Kinetic and Thermodynamic Studies of Extraction Process for Soluble Sugars and Juice Yield from Sweet Sorghum

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Abstract

In this study, the kinetic and thermodynamics study of solid-liquid extraction of sweet sorghum juice was carried out. Five kinetic models namely Patricelli, Peleg, log, power and Page's models were tested in order to determine the one that best fits the recovery of soluble solids (RSS) and the juice yield data obtained at 35–65 °C and 0–100 minutes. The assessment of the performance of the models was achieved from statistical data such as R^2*, adjusted* R^2*, root mean square error (RMSE), and percentage average absolute relative deviation (AARD) obtained by comparing the experimental data with the predicted date. The thermodynamic parameters determined were activation energy (*E_a*), enthalpy change (*ΔH*), entropy change (*ΔS*), and free energy change (*ΔG*). The results showed that the RSS and juice yield increased with an increase in the temperature with the highest values achieved at 65 °C. The extraction process was the fastest at the beginning until after 10 minutes when the effect of time became insignificant. Also, Patricelli's model had the best performance while Page's model had the worst performance. Finally, the extraction processes were endothermic (positive enthalpy change), reversible (negative entropy change), and not spontaneous but endergonic (positive free energy change). The determination of these kinetic and thermodynamic parameters will help in understanding the extraction mechanisms, scaling up and designing the extraction process, and improving energy efficiency.*

Keywords: *Sweet sorghum juice, Recovery of soluble solids, Extraction yield, Kinetic parameters, Thermodynamic parameters*

1. Introduction

Sweet sorghum (*Sorghum bicolor* (L.) Moench), one of the three classes of sorghum (the other two being grain and forage sorghum), is a sugar crop. It is often referred to as a smart and resilient crop with wide adaptation during cultivation as it has an exceptional resistance to adverse climatic conditions

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in contrast to most other crops [1]. The most desirable parts of sweet sorghum are the grains and the stalks. The grains of a mature sweet sorghum are composed mainly of starch and the stalks contain 72 – 73% moisture, 13 – 23% non-structural carbohydrates (i.e., soluble sugars) in the juice, with the remainder constituting the structural carbohydrates (i.e., lignocelluloses) that make up the bagasse. The fermentable or soluble sugar component of the juice contains 53 – 85% sucrose, 9 – 33% glucose, and 6 – 21% fructose [2]. The soluble sugars are converted mainly into ethanol, sugar syrups fodder, and jaggery. However, the crystallization of sucrose from sweet sorghum juice to produce crystal sugars, as it is done with sugarcane juice, has not been as successful and economical. This is due to relatively higher proportions of reducing sugars (glucose and fructose) in the sweet sorghum juice than in the sugarcane juice which inhibits the crystallization process [3].

The traditional method of using roller mills to extract sweet sorghum juice is characterized by the low yield of fermentable sugars as well as high labour and energy costs. Nowadays, the solid-liquid extraction method is being used as an alternative extraction because of its high efficiency and mild operating conditions. Many solid-liquid extraction methods have been investigated, especially aided solid-liquid extraction. They include unaided solvent extraction, microwave-assisted extraction, ultrasound-assisted (or sonification) extraction, accelerated solvent extraction, supercritical fluid extraction, pressurized liquid extraction, and electric field-assisted extraction [4]. Among these, unaided solvent extraction - especially using water as an extraction solvent - is still the cheapest method in terms of energy consumption [5].

Generally, energy, time, and materials consumption in solid-liquid extraction processes can be properly managed during the process design, which is achieved through mathematical modelling. One of the most vital models in solid-liquid extraction is kinetic modelling. Several insights into the solid-liquid extraction processes are provided by kinetic modelling. For instance, it provides a comprehensive understanding of the complex diffusion, mass transfer and thermodynamic parameters affecting the extraction. It also identifies the key operating conditions and helps in the scaling up of the extraction processes for industrial applications [6, 7]. Finally, kinetic studies provide insights into the rate of extraction, which serves as a tool for improving the entire process [8].

So far, the solid-liquid extraction studies of sweet sorghum juice are few and they have been mostly concentrated on the different types of extraction methods and optimization of process parameters [2, 9 – 11]. In contrast, kinetic and thermodynamic studies of vital bioactive compounds and oil extracts from plant oils have been extensively reported. Some of the recent studies in this regard include Hobbi [5], Tusek [6], Motlagh *et al*. [8], Mustapa *et al*. [12], Stamenkovic *et al*. [13], Singh *et al*. [14], Agu *et al*. [15], and Aishi [16]. For instance, Hobbi [5] carried out a kinetic study for the solid-liquid extraction of polyphenolic compounds (TPC) from apple pomace using first and second-order kinetic models. They found the second-order kinetic model to be sufficient to describe the extraction mechanism of TPC from apple pomace. Tusek [6] studied the kinetics and thermodynamics of the solid-liquid extraction of total polyphenols, antioxidants and extraction yield from *Asteraceae* plants. The highest extraction efficiency in terms of these parameters was achieved at the highest extraction temperature of 80 °C. In the work of Bhattacharjee [7], physicochemical analysis in addition to kinetic and thermodynamic studies was carried out for the thermal degradation of orange bagasse. Three different kinetic models such as Kissinger–Akahira–Sunose, Ozawa–Flynn–Wall, and Coats-Redfern were used to correlate their experimental data. Finally, Motlagh {8] studied the kinetics and thermodynamics of a process involving microwave-assisted extraction of lipids from *N. oceanica* microalgae using ionic liquids and transesterification of the extracted lipid to eicosapentaenoic acid. The experimental data were fitted to first-order, second-order, and Patricelli's kinetic models. Based on the obtained thermodynamic parameters, they found the process to be endothermic in nature, irreversible and spontaneous.

