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Hydrodynamic study of a reactor for the electrochemical processing of *Hibiscus sabdariffa l.* extracts

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Abstract

Health requirements in recent years have made food products containing preservatives or treated at high temperatures less popular, explaining the new focus on innovative and interdisciplinary technologies. The calyxes of *Hibiscus sabdariffa* L. are rich in antioxidants such as anthocyanins but sensitive to degradation factors such as oxygen. Several technological alternatives have been proposed to reduce its action, such as bubbling with an inert gas or adding preservatives. This work proposes a new electrochemical approach consisting of cold reduction of dissolved oxygen in aqueous extracts of Hibiscus sabdariffa. An electrochemical treatment reactor consisting of an electrolysis cell designed and dimensioned (L=9cm ; l =3.3cm ; e =1cm) in the laboratory. Knowledge of the hydrodynamic parameters is essential for technology transfer on an industrial scale, so these were determined. For a useful volume of 29.7 cm^3 and a flow rate of 0.28 mL/s, the transit time of the Hibiscus extract is approximately 107 s. The flow is laminar, with a Reynolds number of 71.57, hence the need for a turbulence promoter. The reactor is a piston type (Peclet number = 3). A non-significant difference between the electro-reduced extract and the initial extract was observed, confirming that this reduction does not dilute the product and that the Hibiscus extract does not contain a supporting electrolyte. Monitoring of the anthocyanins in the electro-reduced Hibiscus extract under these conditions showed better preservation of anthocyanins compared to heat treatments. Preservation was 35% in the first month of storage at 25°C and 30% after 15 days of storage at 37°C. This new electrochemical approach preserves the original quality of the extract at low temperatures without adding antioxidants, while maintaining the same organoleptic qualities as traditional methods.

Keywords: Anthocyanins; Oxygen; Electrodes; Hibiscus; Stabilization

1. Introduction

The stabilization of anthocyanins, pigments responsible for the red color of *Hibiscus sabdariffa L* calyxes [1], [2], [3], has been a major challenge for juice preservation in recent years. Traditional methods, such as heat treatment and the use of preservatives, have limitations, particularly in terms of nutrient degradation and potential health risks.

Membrane technologies such as nanofiltration and tangential ultrafiltration are certainly alternatives to heat treatment [4] but have limitations with regard to dissolved oxygen. The latter significantly degrades the anthocyanins in Hibiscus extract during storage [5], [6], [7], [8], [9].

Innovative approaches, such as the electrochemical reduction of dissolved oxygen, offer promising alternatives [8].

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Recent advances have led to the introduction of electrochemical techniques to stabilize anthocyanins in hibiscus extracts. By applying a reduction current through a platinum electrode in a two-compartment electrolysis cell separated by a membrane, dissolved oxygen is removed without the addition of chemicals or heat. This method has been shown to significantly preserve anthocyanins during storage, outperforming traditional methods [10].

K NDIAYE and colleagues [8] set up a batch reactor for the electroreduction of Hibiscus extracts. Electroanalysis confirmed the degrading effect of dissolved oxygen, which is the only electroactive element in *Hibiscus sabdariffa L.* extract. An electrochemical treatment intensity/time combination of -6mA/30min with electrodes immersed 4cm in the solution resulted in 10% anthocyanin preservation at 37°C compared to the extract in which the oxygen was not electrically reduced.

In another study, K. NDIAYE et al [10] monitored anthocyanins in roselle extracts that were electrically reduced in a batch reactor and then stored at 4°C and 37°C. The results showed better anthocyanin stability in the first month and sixth month of storage at both 4°C and 37°C. The reduction of dissolved oxygen in the extract resulted in a 10% difference in anthocyanins at 37°C during the first month of storage, unlike the untreated control. At 4°C, a significant constant difference of 5% between the treated extract and the non-electro-reduced extract was noted between the first and sixth months of storage.

Dissolved oxygen has long been removed from solutions using an inert gas [11], [12], [13], [14], [15]. However, for large volumes, the cost can be enormous.

Unlike electrochemical treatments, methods such as nitrogen gas bubbling require prolonged periods (e.g., 2 hours) to achieve comparable results [8]. In addition, enzymatic systems involving oxidases, catalases, and superoxide dismutases have been explored for oxygen removal [16], [17]. However, these solutions often require the introduction of additional substances into the food matrix, which is not always desirable.

This article presents the results of a hydrodynamic study of a continuous treatment reactor for *Hibiscus sabdariffa L* extracts using an electrochemical method. The study determined the residence time, average flow rate, Peclet number, and Reynolds number. The effect of electrochemical treatment was also monitored prior to a possible transfer of technology to an industrial scale.

The electrochemical reduction of dissolved oxygen is an innovative, effective, and chemical-free method for preserving anthocyanins in extracts of *Hibiscus sabdariffa L.* This approach overcomes the limitations of traditional preservation methods and offers potential for wider applications in the food industry.

2. Materials and Methods

2.1. Materials

2.1.1. Plant material

After cleaning, the roselle calyxes were macerated for 3 hours with a calyx/water ratio of 1:5. The extract obtained is the plant material.

2.1.2. Electrochemical equipment

Filter press-type electrochemical reactors are compartmentalized electrolysers. They consist of a stack of membranes and flat electrodes between which the electrolytes circulate. Rapid circulation of the electrolytes (several tens of centimeters per second) ensures good agitation and efficient removal of thermal energy.

A plastic mesh generally prevents contact between the membranes and electrodes while promoting turbulence. This type of reactor was first used in the MONSANTO process [18], [19] (synthesis of adiponitrile: an intermediate in manufacturing).

The electrolysis cell (reactor) is designed and sized in the laboratory. It consists of two compartments separated by a Nafion membrane. The anionic part contains the electrolyte, a 0.1 N hydrochloric acid solution, in which the stainless steel auxiliary electrode is immersed, and the cathodic part contains the *Hibiscus sabdariffa L* extract and the platinum working electrode (Figure 1).

