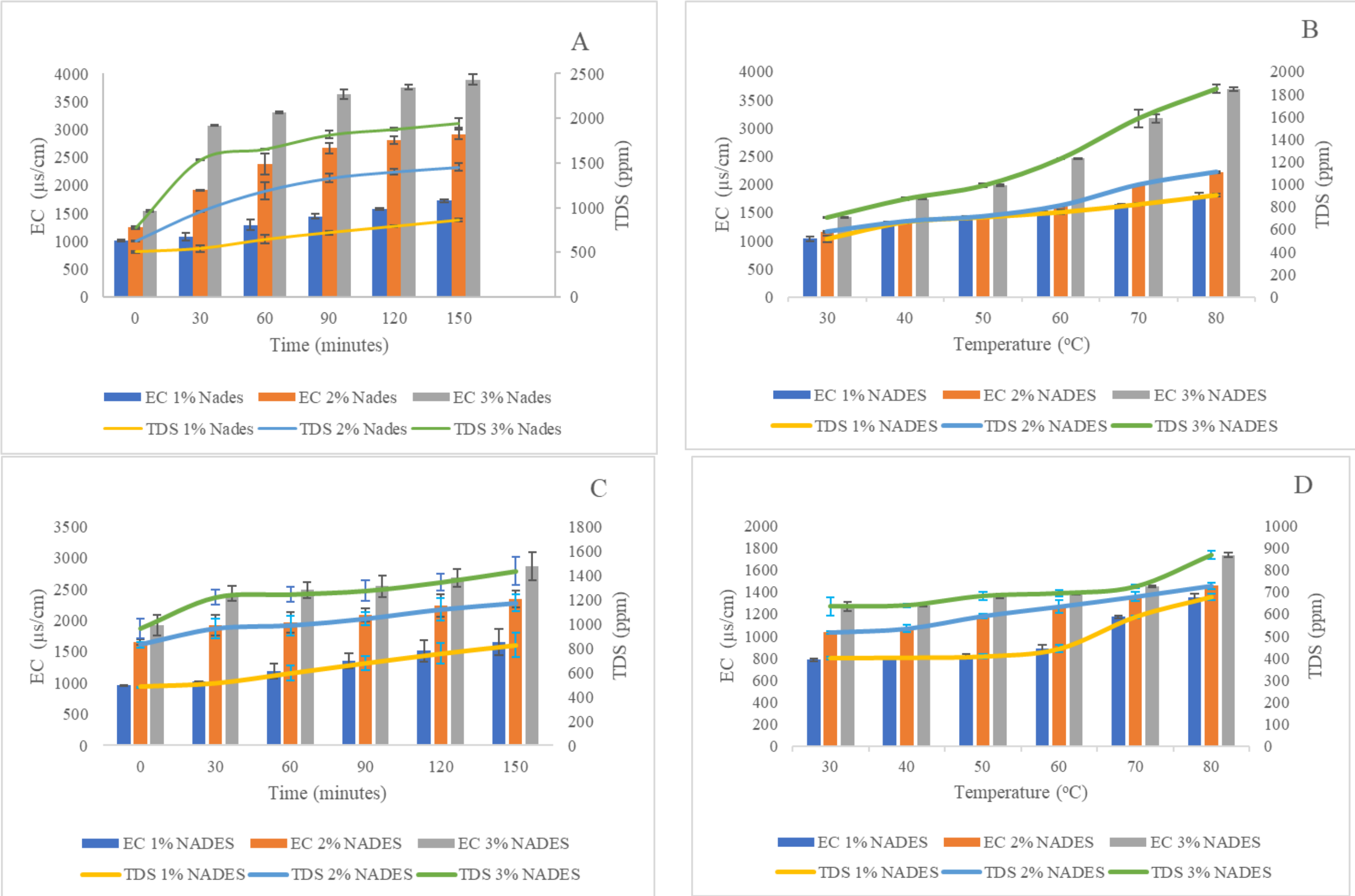


Figure 5. TDS and EC of NADES-CAF during time (A) and temperature (B) in UAE as well as MAE during time (C) and temperature (D)