This paper deals with the determination of the best-suited kinetic model for the description of the solid-liquid extraction process for the recovery of soluble solids and extraction yield from sweet sorghum. Five established kinetic models were tested using water extraction methods at different extraction temperatures and times, and the best kinetic model was used for the determination of thermodynamic parameters.

2. Materials and Methods

2.1. Materials

The plant used in this study (fresh sweet sorghum) was obtained from the National Sugar Development Council at Ahmadu Bello University Zaria, Nigeria. The grains were removed and discarded while the stalks were sorted, stripped and rinsed to eliminate any residual matter and impurities before they were properly stored in a freezer at -15 °C until use. Distilled water was used as the extraction solvent. An analytical balance (Model No.: BA-E2204) with a precision of 0.1 mg was used for measuring the weight of the samples while a water bath was employed as the medium for the juice extraction process of the sweet sorghum juice. A centrifuge (Model No.: CFG-15D) was used to remove fine particles from the juice. The total soluble solids (TSS) from which the RSS was calculated were quantified using an Abbe Refractometer (Model No: RFT-A2S). The analytical balance, centrifuge, and refractometer were all manufactured by Bioevopeak, China. The agitation of the extraction process was provided by using a magnetic stirrer and incubator shaker (Model No.: LH-103D) manufactured by LABOAO, China.

2.2. Methods

2.2.1. Sample preparation

The stored stalks were taken out and subjected to thawing at ambient temperature (25 °C) prior to their utilization, and the rinds were meticulously removed by hand before being subsequently rinsed with tap water to eliminate any residual matter and impurities. The washed stalks were then hand-peeled and sliced utilizing an Andrew James food slicer (Model No.: AJ000339) and were immediately triturated in a blender (Model No.: BLG-570/595) until a homogeneous pulp was achieved [17].

2.2.2. Extraction procedure

The choice of the extraction process parameters for this study was informed by our previous work where the determination of optimum total soluble solids in sweet sorghum juice extraction was carried out [18]. Based on the results obtained, extraction temperatures of 35, 45, 55, and 65 °C, extraction times of 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 min., and a fixed solid-to-liquid ratio of 0.5 g/ml were selected for this kinetic and thermodynamic study. In each run, 10 g of the prepared sweet sorghum pulp was measured using a weighing balance and transferred into a 100 mL Erlenmeyer flask. Then, an appropriate volume of distilled water (20 ml) that ensured the solid-to-liquid ratio of 0.5 g/ml was added into the flask, which was subsequently immersed in a water bath to facilitate the extraction process at an appropriate temperature and time. After the completion of the extraction process, the slurry was filtered with the help of cheesecloth to remove large particulates and insoluble materials. The filtrate – that is the crude juice – was then subjected to centrifugation to separate finer particles utilizing a centrifuge at 10,000 rpm for a duration of 20 minutes. Thereafter, the supernatant was decanted, and the weights of both the supernatant and the remaining cake were recorded. The total soluble solids were quantified employing the Abbe Refractometer by placing a drop(s) of the extracted sweet sorghum juice onto the prism of the refractometer. The prism lid was subsequently closed, and then the adjustable hand wheel was adjusted to ensure accurate focus before the TSS value was read and recorded in degree Brix with the help of the reading display button. All the measurements were carried out in triplicates (n = 3) and the mean was calculated.

2.2.3. Recovery of soluble solids (RSS) and juice yield determination

First, the weight of the extracted juice was calculated by adopting the method of Abdullah and Chin [19] presented in Equation (1).

$$w_E = Weight\ of\ supernatant\ (g) - Weight\ of\ distilled\ water\ (g) \tag{1}$$

where w_E denotes the weight (g) of the extracted juice.

The RSS (ºBrix) of the extracted juice was calculated from the measured TSS using Equation (2).

$$RSS = \frac{w_E \times TSS}{w_S} \tag{2}$$

where w_S denotes the weight (g) of the initial sweet sorghum pulp.

Finally, the juice yield (%) was determined using Equation (3).

$$Juice\ Yield\ (\%) = \frac{w_E}{w_S} \times 100 \tag{3}$$

2.2.4. Kinetic study

Five kinetic models, namely Patricelli's, Peleg's, Log's, Power's and Page's models were tested for the RSS and juice yield in the extraction process of sweet sorghum juice.

In Patricelli's model, it is assumed that the extraction process consists of two steps namely washing and diffusion steps. The washing step is the first phase of extraction during which a fast dissolution of the solutes (in this case, soluble solids in the sweet sorghum) from the surface of the solid matrix to the solvent occurs. In this phase, the extraction system at elevated temperature promotes the penetration of the solvent into the ruptured wall cells of the solid matrix. The diffusion step, a much slower step than the first step, is the second phase of extraction during which there is a movement of solutes from the interior of the solid matrix to the bulk solvent [12]. Patricelli's model is expressed in Equation (4).

$$C(t) = C_1[1 - exp(-k_1 t)] + C_2[1 - exp(-k_2 t)] \tag{4}$$

$C(t)$ is the concentration (in this case, RSS/juice yield) as a function of time (t), C_1 and C_2 are the equilibrium RSS/juice yield at the washing and diffusion steps, respectively. Similarly, k_1 and k_2 are the mass transfer coefficients at the washing and diffusion steps, respectively.