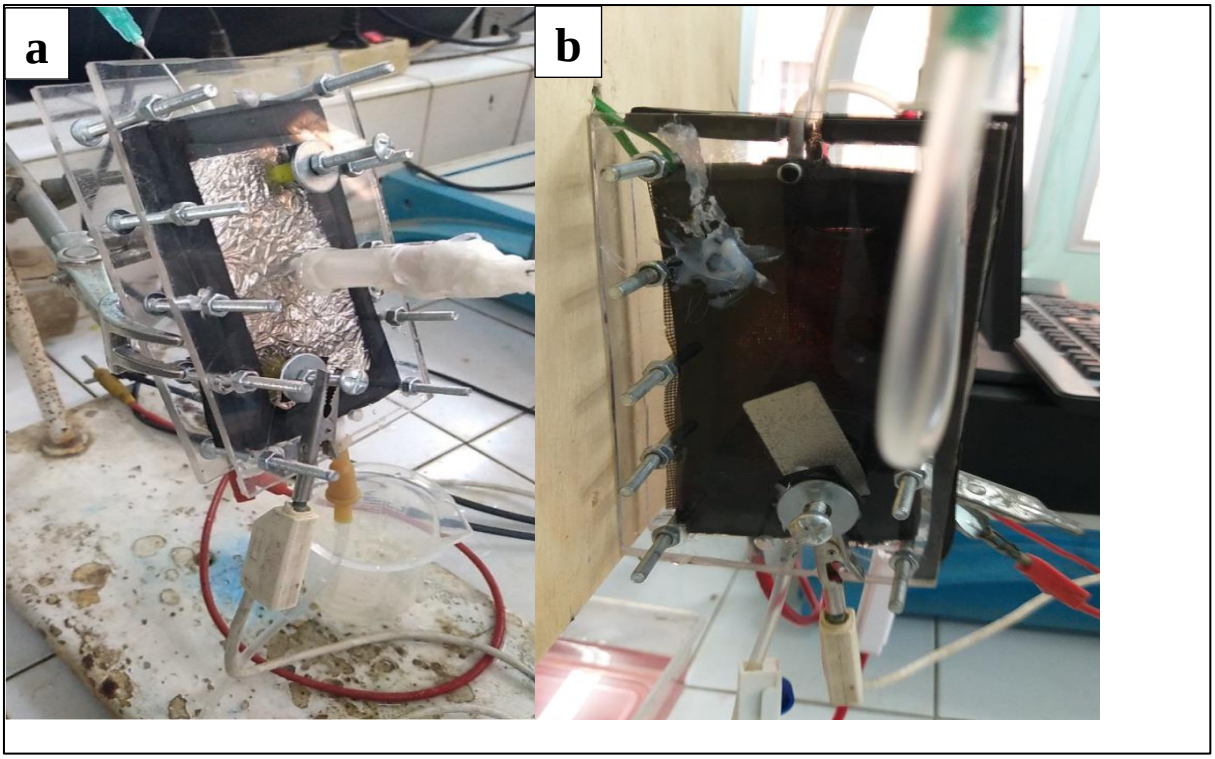


Figure 1 Continuous reactor with two compartments separated by a Nafion-type cationic membrane : a) cathode section with platinum working electrode b) anode section with stainless steel auxiliary electrode

The electrochemical cell designed is inserted into the following device (Figure 2). The roselle extract feeds the cathode, while a hydrochloric acid solution circulates in the anion section. The whole system is connected to a PGZ100 potentiostat linked to a computer equipped with voltammetry software. The processing time and current density (or potential) are determined by cyclic voltammetry.

Figure 2 Experimental setup for the continuous electroreduction of *Hibiscus sabdariffa L* extract

2.2. Methods

2.2.1. Electrochemical methods

Cyclic voltammetry

The electroanalysis of the hibiscus extract was performed by cyclic voltammetry, applying a potential ramp between -500 and 1500 mV with a constant scan rate of 100 $m.s^{-1}$.

Chronoamperometry

The oxygen dissolved in the bissap extract was electrically reduced by imposing the reduction peak potential, obtained by cyclic voltammetry, as a function of time.

Chronopotentiometry

Chronopotentiometry is also a method of reducing the electroactive element. The intensity of the reduction peak was used to reduce the dissolved oxygen as a function of time.

2.2.2. Anthocyanin assay

The assay was performed on extracts of *Hibiscus sabdariffa L.*

The principle is based on the change in color of anthocyanins depending on pH (pH differential method) [20].

After diluting the calyx extract in two buffer solutions at pH = 1 and pH = 4.5, the absorbance is measured at wavelengths of 510 nm and 700 nm, allowing the anthocyanin concentration to be calculated using the following formula:

$Ca=(P\_m*Fd*A*1000)/\varepsilon$ Equation 1

Ca: Anthocyanin concentrations in $mg.L^{1}$

Pm: Molecular weight of anthocyanin; in this case, Ca is expressed in relation to delphinidin sambibioside, which is the main anthocyanin in the calyxes of *Hibiscus sabdariffa* L. Its molecular weight is 597 $g.mol^{-1}$

- Fd: Dilution factor
- ε: Molecular extinction coefficient equal to 26,000 $mol.L^{-1}.cm^{-1}$
- A: Absorbance calculated using the formula:

$$A = (A1 – A2) – (A3 – A4)$$

- A1: Absorbance measured at pH 1 at 510 nm
- A2: Absorbance measured at pH 1 at 700 nm
- A3: Absorbance measured at pH 4.5 at 510 nm
- A4: Absorbance measured at pH 4.5 at 700 nm

3. Results and discussion

3.1. Determination of residence time

The distribution of residence times was determined between the inlet and outlet of the reactor. Figure 3 shows the distribution of residence times obtained for a flow rate of 0.28 $mL.s^{-1}$. This flow rate was obtained by considering the volume and processing time of the batch reactor [8].