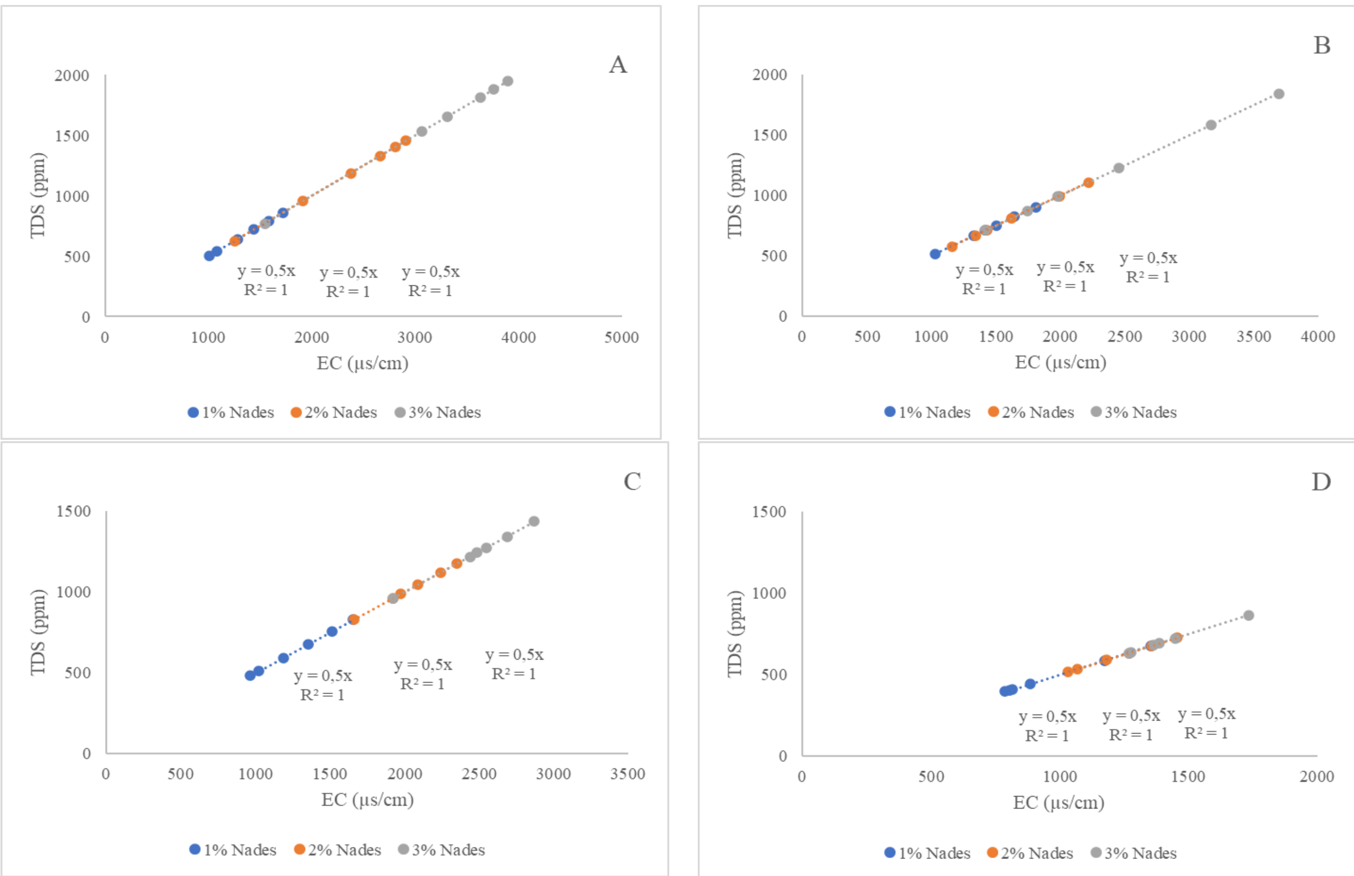


Figure 6. The TDS-EC of NADES-CAF during time (A) and temperature (B) in UAE as well as MAE during time (C) and temperature (D)

Overall, the higher TDS and EC values indicate the increase of ionization, enhancing solvent polarity, which can improve extraction performance. The maximum EC value in NADES-CAF 3% solvent using UAE was attained at 150 minutes, with a concentration of 3558 µs/cm, while under similar conditions, MAE yielded 2725 µs/cm.

3.1.4 The correlation between TDS and EC

TDS and EC are water quality parameters in various applications, including water assessment, environmental monitoring, and agricultural practices. TDS concentration describes the amount of organic matter in water, while EC measures the ability of water to conduct electricity. Furthermore, the relationship between TDS and EC is also evaluated as an essential aspect of water quality assessment, providing information about the concentration of dissolved materials in water to support the conductivity of electric charge. Based on Figure 6, the TDS/EC ratio of NADES-CAF was measured at 0.5 (R^2= 1), consistent with existing literature showing the TDS/EC ratio or k value is 0.5 for distilled water [27].