The extraction rate (υ) in every time t can be obtained by differentiating Equation (4) with respect to time to give:

$$\upsilon = \left[\frac{C(t)}{dt}\right] = k_1 C_1 exp(-k_1 t) + k_2 C_2 exp(-k_2 t) \tag{5}$$

k_1 is obviously higher than k_2 due to the much faster extraction rate during the first phase of extraction. The initial extraction rate (υ_0) is the rate at the beginning of the extraction process and it is obtained when t = 0 as follows:

$$\upsilon_0 = k_1 C_1 + k_2 C_2 \tag{6}$$

The overall equilibrium RSS/juice yield (C_e) is obtained from the summation of equilibrium RSS/juice yield at both the washing step and the diffusion steps, that is:

$$C_e = C_1 + C_2 \tag{7}$$

Peleg's model is a non-exponential empirical model that has been successfully applied to describe the mass transfer mechanism of soli-liquid extraction of active compounds or solutes from a solid matrix. It is mathematically expressed as;

$$C(t) = C_0 + \frac{1}{k_1 + k_2 t} \tag{8}$$

$C(t)$ and C_0 represent the concentration (in this case, RSS/juice yield) at time t and the beginning of extraction (i.e., at t = 0), respectively. $k_1$and k_2 are rate and capacity constants, respectively. The rate constant is related to the rate of RSS/juice yield at the beginning of the extraction process while the capacity constant is related to the maximum RSS/juice yield during the extraction process.

C_0 is 0 at the beginning of the extraction process when t = 0 and therefore, Equation (8) reduces to:

$$C(t) = \frac{1}{k_1 + k_2 t} \tag{9}$$

Now, the differentiation of Equation (9) with respect to time, t will give the rate of the extraction process as follows:

$$\left[\frac{C(t)}{dt}\right] = \frac{1}{(k_1 + k_2 t)^2} \tag{10}$$

The initial rate of RSS/juice yield (B_0) can be determined from equation (10) by setting t = 0 while the maximum or the equilibrium RSS/juice yield (C_e) can be determined from Equation (9) by setting $t = \infty$ as follows:

$$\left.\frac{C(t)}{dt}\right|_{t=0} = B_0 = \frac{1}{k_1} \tag{11}$$

$$C(t)|_{t=\infty} = C_e = \frac{1}{k_2} \tag{12}$$

The log's (logarithmic), power's, and Page's models are presented in Equations (13 – 15).

$$C(t) = a \cdot logt + b \tag{13}$$

$$C(t) = kt^n \tag{14}$$

$$C(t) = exp(-kt^n) \tag{15}$$

In all the three models, $C(t)$ still represents RSS/juice yield at time t while a, b, k, and n are kinetic constants.

All the models' parameters were estimated by fitting the experimental data with the help of the solver program package in Microsoft Excel. Using non-linear regression analysis, root mean square error (RMSE) in Equation (16) and percentage average absolute relative deviation (AARD) in Equation (17) were selected as the objective functions for the minimization of the deviation between the experimental and the predicted data. Finally, the accuracy of the prediction was assessed using R^2 and adjusted R^2.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(y_{exp} - y_{pred}\right)^2}{N}} \tag{16}$$

$$AARD\ (\%) = \frac{100}{N}\sum_{i=1}^{N}\left(\frac{\left|y_{exp} - y_{pred}\right|}{y_{exp}}\right) \tag{17}$$

y_{exp} and y_{pred} denote experimental and predicted data, respectively while N denotes the number of experimental data.

2.2.5. Thermodynamic study

The thermodynamic parameters of the solid-liquid extraction process were determined using the Arrhenius equation in Equation (18).

$$k = A\,exp\left(-\frac{E_a}{RT}\right) \tag{18}$$

Here, k stands for the initial extraction rates (υ_0) at different temperatures that were obtained from Equation (6) since the best kinetic model was found to be Patricelli's model and was therefore used for the thermodynamic study. However, the usual meanings of A, E_a, R, and T as Arrhenius constant, activation energy, universal gas constant, and temperature, respectively still hold. Plotting $\ln k$ against $1/T$ gave a straight line from which E_a and A were obtained from the slope and intercept, respectively.

The thermodynamic parameters such as entropy change (ΔS), enthalpy change (ΔH), and Gibbs free energy change (ΔG) were determined using the following equations according to Tusek [6].

$$A = \frac{RT}{Nh} exp\left(\frac{\Delta S}{R}\right) \tag{19}$$

$$\Delta H = Ea - R \cdot T \tag{20}$$

$$\Delta G = \Delta H - T \cdot \Delta S \tag{21}$$

N is Avogadro's number and h is Plank's constant.