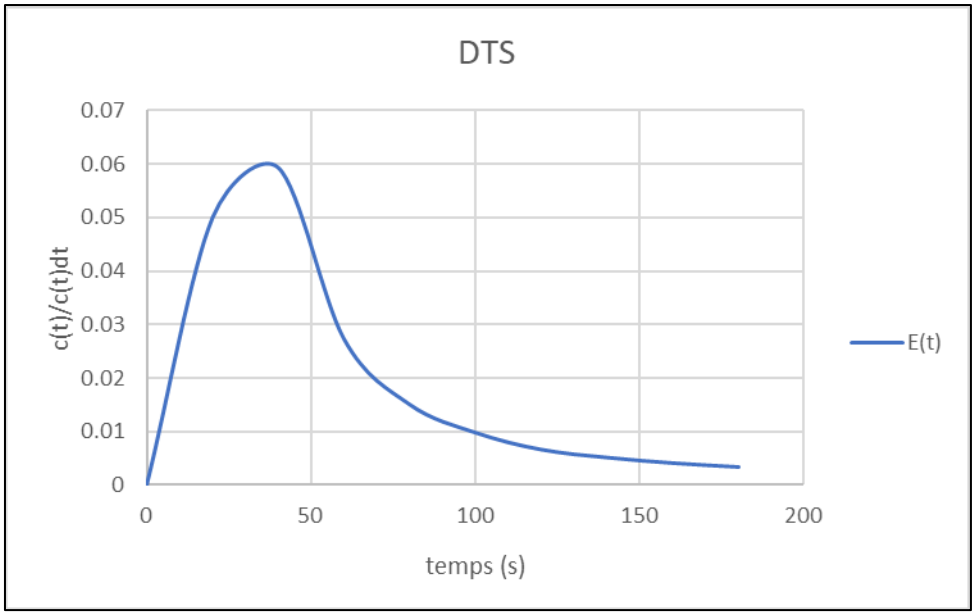


Figure 3 Distribution of dwell times as a function of time [21]

The trace of the tracer fraction that remained in the reactor between t and t+dt as a function of time allows the curve to be compared with the response of a dispersion piston reactor. The average residence time tm in the reactor is 193 seconds, and the transit time, i.e., the ratio of the volume of the solution in the reactor to the flow rate, is 107 seconds.

3.2. Reactor dimensions

The dimensions of the designed electrolysis cell are shown in Table 1 below.

Table 1 Dimensions of the continuous reactor

Dimension	Valeurs	Unités
Longueur	9	cm
Largeur	3.3	cm
Epaisseur	1	cm
Distance inter-électrodes	1	cm
Volume total	59.4	cm^3
Volume utile	29.7	cm^3
Surface spécifique	1	$m^2 \cdot m^{-3}$
Densité du courant	6	$mA.cm^{-2}$

To improve the efficiency of dissolved oxygen reduction or reduce secondary reactions such as solvent oxidation, which increases energy consumption, three parameters are adjusted (current density, specific surface area, and inter-electrode distance). These parameters can significantly influence the efficiency of electroreduction [22] [23].

Similarly, the distance between electrodes crossed by the electric current increases electrical resistance, which can alter current density and cause secondary reactions [22].

To improve the reactor's production capacity, the surface area of the electrodes and, consequently, the volume of the reactor can be increased [24], [25]. However, a very large electrode surface area can lead to uneven current density at the electrodes and may cause secondary reactions.

3.3. Dimensionless numbers (Reynolds and Peclet)

Table 2 below shows the dimensionless values determined during the hydrodynamic study.

Table 2 Reynolds number and Peclet number values

Reynolds	71.57
Peclet	3

We used the Reynolds number to determine whether or not we needed to put a turbulence promoter in the reactor, as we have a fairly low flow rate. The value found clearly shows laminar flow, so a turbulence promoter is needed to allow the dissolved oxygen to migrate from the surface layers to the working electrode.

The Peclet number is needed to determine the type of flow in the reactor. According to the DTS curve, we have a piston-type flow with the presence of a short circuit or preferential path. Perhaps this short circuit could explain the low value of the Peclet number, which tends more towards the flow of a perfectly stirred reactor[26].

3.4. Monitoring of anthocyanins

The electrochemical treatment was carried out in the continuous reactor (Figure 1). The current density and peak reduction potential were determined by cyclic voltammetry. Figure 4 below shows the results of the electroanalysis of the *Hibiscus sabdariffa L*. extract.

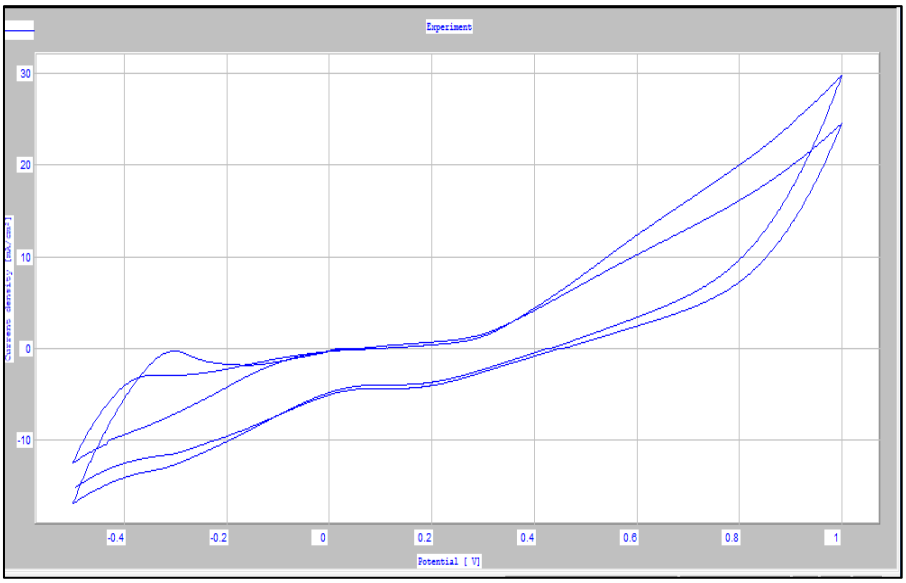


Figure 4 Votammogram of *Hibiscus sabdariffa L* extract

Electroanalysis of the bissap drink confirms the presence of dissolved oxygen at a current density of -6mA.cm^{-2} and a potential of -200mV. This result corroborates those obtained with the batch reactor [8], [10].

Figure 5 below shows the anthocyanin concentration of the electrically reduced extracts and the control, stored at 4°C, 25°C, and 37°C as a function of time. The flow rate is 0.28 mL.s^{-1}.

Chronopotentiometry, which consists of performing electrochemical treatment by fixing the current intensity, corresponds to the sample (-13mA).

Chronoamperometry was used to perform the electroreduction with a potential of -200mV corresponding to the sample (-200mV).

The control is the untreated *Hibiscus sabdariffa* extract, stored under the same conditions as the samples.