3.2 The performances of NADES-CAF in UAE and MAE

3.2.1 Profile of TDS and EC in aqueous extract during UAE and MAE

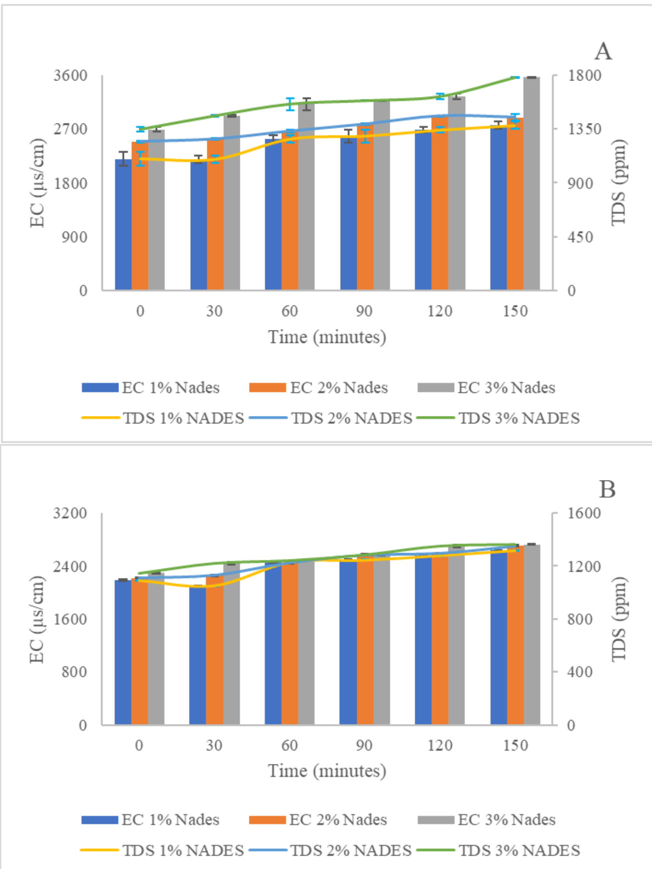


Figure 7. The TDS and EC of NADES-CAF with UAE (A) and MAE (B)

During the extraction, some compounds are released from the inner part into the bulk of the solvent. Figure 7 compares the TDS value in the aqueous extract in UAE and MAE with NADES-CAF, which increased with higher concentrations. NADES-CAF, with a concentration of 3%, has a higher TDS value. The higher the concentration of NADES-CAF, the more organic and inorganic compounds are released from the material, increasing the TDS value [30]. In this research, the maximum TDS value in the NADES-CAF 3% solvent using UAE was achieved at 150 minutes, with a concentration of 1779 ppm, while under the same conditions, MAE produced 1362 ppm. In the same extraction time and also at the same temperature, the ultrasound performs a higher TDS value than MAE. It can be correlated with the solvent properties, as discussed before.

Figure 7 also illustrates the EC value of *Arthrospira platensis* using UAE and MAE. The EC value increases during the extraction time. The higher the concentration of NADES-CAF used, the higher the EC value and the greater the electrical conductivity efficiency value. Higher concentrations of NADES-CAF produce more ions in the solution, so the ability to conduct electricity is higher. This shows that conductivity is directly proportional to ion concentration [31].

3.2.2 Profile of phycocyanin content in aqueous extract during UAE and MAE

This research aims to gain the P compound from *Arthrospira platensis* under UAE and MAE with NADES-CAF concentration—the concentration of P in the solvent increases during extraction (Figure 8). The increase of P content in the solvent is faster at the beginning of the process and then tends to reach the equilibrium value. The NADES-CAF concentration of 3% showed the most effective solvent mode to extract the P content. The highest concentration of P in NADES-CAF 3% solvent conditions using UAE was achieved in 150 min with a value of 0.0180 mg/mL, while MAE resulted was 0.0122 mg/mL under similar conditions.