3. Results and Discussion

3.1. Kinetic study

The experimental data as a function of temperature are presented and compared graphically with predicted data by each of the five tested models in Figures (1 – 5). It is clear from the experimental data that the increase in the temperature resulted in an increase in the RSS and the juice yield. This is a usual observation in the solid-liquid extraction process where high temperature favours the process by enhancing the solubility and diffusivity of the solutes while simultaneously causing a decrease in the viscosity. With this enhanced extraction system by high temperatures, the accessibility and release of solutes from ruptured plant cells will be easily facilitated [12]. Two stages of extraction rates were observed with respect to the variation of the RSS and juice yield with extraction time. At the beginning especially from 0 to 10 minutes, high increases in the RSS and yield were observed resulting in over 1.3 °Brix and 55 wt. %, respectively at the highest temperature of 65 °C. Beyond 10 minutes of extraction, there were no significant increases in the RSS and the yield as a function of time. This trend implies that the extraction of soluble solids, which were mostly soluble sugars, was only effective for up to 10 minutes beyond which the extraction seized to depend on time and therefore the extraction could be terminated after 10 minutes to conserve time and energy without any significant loss in the RSS and the yield. Again, this observation agrees with previous works on the kinetic study of solid-liquid extraction [6, 8, 12, 15]. The highest values of RSS and yield are 1.75 °Brix and 70 wt. %, respectively which were achieved at the highest extraction time of 100 min and the highest temperature of 65 °C. It is difficult to compare the extraction performance in this work with previous works because similar works have not been reported. Most sweet sorghum juice extractions use mechanical squeezing for the stalks. For instance, Djomdi [20] investigated the extraction performance of juice from sweet sorghum for bioethanol production. Although the extraction yield of about 91 % was reported, it was only achieved after two cycles of mechanical pressing using fresh sweet sorghum stalks for the first cycle and the bagasse obtained for the second cycle. The only similar work to the current one is the water extraction of sweet sorghum juice carried out by Jia [10]. They reported a maximum of 90 % sugar recovery but it was achieved after adopting different water extraction methods that include three cycles of substrates (stalks) and five cycles of extraction solvent (water).

The effectiveness of each tested kinetic model in fitting the experimental data can also be deduced from Figures (1)-(5). The experimental data was best fitted by Patricelli's model followed by Peleg's, log's, power, and Page's models. This observation is corroborated by the results of the statistical and error analyses in Tables 1 – 5. For instance, the average values of R^2, adjusted R^2, RMSE, and AARD for the fitting of RSS data using Patricelli's model were 0.978, 0.977, 0.055, and 5.35 %, respectively while those for the fitting of juice yield data were 0.986, 0.985, 2.1, and 4.94 % respectively. This result for Patricelli's model was the best among the five tested models. It was closely followed by Peleg's model with average values of 0.968, 0.967, 0.0625, and 6.84 %, respectively for fitting the RSS data and 0.974, 0.973, 2.85, and 5.21 %, respectively for fitting the juice yield data. The weakest kinetic model was Page's model with average values of 0.278, 0.236, 0.2725, and 26.03 %, respectively for fitting the RSS data and 0.844, 0.835, 7.08, and 16.3 %, respectively.

With respect to Patricelli's and Peleg's models which displayed the best performances in fitting the experimental data, the key kinetic parameters are initial extraction rates of RSS/juice yield and equilibrium values of RSS/juice yield. These two parameters in the two models increased with an increase in the temperature for both RSS and juice yield which also corroborated the positive impact of the temperature on the extraction process. For Patricelli's model, the average values of initial rates of RSS and juice yield were 0.446 °Brix/min. and 15.62 wt. %/min., respectively while the average values of the equilibrium RSS and juice yield were 1.331 °Brix and 66.24 wt. %, respectively. Similarly, for Peleg's model, the average values of initial rates of RSS and juice yield were 0.592 °Brix/min. and 23.81 wt. %/min., respectively while the average values of the equilibrium RSS and juice yield were 1.411 °Brix and 67.09 wt. %, respectively.

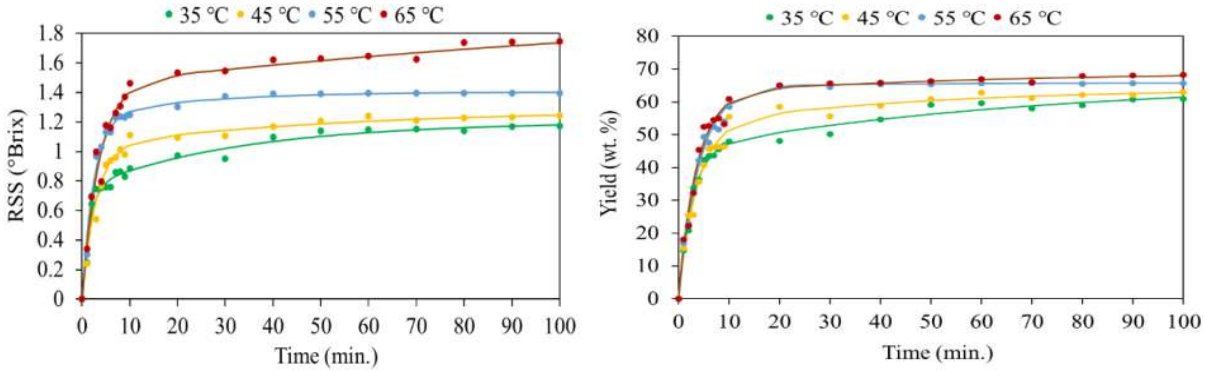

Figure 1: Comparison of experimental data with Patricelli's model predicted data for RSS and juice yield

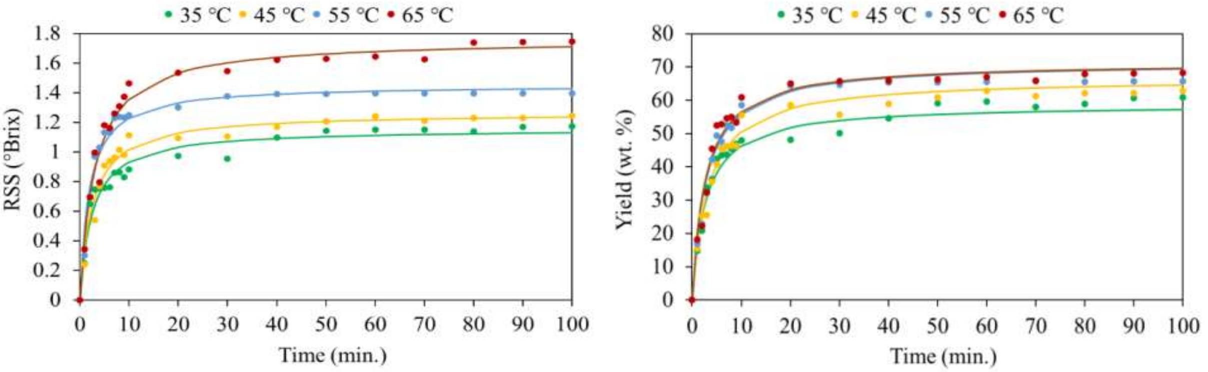

Figure 2: Comparison of experimental data with Peleg's model predicted data for RSS and huice yield