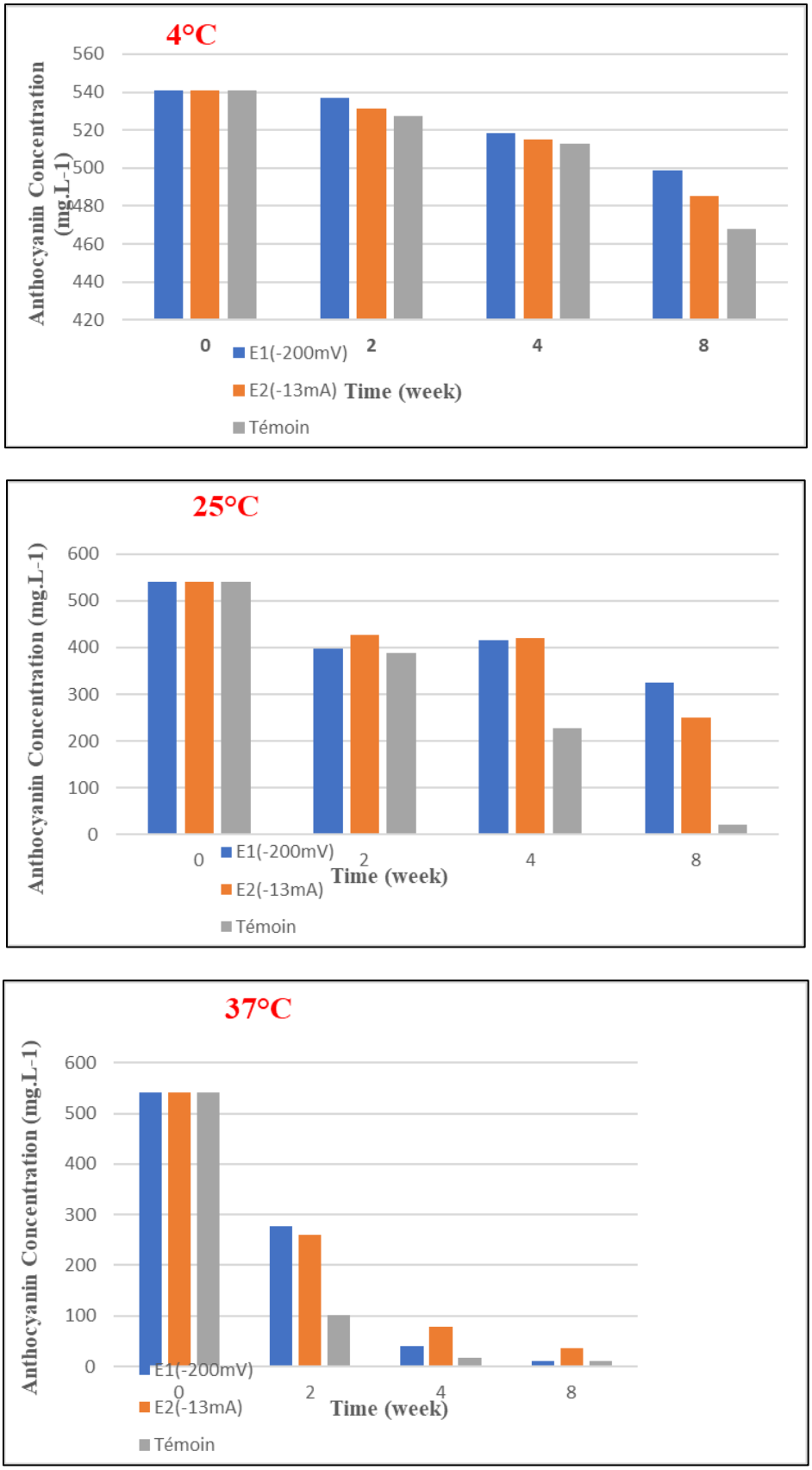


Figure 5 Concentrations of electro-reduced *Hibiscus sabdariffa L* extracts stored at 4°C, 25°C, and 37°C as a function of storage time

The monitoring of *Hibiscus sabdariffa* extracts, treated electrochemically (samples) and untreated (control) in a continuous reactor, after 2 months of storage at 4°C, 25°C, and 37°C (Figure 5) show the positive effect of dissolved oxygen reduction on the anthocyanins of *Hibiscus sabdariffa L.*

The predominance of temperature over other factors in anthocyanin degradation was also observed at 37°C.

The reduction of dissolved oxygen in *Hibiscus sbdariffa L.* extracts stored at 25°C shows a significant difference between the sample (18% loss) and the control (36% loss) from the second week of storage. This represents an 18% greater loss for the control compared to the sample whose oxygen was electrically reduced.

In the fourth week of storage at 25°C, there was a 27% loss for the sample and a 58% loss for the control. This represents a significant difference of 36% loss in anthocyanin between the electrically reduced extract and the control.

Similarly, in the eighth week, a 36% loss in anthocyanin was noted for the sample, compared to a 98% loss for the control.

Electrochemical treatment of bissap extracts stored at 37°C also revealed the degrading effect of dissolved oxygen on the anthocyanins in *Hibiscus sabdariffa L.*

In fact, by the second week of storage, the sample had lost 50% of its anthocyanins, while the control sample had lost nearly 84%.

After one month of storage, the sample recorded an 86% loss, while the control sample lost 97% of its anthocyanins. Nevertheless, the differences are significant.

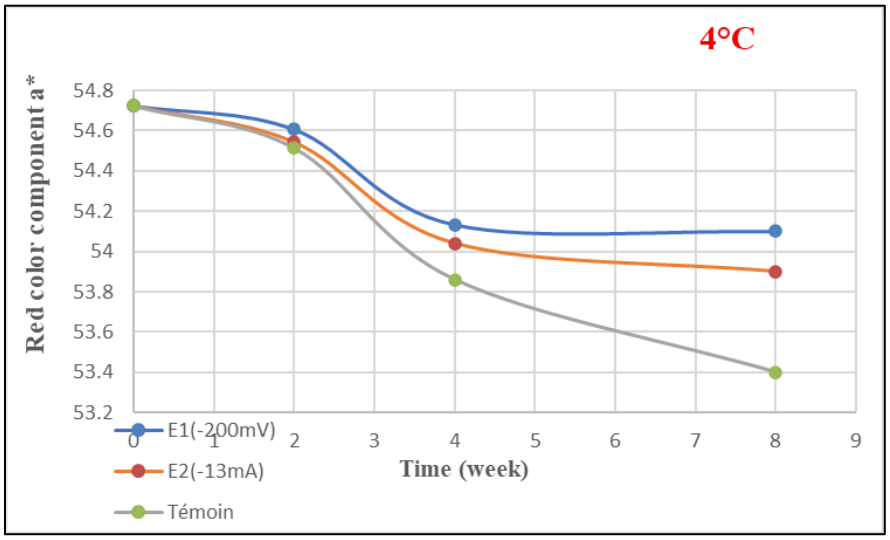
After two months of storage, a 95% loss was noted for both the sample and the control sample: temperature predominates over the oxygen factor.