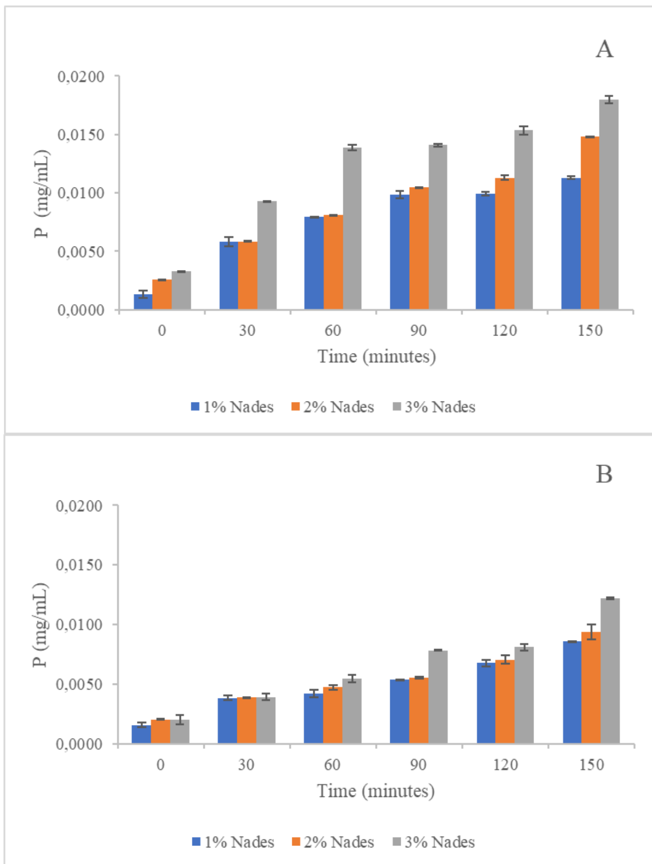


Figure 8. The phycocyanin content in UAE (A) and MAE (B) using NADES-CAF

The higher the concentration of NADES used, the higher the TDS and EC values. The value of TDS and EC in the solvent indicates higher ionization and solvent polarity, which can improve extraction performance and support the phycocyanin extraction process. Therefore, 3% NADES produces the highest phycocyanin concentration in UAE and MAE. The extraction rate value and maximum capacity, as calculated in Table 1, can explain this mechanism's effect.

Table 1. The value of Peleg's model under UAE and MAE with NADES-CAF concentration

Extraction	Concentration NADES (%)	B_0 (mg/mL.min)	C_e (mg/mL)	SSE	RMSE	χ^2	R^2
	1	0.0316	1.4353	0.0047	0.0281	0.0009	0.9989
UAE	2	0.0340	2.4496	0.0307	0.0716	0.0061	0.9945
	3	0.0411	2.7389	0.1570	0.1618	0.0314	0.9866
	1	0.0111	1.5243	0.0243	0.0636	0.0049	0.9966
MAE	2	0.0159	1.7962	0.0304	0.0661	0.0061	0.9852
	3	0.0186	1.9453	0.1222	0.1429	0.0245	0.9771

3.3 The kinetic approach in UAE and MAE of phycocyanin

The changes of P content in the aqueous extract were evaluated using Peleg's model as an empirical kinetic approach. This model describes the extraction rate and maximum capacity in extraction processes, as shown in Table 1.

Using this model, the parameter value extraction rate (B_0) ranged from 0.0316 to 0.0411 mg/mL.min for UAE and from 0.0111 to 0.0186 mg/mL.min for MAE. The application of NADES-CAF in UAE has a positive effect on accelerating the extraction process. The higher the concentration of NADES-CAF used, the higher the extraction rate value. This shows a positive synergy between UAE and NADES-CAF. The role of NADES-CAF in accelerating extraction is also seen in the use of MAE. From the extraction rate value results, the role of NADES-CAF is more effective in accelerating extraction when using UAE compared to MAE, which is supported by the value of UAE, which is greater than MAE.

Meanwhile, the maximum capacity ranges (C_e) from 1.4353 to 2.7389 mg/mL for UAE and from 1.5243 to 1.9453 mg/mL for MAE. Ultrasonic waves cause cavitation in microalgae and accelerate the release of compounds. When ultrasonic waves pass through a liquid medium, the resulting pressure fluctuates. In the low phase, small gas bubbles are formed, and in the high phase, these bubbles collapse. The rupture of these bubbles produces enormous kinetic energy, thus accelerating the collisions between particles, which causes damage to the microalgae structure [32]. The higher concentration of NADES in the solvent also improved maximum capacity. This trend suggests that higher concentrations of NADES enhance the solubilization and release of target compounds, allowing for more efficient extraction. In UAE, elevated NADES concentrations increase the extraction rate, increase the maximum capacity of the solvent, and maintain the stability of the compounds, resulting in better yields.