With respect to Patricelli's and Peleg's models which displayed the best performances in fitting the experimental data, the key kinetic parameters are initial extraction rates of RSS/juice yield and equilibrium values of RSS/juice yield. These two parameters in the two models increased with an increase in the temperature for both RSS and juice yield which also corroborated the positive impact of the temperature on the extraction process. For Patricelli's model, the average values of initial rates of RSS and juice yield were 0.446 °Brix/min. and 15.62 wt. %/min., respectively while the average values of the equilibrium RSS and juice yield were 1.331 °Brix and 66.24 wt. %, respectively. Similarly, for Peleg's model, the average values of initial rates of RSS and juice yield were 0.592 °Brix/min. and 23.81 wt. %/min., respectively while the average values of the equilibrium RSS and juice yield were 1.411 °Brix and 67.09 wt. %, respectively.

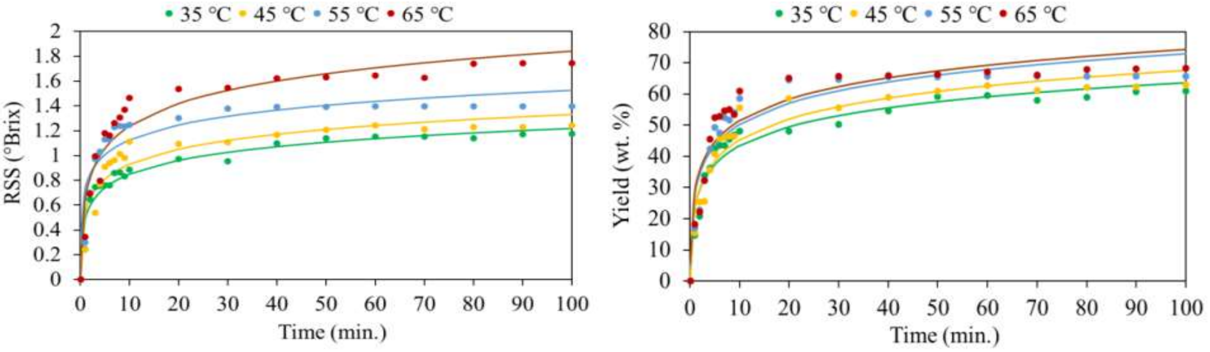

Figure 3: Comparison of experimental data with log model predicted data for RSS and yield

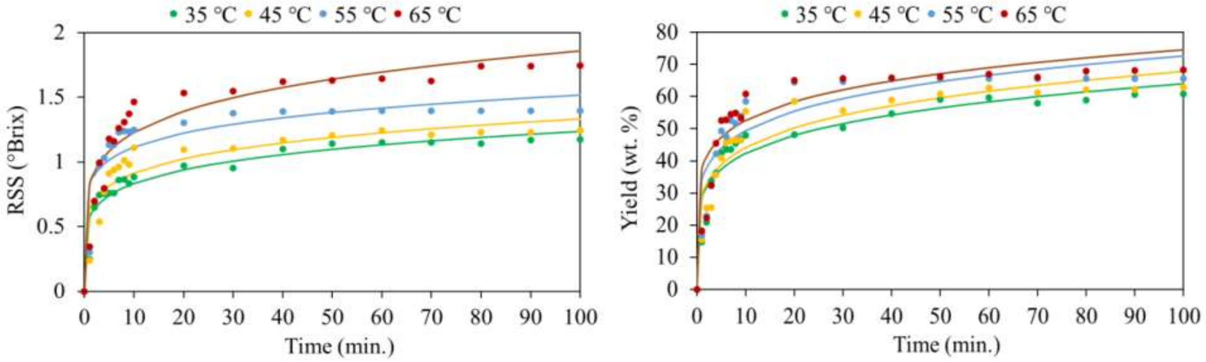

Figure 4: Comparison of experimental data with power model predicted data for RSS and juice yield

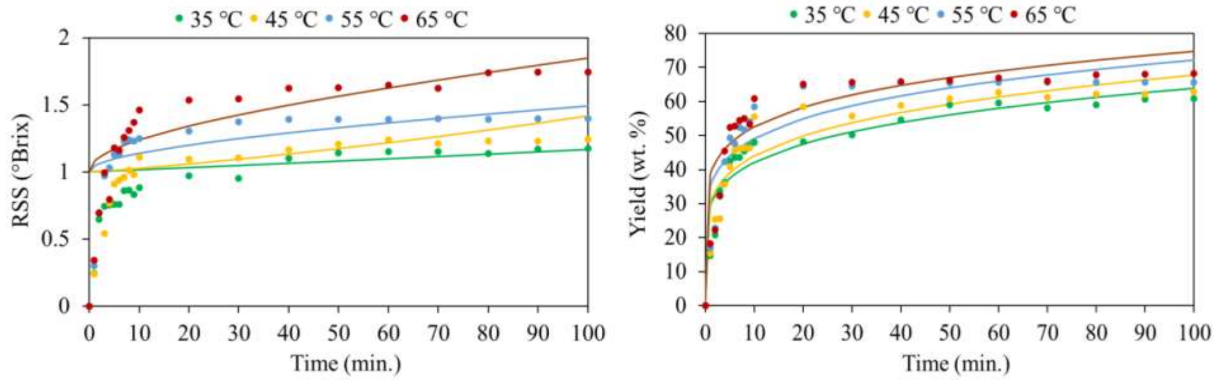

Figure 5: Comparison of experimental data with Page's model predicted data for RSS and juice yield