However, at 4°C, losses were less than 1% in two weeks, approximately 2% in the first month, and 7% in the second month of storage. This result could be explained by the fact that the effect of dissolved oxygen on the anthocyanins in *Hibiscus sabdariffa* is catalyzed by a certain temperature [9].

Reducing the dissolved oxygen in *Hibiscus sabdariffa L* extracts (samples) significantly reduces anthocyanin losses, especially at room temperature (25°C), confirming the results obtained with the batch reactor [10], [27].

3.5. Color monitoring

The color of anthocyanins was also monitored over time. The a*, b*, and L* coordinates were measured using the CIElab system [28] [29] with a CR-5 colorimeter. Curves A, B, and C in Figure 6 below show the evolution of the red color, represented by the red/green component a*, over time.



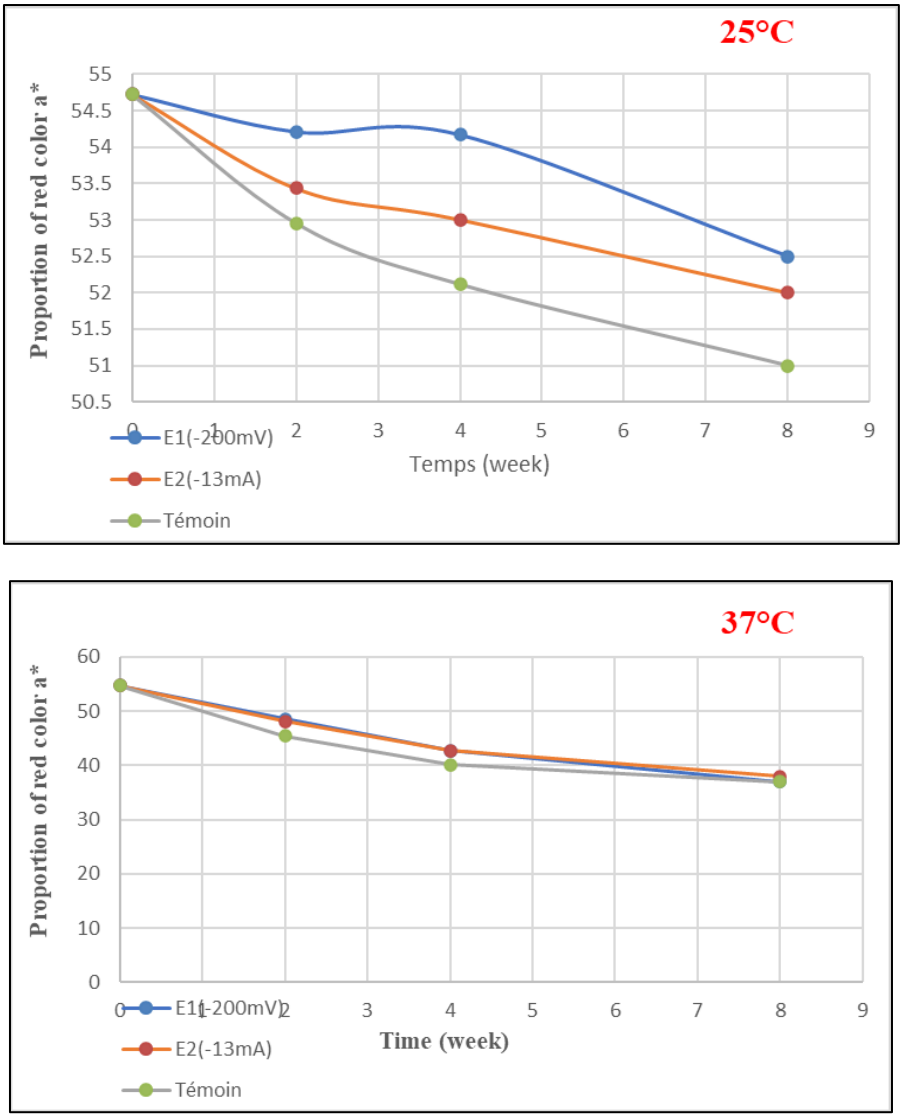


Figure 6 Monitoring of the red/green color component of electrically reduced extracts (Samples) and untreated extracts (Control) over time at 4°C, 25°C, and 37°C.

The results for color corroborate those for anthocyanins.

At 4°C, 25°C, and 37°C, the red color of the electrically reduced samples was more intense than that of the control sample during the first four weeks of storage.

Similarly, after two months of storage at 4°C and 25°C, significant differences were noted between the sample and the control.

We have a* = 54 for the sample and a* = 53 for the control at 4°C at one month and two months.

At 25°C, a* = 54 for the sample and a* = 52 for the control at one month, and at two months, a* = 52 for the sample and a* = 17 for the control.

Xu et al [30] showed that the aqueous polyphenol content was stable under low pH conditions. Variations in pH influence the stability of polyphenols by changing their chemical structure, including a variation in color [31].

Polyphenols in fruits and vegetables are more stable when the pH value is low. Their stability also depends on the technology used, ions [32], and oxygen [8].

Furthermore, these results also demonstrate the effectiveness of the method (chronoamperometry) imposing the potential of the electroactive element compared to chronopotentiometry (reduction peak intensity) (Figures 5 and 6).

3.6. Concentration and color of anthocyanins immediately after electrochemical treatment as a function of flow rates

The effect of flow rate on treatment was characterized by varying it on different extracts of *Hibiscus sabdariffa*. The minimum flow rate is Qmin = 0.03 mL.s^{-1}; the maximum flow rate is Qmax = 3.17 mL.s^{-1} and the intermediate flow rate is Q = 0.28 mL.s^{-1}.