The MAE demonstrates a broader range of maximum capacity values than the UAE. The concentration of NADES remains crucial for enhancing extraction performance, albeit with a less pronounced impact on its increasing extraction rate compared to the UAE. However, the concentration of NADES significantly affects the maximum capacity. Overall, optimizing NADES concentration is essential for maximizing the effectiveness of both extraction methods, particularly in the UAE, where its advantages are most evident. This phenomenon is also illustrated in Figure 9.

As presented in Table 1, the parameter value is applied to predict the change of P content in the solvent during the extraction. The correlation between the predicted and the observed P content shows a good fit. Peleg's model is used under both UAE and MAE extraction methods. This was indicated by lower SSE, RMSE, and χ^2, as well as higher R^2 [33]. These values indicate that the model accurately predicted the P concentration value during UAE and MAE. This information possibly optimizes the extraction based on the balance of the solvent or solute ratio.

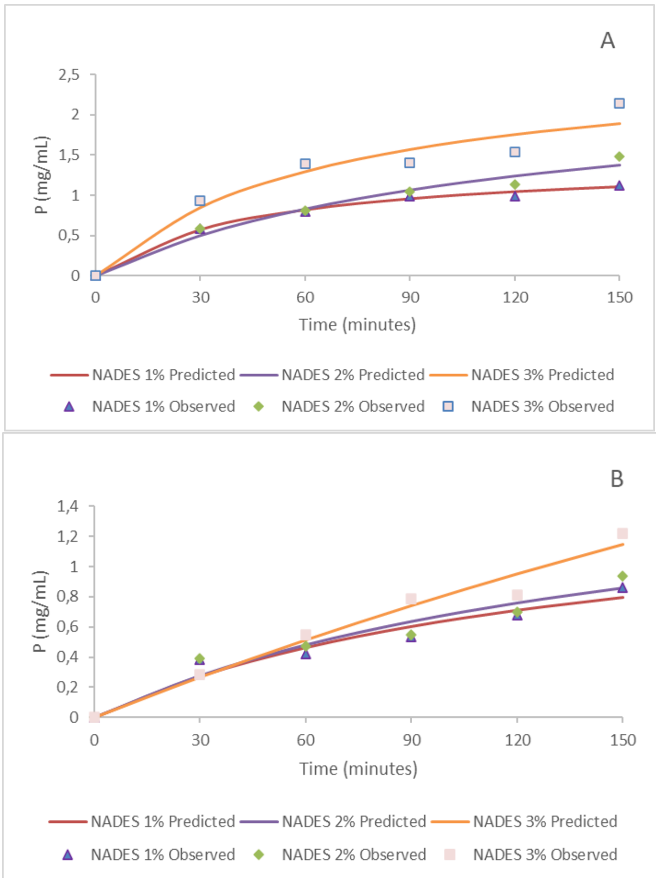


Figure 9. The observed and predicted P content with UAE (A) and MAE (B) applying Peleg's model

The kinetic findings have the potential to be scaled up and implied on an industrial scale. So, the accuracy of the Peleg model in predicting phycocyanin extraction kinetics is required to support several practical benefits and insights for industrial applications, such as optimized process design - the kinetic data obtained from the Peleg model can help maximize extraction conditions for maximum yield; process control and monitoring - the kinetic parameters derived from the model can be integrated into process control systems to maintain consistency during production; predictive capability for scaling - it can predict the behavior of the extraction process under various conditions. This predictive capability allows engineers to design larger-scale reactors and systems with confidence in achieving consistent product quality and yield.

4. CONCLUSIONS

This study successfully characterized NADES-CAF as a solvent in UAE and MAE to extract phycobiliproteins from *Arthrospira platensis*, especially phycocyanin. It demonstrated that NADES-CAF enhances solvent properties such as density, viscosity, electrical conductivity, and total dissolved solids, especially at higher concentrations. UAE exhibited faster extraction rates and achieved higher maximum extraction capacities than MAE. Peleg's model accurately analyzed extraction kinetics, predicting the extraction rate and maximum phycocyanin yield. These results indicate the potential of NADES-CAF as an environmentally friendly green solvent. Further research is expected to explore variations in other NADES compositions or use different raw materials. With this, the extraction method with NADES green solvents is expected to contribute more to sustainable extraction innovation.

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NOMENCLATURE

B	dimensionless heat source length
CP	specific heat, J. kg^{-1}. K^{-1}
g	gravitational acceleration, $m.s^{-2}$
Nu	local Nusselt number along the heat source