Table 1: Kinetic parameters of Patricelli's model for RSS and juice yield

RSS

T (°C)	C_1 (°Brix)	C_2 (°Brix)	k_1 (min^{-1})	k_2 (min^{-1})	v_0 (°Brix/min.)	C_e (°Brix)	R^2	Adj R^2	RMSE	AARD (%)
35	0.444	0.758	0.03	0.112	0.098	1.202	0.978	0.977	0.04	5.84
45	0.251	1.03	0.02	0.346	0.361	1.281	0.971	0.969	0.06	5.8
55	0.175	1.229	0.044	0.41	0.512	1.404	0.991	0.990	0.04	3.55
65	0.152	1.286	0.099	0.619	0.811	1.438	0.971	0.969	0.08	6.19

Yield

T (°C)	C_1 (%)	C_2 (%)	k_1 (min^{-1})	k_2 (min^{-1})	v_0 (%/min.)	C_e (%)	R^2	Adj R^2	RMSE	AARD (%)
35	45.311	20.746	0.312	0.015	14.45	66.057	0.989	0.989	1.65	6.75
45	52.145	11.843	0.275	0.024	14.62	63.988	0.985	0.985	2.11	4.55
55	63.857	1.886	0.247	0.04	15.85	65.743	0.985	0.984	2.3	3.88
65	62.247	6.911	0.28	0.018	17.55	69.158	0.985	0.984	2.35	4.57

Table 2: Kinetic parameters of Peleg's model for RSS and juice yield

RSS

T (°C)	k_1 (min/°Brix)	k_2 (°Brix^{-1})	B_0 (°Brix/min.)	C_e (°Brix)	R^2	Adj R^2	RMSE	AARD (%)
35	2.099	0.865	0.476	1.156	0.958	0.956	0.06	7.46
45	1.938	0.789	0.516	1.267	0.964	0.962	0.06	7.63
55	1.269	0.687	0.788	1.456	0.974	0.972	0.06	6.5
65	1.703	0.567	0.587	1.764	0.977	0.976	0.07	5.78

Yield

T (°C)	k_1 (min/%)	k_2 (%$^{-1}$)	B_0 (%/min.)	C_e (%)	R^2	Adj R^2	RMSE	AARD (%)
35	0.046	0.017	21.74	58.82	0.977	0.976	2.42	4.93
45	0.048	0.015	20.83	66.67	0.981	0.981	2.35	3.81
55	0.039	0.014	25.64	71.43	0.968	0.966	3.39	5.69
65	0.037	0.014	27.03	71.43	0.970	0.969	3.24	6.42

Table 3: Kinetic parameters of log's model for RSS and juice yield

RSS						
T (°C)	a (ºBrix)	b (ºBrix)	R^2	Adj R^2	**RMSE**	**AARD (%)**
35	0.369	0.481	0.912	0.906	0.07	8.97
45	0.401	0.527	0.831	0.821	0.11	13.5
55	0.401	0.725	0.749	0.734	0.14	14.85
65	0.605	0.632	0.886	0.879	0.13	12.19
Yield						
T (°C)	a (%)	b (%)	R^2	Adj R^2	**RMSE**	**AARD**
35	20.249	23.049	0.903	0.898	3.96	10.07
45	22.342	22.852	0.891	0.885	4.67	10.1
55	22.76	27.463	0.807	0.796	6.63	13.66
65	22.813	28.565	0.818	0.807	6.45	14.09

Table 4: Kinetic parameters of power model for RSS and juice yield

RSS						
T (°C)	k	n	R^2	Adj R^2	**RMSE**	**AARD (%)**
35	0.562	0.171	0.925	0.921	0.08	10.73
45	0.626	0.164	0.862	0.854	0.12	16.18
55	0.819	0.134	0.833	0.824	0.15	16.62
65	0.811	0.18	0.863	0.856	0.18	16.48
Yield						
T (°C)	k	n	R^2	Adj R^2	**RMSE**	**AARD (%)**
35	27.98	0.18	0.907	0.902	4.89	12.46
45	28.718	0.187	0.889	0.883	5.8	14.05
55	33.508	0.168	0.835	0.826	7.64	16.75
65	37.023	0.152	0.784	0.772	9.05	19.45

Table 5: Kinetic parameters of Page’s model for RSS and juice yield

			RSS			
T (°C)	k	n	R^2	**Adj** R^2	**RMSE**	**AARD (%)**
35	-0.001	1.739	-0.024	-0.085	0.23	31.26
45	-0.002	1.122	0.242	0.197	0.23	28.94
55	-0.042	0.489	0.359	0.323	0.3	21.07
65	-0.075	0.457	0.536	0.510	0.33	22.84
			Yield			
T (°C)	k	n	R^2	**Adj** R^2	**RMSE**	**AARD (%)**
35	-3.365	0.046	0.899	0.893	5.11	13.05
45	-3.395	0.047	0.879	0.872	6.06	14.83
55	-3.544	0.041	0.824	0.815	7.89	17.38
65	-3.638	0.037	0.774	0.761	9.25	19.95