Q is the flow rate characterized with the batch reactor [8]. Qmax and Qmin bound Q ; they were determined with the continuous reactor.

Table 3 below shows the concentration and color of anthocyanins immediately after electroreduction by varying the flow rate. The electrochemical treatment was performed with a potential of –200 mV.

Table 3 Concentration and red color (a*) of anthocyanins as a function of flow rates immediately after electroreduction with a potential of -200 mV

	Concentration (mg/L)	**Color (a*)**
Initial	359.39^{a}	61.09^{a}
Q	362.99^{a}	61.17^{b}
Qmax	360.65^{a}	61.15^{ab}
Qmin	354.45^{a}	60.19^{c}

Immediately after electrochemical treatment, the electrically reduced extracts with a flow rate of 0.03 mL.s^{-1} displayed a red color (a*) that differed significantly from the initial sample and the other extracts treated with flow rates Q = 0.28 mL.s^{-1} and Qmax = 3.17 mL.s^{-1}.

The flow rates Q and Qmax did not show any significant difference from the initial extract.

However, the anthocyanin concentration did not show any significant difference between the initial extract and the electro-reduced extracts depending on the flow rates. This could be explained by the fact that anthocyanins have a wide range of colors, including red, yellow, purple, etc., whereas the a* parameter only characterizes the red coordinate.

The difference noted between the initial compound and the product treated with a minimum flow rate of 0.03 mL.s^{-1}, where the extract remains in the reactor for a long time, could be explained by the fact that, in addition to reducing all dissolved oxygen, the treatment also degrades anthocyanins.

Table 4 below shows the red (a*), yellow (b*), luminescence L*, and yellowness YI parameters of Hibiscus extracts treated at different flow rates and the initial non-electro-reduced extract.

Table 4 CIELab color parameters immediately after electrochemical treatment of bissap extracts as a function of flow rates

	L*	a*	b*	YI
Initial	25.76^{a}	61.09^{b}	44.31^{c}	99.86^{d}
Qmin	25.14$^{a'}$	60.19$^{b'}$	43.28$^{c'}$	99.89^{d}
Q	25.99^{a}	61.17^{b}	44.69^{c}	99.84^{d}
Qmax	25.92^{a}	61.15^{b}	44.57^{c}	99.83^{d}

A significant difference was noted only between the extract reduced with a flow rate of Qmin = 0.03 mL.s^{-1} and the other extracts (initial, Q, and Qmax).

The initial extract is more luminescent, redder, and retains its yellow color better than the extract in which the dissolved oxygen was reduced at the Qmin flow rate. This means that the product should not remain in the reactor for too long because once all the dissolved oxygen has been reduced, the treatment appears to degrade other elements.

This result is understandable since the treatment flow rate has already been optimized with the batch reactor (Q = 0.28 $mL.s^{-1}$), but it was necessary to see the treatment with a lower flow rate and a higher flow rate with the continuous reactor.

3.7. Monitoring anthocyanin concentration and pH as a function of flow rate

3.7.1. Monitoring anthocyanin concentration as a function of flow rate

Electrochemical treatment with the continuous reactor was carried out at different flow rates. In our treatment device, the maximum flow rate is 3.17 $mL.s^{-1}$, the average flow rate is 0.28 $mL.s^{-1}$, and the minimum flow rate is 0.03 $mL.s^{-1}$.

The reduction of dissolved oxygen in the Hibiscus extract was carried out according to these flow rates. The Hibiscus samples, electrically reduced with a potential of -200 mV and an intensity of -13 mA, and the control (untreated extract) were stored at 25°C for four weeks. The anthocyanin concentration of the samples and the control after one month of storage at 25°C is shown in Figure 7 below.

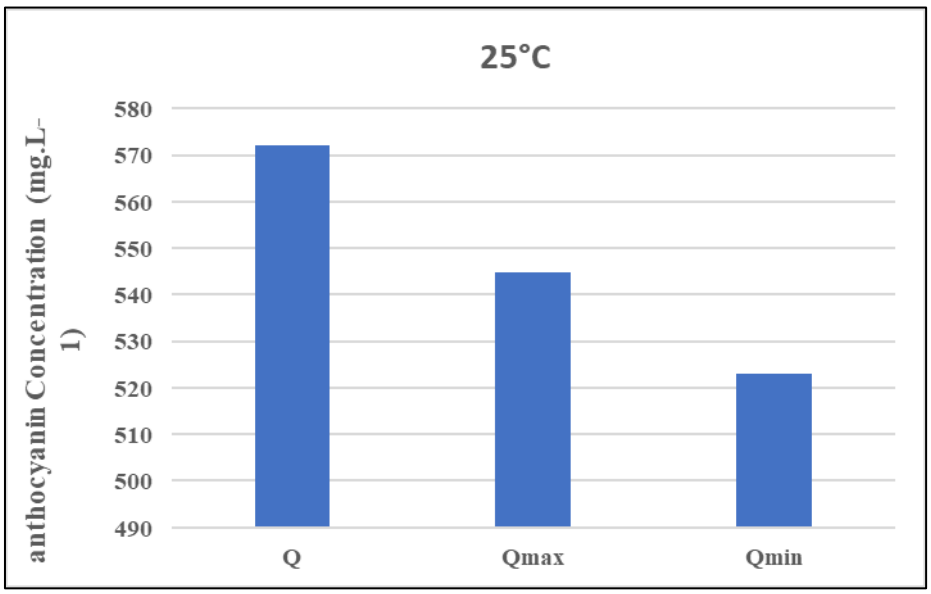


Figure 7 Monitoring of anthocyanins in *Hibiscus sabdariffa L* extract as a function of flow rate after one month of storage at 25°C

The results in Figure 7 show the impact of flow rate on the continuous electrochemical treatment of Hibiscus extract. After one month of storage at 25°C, the anthocyanin concentration in the extract treated at a flow rate of 0.03 $mL.s^{-1}$ is 523.02 $mL.s^{-1}$, and in the extract treated at a flow rate of 3. 17 $mL.s^{-1}$ is 544.72 $mL.s^{-1}$, while the extract electro-reduced at a flow rate of 0.28 $mL.s^{-1}$ is 572.2 $mL.s^{-1}$. The results show that an incorrect treatment flow rate can lead to considerable anthocyanin losses during storage.