3.2. Thermodynamic study

The linear dependence of the initial extraction rate on the inverse temperature in Kelvin for both RSS and juice yield using Equation (19) as presented in Figure 6 allowed the determination of activation energy and Arrhenius constant. These two thermodynamic parameters are required to determine the entropy change, enthalpy change, and free energy change from Equations (20), (21), and (22), respectively as presented in Table 6. The calculated activation energies for RSS and juice yield were 58249.5 kJ/mol and 8316.49 kJ/mol respectively, indicating that the initial extraction rate in the case of the RSS was more sensitive to temperature than the initial extraction rate in the case of the juice yield according to Tusek [6]. The changes in enthalpies were all positive indicating that the extraction process was endothermic and as such, the external energy source is required to elevate the energy level of recovery of soluble solids and juice yield to their transition state [6]. In addition, there is a very slight decrease in the enthalpy change with an increase in the temperature for both RSS and juice yield and this implies that approximately the same amounts of external energy are required for the extraction process. The negative values of all the entropy changes reveal that the extraction process is reversible and that the active species in the extraction process lost their degree of freedom after coming together to form an activated complex through an association mechanism. Finally, the free energy changes of the extraction process are all positive which is an indication that the process is not spontaneous but endergonic [21].

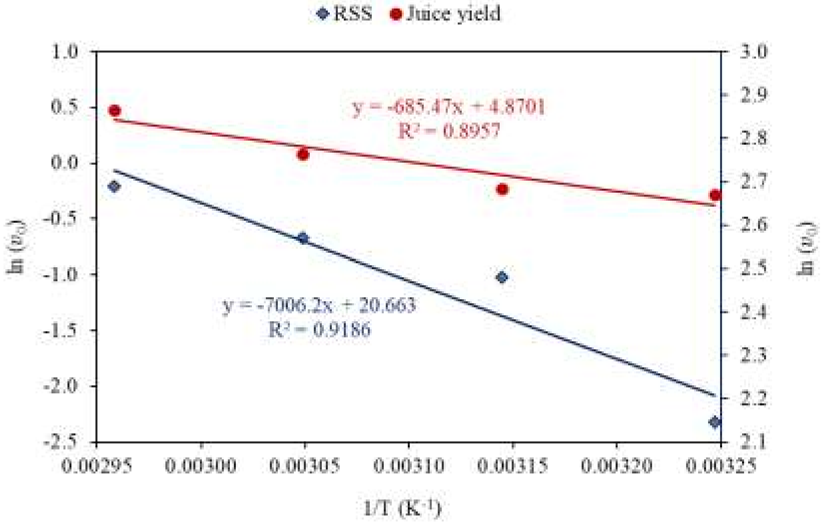

Figure 6: Dependence of initial extraction rate on temperature for RSS and juice yield

Table 6: Thermodynamic parameters of the extraction process for RSS and juice yield

E_a(kJ/mol)	T (K)	ΔH (kJ/mol)	ΔS (J/K mol)	ΔG (kJ/mol)
		RSS		
58249.5	308	55.689	-73.388	78.292
	318	55.607	-73.654	79.028
	328	55.523	-73.911	79.765
	338	55.439	-74.161	80.506
		Yield		
8316.49	308	3.138	-204.69	66.183
	318	3.055	-204.956	68.231
	328	2.972	-205.213	70.282
	338	2.889	-205.463	72.335

4. Conclusion

The kinetic and thermodynamic study of the extraction process for soluble sugars and juice yield from sweet sorghum was carried out. It could be concluded that the increase in the RSS and juice yield was high at the beginning of the extraction, particularly from 0 to 10 minutes and the increase became insignificant afterwards. Secondly, it was found that the values of the RSS and juice yield during the extraction process increased with an increase in the temperature. Based on the statistical analysis data, it was found that Patricelli's model produced the best performance in fitting the RSS and juice yield experimental data. Finally, the extraction processes were endothermic (positive enthalpy change), reversible (negative entropy change), and not spontaneous but endergonic (positive free energy change).

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Conflict of interest

We declare no conflict regarding the publication of the study.

References

[1] Nandeshwar, B. C., Bhoite, A. G., Gadkari, P.A., Garoma, B., Jalata, Z., Sreekrishna, V., Gurmesa, K., & De, D. K. (2018). Sweet sorghum: An alternative source of food, feed, sugar and bio-fuel (A review). *International Journal of Tropical Agriculture*, *36(3),* 783-791.

[2] Appiah-Nkansah, N. B., Li, J., Zhang, K., Rooney, W., & Wang, D. (2019). A review of sweet sorghum as a viable renewable bioenergy crop and its techno-economic analysis. *Renewable Energy*, *143,* 1121-1132. https://doi.org/10.1016/j.renene.2019.05.066

[3] Chibrikov, V., Vakuliuk, P, & Sobczuk, H (2023). Sweet sorghum juice clarification and concentration: a review. *Critical Reviews in Food Science and Nutrition*, *64(32),* 11850–11870. https://doi.org/10.1080/10408398.2023.2245033.

[4] Jugwanth, Y., Sewsynker-Sukai, Y., & Gueguim Kana, E. B. (2020). Valorization of sugarcane bagasse for bioethanol production through simultaneous saccharification and fermentation: Optimization and kinetic studies. *Fuel. 262*, 116552. https://doi.org/10.1016/j.fuel.2019.116552.

[5] Hobbi, P., Okoro, O. V., Delporte, C., Alimoradi, H., Podstawczyk, D., Nie, L., Bernaerts, K. V., & Shavandi, A. (2021). Kinetic modelling of the solid–liquid extraction process of polyphenolic compounds from apple pomace: influence of solvent composition and temperature. *Bioresources and Bioprocessing, 8*, 114. https://doi.org/10.1186/s40643-021-00465-4

[6] Tusek, A. J., Benkovic, M., Cvitanovic, A. B., Valinger, D., Jurina, T., & Kljusuric, J. G. (2016). Kinetics and thermodynamics of the solid-liquid extraction process of total polyphenols, antioxidants and extraction yield from Asteraceae plants. *Industrial Crops and Products*, *91*, 205-214. https://doi.org/10.1016/j.indcrop.2016.07.015.

[7] Bhattacharjee, N., & Biswas, A. B. (2020). Physicochemical analysis and kinetic study of orange bagasse at higher heating rates, *Fuel, 271*, 117642. https://doi.org/10.1016/j.fuel.2020.117642.

[8] Motlagh, S. R., Khezri, R., Harun, R., Awang Biak, D. R., Hussain, S. A., Chee, C. Y., & Kheawhom, S. (2022). Kinetic and thermodynamic studies of eicosapentaenoic acid extraction from *Nannochloropsis oceanica* using tetramethyl ammonium chloride and microwave irradiation. *PLOS ONE, 17(5),* e0267626. https://doi.org/10.1371/journal.pone.0267626.

[9] Pamu, V. S. (2014). Effect of different diffusion strategies on extraction of sugar from sweet sorghum. *M.Sc. Thesis*, Oklahoma State University, USA.

[10] Jia, F., Chawhuaymak, J., Riley, M. R., Zimmt. W., & Ogden, K. L. (2013). Efficient extraction method to collect sugar from sweet sorghum. *Journal of Biological Engineering*, *7*. http://www.jbioleng.org/content/7/1/1.

[11] Appiah-Nkansah, N. B., Zhang, K., & Rooney, W. (2016). Model study on extraction of fermentable sugars and non-structural carbohydrate from sweet sorghum using diffusion process. *Industrial Crops and Products*, *83*, 654–662. https://doi.org/10.1016/j.indcrop.2015.12.056.

[12] Mustapa, A. N., Martina, A., Gallegoa, J. R., Matoa, R. B., & Cocero, M. J. (2015). Microwave-assisted extraction of polyphenols from Clinacanthus nutans Lindau medicinal plant: Energy perspective and kinetics modeling. *Chemical Engineering and Processing*, *97*, 66-74. https://doi.org/10.1016/j.cep.2015.08.013.

[13] Stamenkovic, O. S., Milan D. Kostic, M. D., Tasic, M. B., Djalovic, I. G., Mitrovic, P. M., Biberdzic, M. O., & Veljkovic, V. B. (2020). Kinetic, thermodynamic and optimization study of the corn germ oil extraction process. *Food and Bioproducts Processing, 120*, 91-103. https://doi.org/10.1016/j.fbp.2019.12.013.

[14] Singh, S., Sharma, S. K., & Kansa, S. K. (2020). Dataset on aqueous solid-liquid extraction of gossypol from defatted cottonseed in acidic medium using green solvent, its kinetics and thermodynamics study and mass transfer effects. *Data in Brief*, *31*, 105620. https://doi.org/10.1016/j.dib.2020.105620.

[15] Agu, C. M., Menkiti, M. C., Ohale, P. E., & Ugonabo, V. I. (2021). Extraction modeling, kinetics, and thermodynamics of solvent extraction of Irvingia gabonensis kernel oil, for possible industrial application. *Engineering Reports, 3*, e12306. https://doi.org/10.1002/eng2.12306.

[16] Aishi, Z. (2022). Kinetics and thermodynamics of water extraction of foxtail millet polysaccharides. *Iranian Journal of Chemistry and Chemical Engineering*, *41(2)*, 510–520.

[17] Rayo-Mendez, I. M., Gómez, A. V., & Tadini, C. C. (2019). Extraction of soluble sugars from banana puree to obtain a matrix rich in non-starch polysaccharides. *Food Chemistry*, 294, 539-546. https://doi.org/10.1016/j.foodchem.2019.05.079.

[18] Abdullahi, A., Abubakar, A., Yunusa, S., Shuwa, S. M., & Ameh, A. O. (2024). Determination of optimum total soluble solid in sweet sorghum juice extraction. In Proceeding of the *2nd International Conference on Renewable Energy*, Katsina Sate, Nigeria.

[19] Abdullah, N., & Chin, N. I. (2020). Optimising tropical fruit juice quality using thermosonication-assisted extraction via blocked face-centered composite design. *Processes. 9(1)*, 3. https://doi.org/10.3390/pr9010003.

[20] Djomdi, D, Hamadou, B, Klang, M. J., Djoulde, D. R., Christophe, G., & Michaud, P. (2019). Extraction performance of juice and bioethanol production from sweet sorghum (Sorghum bicolor, (l.) Moench). *Global Journal of Engineering Science and Research Management*, *6(7)*, 57-66. https://doi.org/10.5281/zenodo.3357842.

[21] Stamenkovic, O. S., Djalovic, I. G., Kostic, M. D., Mitrovic, P. M., & Veljkovic, V. B. (2018). Optimization and kinetic modeling of oil extraction from white mustard (Sinapis alba L.) seeds. *Industrial Crops and Products*, *121*, 132-141. https://doi.org/10.1016/j.indcrop.2018.05.001.