3.7.2. Monitoring pH based on flow rate

The pH of the electrically reduced extracts based on flow rates Q, Qmin, and Qmax was measured and recorded in Table 5 below.

Table 5 Characterization of the pH of electrically reduced Hibiscus extracts based on flow rate after 4 weeks of storage at 25°C

Flow rate	pH
Q	3.02
Qmax	3.04
Qmin	3.10

The results of pH monitoring based on treatment flow rate confirm those obtained with anthocyanins: pH increases with flow rate Qmin = 0.03 $mL.s^{-1}$. This means that when the product remains in the reactor for a long time, other reactions occur.

Polyphenols are stable if the pH value is low. pH influences the degradation of flavonoids [30], [33].

3.8. Verification of the effect of electrochemical treatment

3.8.1. Verification of the supporting electrolyte

In order to verify the electrical conductivity in the electrolysis cell, a single-compartment electrolysis cell and a two-compartment cell separated by a Nafion-type cationic membrane were used.

In the single-compartment cell containing *Hibiscus sabdariffa L* extract (Sample 1), the three electrodes (platinum working electrode, saturated calomel reference electrode, and stainless steel auxiliary electrode) were immersed.

In the two-compartment cell, the cathode contained the Hibiscus extract (Sample 2) and the anode contained a 0.1N hydrochloric acid solution (the electrolyte).

The *Hibiscus sabdariffa L* extracts were treated by chronopotentiometry with a potential/time pair of -250 mV/30 min.

The experimental results of the electroreduction of bissap extracts (single-compartment cell and two-compartment cell) are shown in the following figures.

Figures 8 and 9 show the anthocyanin concentrations of two bissap extracts electrolysed in different cells: single-compartment cell (Sample 1) and double-compartment cell (Sample 2).

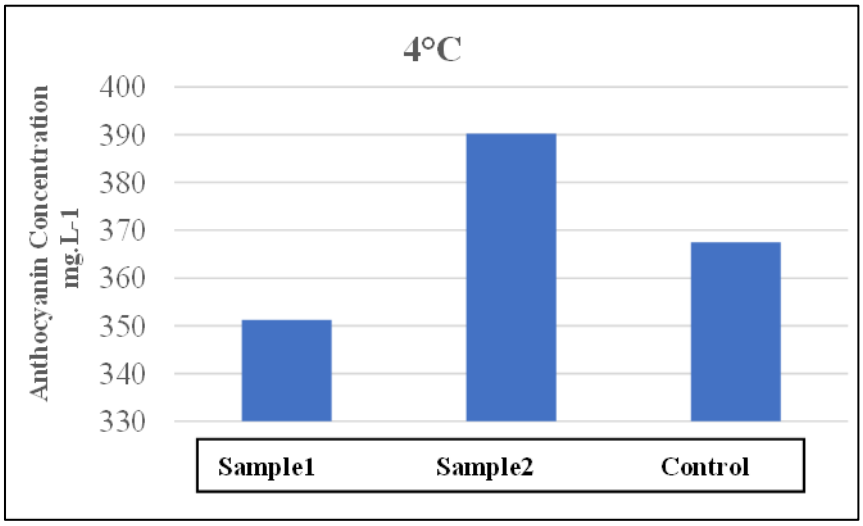


Figure 8 Anthocyanin concentration in electrically reduced hibiscus juice in a single-compartment cell (Sample 1), a double-compartment cell (Sample 2), and the untreated control stored for 4 weeks at 4°C.

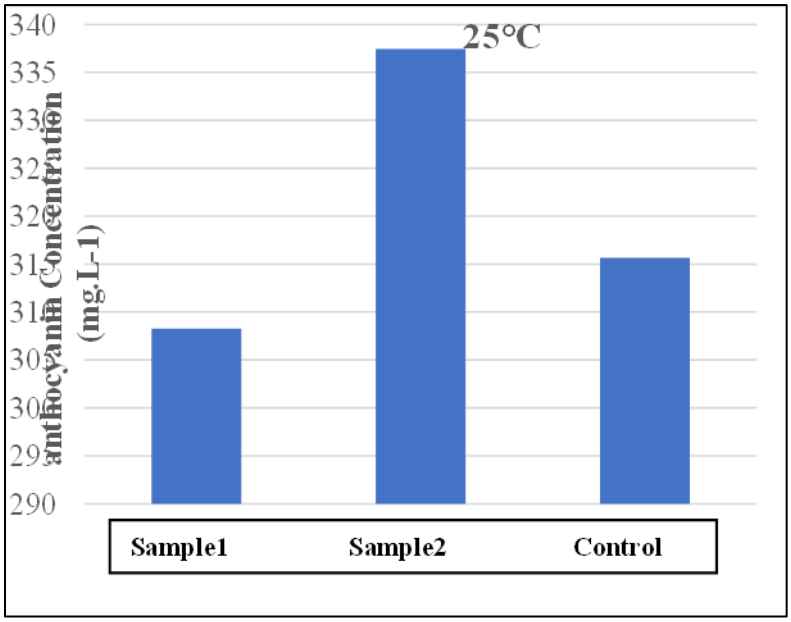


Figure 9 Anthocyanin concentration of electroreduced Hibiscus juice in a single-compartment cell (Sample 1), a two-compartment cell (Sample 2), and the untreated control stored for 4 weeks at 25°C

After 4 weeks of storage at 4°C, the anthocyanin concentration of the electroreduced Hibiscus extract (Sample 1) in a single cell is significantly lower (351.23 $mg.L^{-1}$) than the anthocyanin concentration of Sample 2 (390.7 $mg.L^{-1}$) treated in the cathode portion of the two-compartment cell; in the anodic portion, the hydrochloric acid solution is the electrolyte. The anthocyanin concentration of the control stored under the same conditions (367.5 $mg.L^{-1}$) is significantly different from the samples. Similarly at 25°C, anthocyanins degrade considerably for sample 1 (308.26 $mg.L^{-1}$) compared to sample 2 (334.82 $mg.L^{-1}$) and the control (315.64 $mg.L^{-1}$) during the 4 weeks of storage.

The HCl support electrolyte in the anode portion of the two-compartment cell, separated by a cationic membrane and in which the counter electrode is placed, promotes good electrical current conductivity compared to sample 1, which is treated in a single-compartment cell; the current conductivity is low, resulting in a slight reduction in dissolved oxygen.

These results are corroborated by those for color, obtained using a colorimeter (Konica Minolta CR-5). Tables 6 and 7 below present the color results at both 4°C and 25°C.

Table 6 Monitoring of color ratios a* (Red/Green), b* (Yellow/Blue) and L* (Luminescence) of *Hibiscus sabdariffa* extract after 4 weeks of storage at 4°C

4°C	Sample1	Sample2	Control
L*	17.66	18.88	17.41
a*	53.43	54.87	53.11
b*	29.16	31.28	28.82

Table 7 Monitoring of color ratios a* (Red/Green), b* (Yellow/Blue) and L* (Luminescence) of *Hibiscus sabdariffa* extract after 4 weeks of storage at 25°C

25°C	Sample1	Sample2	Control
L*	15.46	16.7	15.68
a*	50.3	51.64	50.61
b*	25.35	27.47	25.75

Tables 6 and 7 present the color measurements of the electroreduced juice in a single cell (Sample 1) and of the electroreduced bissap juice in the cathode part of a two-compartment cell after one month of storage at 4°C.

The results corroborate those obtained by monitoring the anthocyanin concentration for the same storage period at the same temperatures (Figures 8 and 9).

3.8.2. Verification of the effect of the electrochemical treatment

3.8.2.1. On anthocyanins

Monitoring the anthocyanins immediately after electrochemical reduction showed that the treatment did not degrade the anthocyanins. The experiment was carried out in a cell (L=19cm; W=10cm; H=11cm) with a potential/time torque of -350mV/30mn on the one hand and in a small cell (L=8cm; W=7; H=8.5) with a torque of -250mV/15mn on the other hand.

The experimental results are presented in Tables 8 and 9 below.

Table 8 Concentration and red color of anthocyanins before and immediately after electroreduction with a potential of -350 mV for 30 minutes

	Anthocyanin Concentration ($mg.L^{-1}$)	Red/Green color ratio (a*)
Initial	323.99^{a}	$56.6^{a'}$
Immediately after treatment	317.79^{a}	$56.5^{a'}$

The results in Table 8 show non-significant differences between the initial anthocyanin concentrations and those immediately after electroreduction.

Table 9 presents the anthocyanin concentration and color, characterized immediately after electrochemical treatment with a potential of -250 mV for 15 minutes.

Table 9 Anthocyanin concentration and red color before and immediately after electroreduction with a potential of -250 mV for 15 minutes.

	Anthocyanin Concentration ($mg.L^{-1}$)	**Red/Green color ratio (a*)**
Initial	413.3^{a}	$51.1^{a'}$
Immediately after treatment	405.96^{a}	$50.9^{a'}$

The results in Table 9 show non-significant differences between the initial anthocyanin concentrations and those immediately after electroreduction.

Table 10 presents the anthocyanin concentration and color, characterized immediately after electrochemical treatment with a potential of -250 mV for 15 minutes.

Table 10 Anthocyanin concentration and red color before and immediately after electroreduction with a potential of -250 mV for 15 minutes.

	Concentration des anthocyanin ($mg.L^{-1}$)	**Red/Green color ratio (a*)**
Initial	$413,3^{a}$	$51,1^{a'}$
Immediately after treatment	$405,96^{a}$	$50,9^{a'}$

A repeated experiment using a different-sized cell and a different potential/time ratio (-250 mV/15 min) also showed (Table 9) non-significant differences between the initial and electroreduced extracts.

These results confirm experimentally that the electrochemical reduction of dissolved oxygen in the roselle extract does not dilute the product.

3.8.2.2. Minerals

Mineral concentrations were determined by ion chromatography.

The analyses were conducted on *Hibiscus sabdariffa L.* extracts before and after electrochemical treatment.

The following table 11 presents the results of the mineral characterization of the extract before and after electrochemical treatment.

Table 11 Mineral characterization of the electroreduced (samples) and untreated (control) *Hibiscus sabdariffa L*. extract.

Concentration of minerals (mg.L^{-1})	**Ca^{2+}**	**Mg^{2+}**	**Fe^{2+}**	**Cu^{2+}**	**Zn^{2+}**	**P^{+}**	**Na^{+}**	**K^{+}**
Echantillon1	8.44	3.31	0.32	1.22	0.51	67.8	13.05	5.11
Echantillon2	8.19	3.12	0.41	1.16	0.56	68.1	12.76	5.17
Témoin	9.17	3.85	0.36	1.35	0.76	67.3	11.34	5.03

The analysis results generally show slight differences between the samples and the control.

These differences may be due, on the one hand, to metal migration on the electrode.

On the other hand, biosorption could explain some of the losses noted in the control hibiscus extract (P, Na, K).

4. Conclusion

The aim of this article was to determine the hydrodynamic parameters of a continuous processing reactor for *Hibiscus sabdariffa* L. extracts using an electrochemical approach.

The study determined a flow rate of 0.28 mL.s^{-1} and a flow time of 193 seconds in a laminar flow piston-type reactor (Reynolds number 71) measuring 9 cm x 3.3 cm with a working volume of 29.7 cm3.

The study demonstrated the stability of anthocyanins in electroreduced *Hibiscus sabdariffa L.* extracts. Indeed, the anthocyanin concentration in the oxygen-reduced sample was 498.69 mg.L^{-1}, compared to 467.9 mg.L^{-1} for the control at 4°C after 2 months of storage. At 25°C, the electrochemically treated extract had a concentration of 419.17 mg.L^{-1}compared to 226.55 mg.L^{-1} for the untreated extract after 4 weeks of storage. At 37°C; a concentration of 276.86 mg.L^{-1} was noted for the electroreduced roselle extract while the control had 101.91 mg.L^{-1} for a storage period of 2 weeks.

These results on anthocyanin concentration are corroborated by the color parameters.

The study results also demonstrated the need for a membrane separating the electrolyte from the extract to be treated.

Experimental results on the electrochemical treatment of aqueous hibiscus extract showed that reducing dissolved oxygen on a platinum electrode could help stabilize the juice without denaturing the product, while preserving its nutritional and organoleptic qualities.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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