

Development of a Model to Predict the Extraction of Juice from Date Palm Fruit

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Abstract: A model for predicting juice extraction from date palm fruit using an existing mechanical extractor was developed in the study. Model development was based on principle of continuity and momentum transport. Optimum values of factors such as steaming time, diffusion coefficient, digestion time and quantity of water required for optimum juice yield were determined. Effect of steaming time, diffusion coefficient and pressure on experimental and predicted yield were also determined. Results obtained gave optimum values for steaming time, diffusion coefficient, digestion time and quantity of water as 90 minutes, $4.38 \times 10^{-9} \text{ m}^2/\text{s}$, 15 minutes and 8 litres, respectively. Statistical analysis showed that the effects of factors on yield were significant ($P < 0.01$). The overall deviation of experimental yield from theoretical prediction was 2.56%. The results obtained showed that the mechanical extractor been optimized in the study is appropriate to be applied for economic purposes.

Keywords: Model, Predicting, Juice, Extraction, Mechanical Extractor, Developed, Factors, Optimum, Economic

1. Introduction

Modelling juice extraction from fruit is possible when the extraction and operation parameters are known. The modelling process involves the development of mathematical equations using available facts or results obtained from experimentation. It is a step by step process which is based on scientific principles and logics. Models are simulated in order to predict outcomes that have addressed all defects or most of the inadequacies that accompany a particular problem or design. Models are useful in process control and optimization since they are used to predict process efficiencies for a wide range of process conditions. They serve as veritable tools in improving operational performance

of process equipment through design. Models facilitate design changes for varying input materials without opting for expensive experimentations.

It was learnt from literature that extraction of juice from fruit is based on three phenomena which are juice flow through cell wall, flow through inter-mesocarp voids and flow through compressed biomass (mash). Hagen poiseuille equation for flow of fluids in pipes is used to describe the flow of substrate through pores in cell wall [1]. Darcy's law of fluid flow through porous media is used to describe flow of fluid through inter-mesocarp voids and a modified form of Terzaghi's equation for consolidation of saturated juice to describe the flow behaviour of compressed biomass [1].

Table 1. Symbols used and definition.

Symbol	Definition	Symbol	Definition
t	time (seconds)	S_e^2	error associated with experimental yield
t_s	steaming time (seconds)	S_p^2	error associated with predicted yield
∂	partial derivative	\bar{X}_p	mean of predicted yield
ρ	density	\bar{X}_e	mean of experimental yield
$\partial_t \rho$	change in density with respect to time	n_e	frequency of experimental yield
V	Velocity vector	n_p	frequency of predicted yield

Symbol	Definition	Symbol	Definition
σ	standard deviation	S_d	standard error of difference
M	mass (kg)	C_f	diffusion coefficient of date palm fruit (m^2/s)
A	area (m^2)	k	model constant
$\Delta P = P_2 - P_1$	change in pressure (MPa)		
L	length of extractor (m)		
l	length of macerator (m)		

The distribution of extractable materials within a solid structure is a factor of the model to be developed. Some extraction models used for the removal of fluid from plants may be classified into two main groups as follow:

- i. Empirical models.
- ii. Differential mass balance models.

1.1. Empirical Models

These are based on results obtained from experimentation. Extraction factors such as speed of flow, pressure, temperature, particle size, solubility, time of activity, etc were used in the development of extraction models [2].

1.2. Differential Mass Balance Model

Differential mass balance model was based on conservation of mass, energy and momentum. This has three basic classifications: (i) mass transfer, (ii) heat transfer and (iii) shrinking core.

- (i) Model based on mass transfer [3-6]

The model predicted the extraction of material when there was a difference in the concentration of the material to be extracted and the bulk phase that contained solid and solvent [7].

- (ii) Model based on heat transfer [8-10]

The model for the separation process was based on heat transfer phenomenon. Each plant cell was assumed to be spherical in shape and the equation for a cooling hot sphere in a cold medium was used to express the concentration profile inside a particle as a function of time [7].

- (iii) Shrinking core model

Plant cell was assumed to be spherical in shape. The extraction process described an irreversible desorption or removal of materials by diffusion through pores in porous media.



Figure 1. Date palm with fruits.

In the current study, the major focus was to develop a model to predict the extraction of juice from date palm fruit. The fruit has nutritional and medicinal values [11-13], hence the interest on the crop. Table 1 shows symbols and their definitions as used in the study while Table 2 shows the composition of date palm fruit juice among other constituents [14]. Figure 1 shows some date palm fruits on a date palm.

Table 2. Composition of date palm fruit juice.

Substance	Quantity
Vitamin C	0.13 mg/ml
Proteins	1.78%
Iron	94.33 ppm
Magnesium	578.43 ppm
Calcium	127.93 ppm
Phosphorus	342.70 ppm
Manganese	31.00 ppm
Copper	16.60 ppm
Potassium	117.43 ppm
Sodium	0.10 ppm
Total Sugars	8.94%
Reducing Sugars	7.13%
Total Solid	8.99%
Titrateable acidity	0.48 g/l
Ph	5.07

2. Materials and Methods

An existing mechanical extractor was used to develop a mathematical model to predict the extraction of juice from date palm fruit by applying some factors of extraction with water as solvent.

Optimum values of factors which were steaming time, diffusion coefficient, digestion time and quantity of water employed in the extraction process were determined. A 2^4 factorial experimental design was employed to determine the effect of factors on yield with the determination of analysis of variance (anova) using System Analysis System [15]. Predicted and experimental yield were compared with each other.

2.1. Materials

The materials used in the research included the followings.

2.1.1. Raw Materials

Dry date palm fruits were obtained from Nigerian Institute for Oil Palm Research (NIFOR), Date Palm Substation, Dogon-Dutse, Jigawa State, Nigeria.

2.1.2. Equipment

(i) Date palm fruit juice extraction machine: This was the extractor used to extract juice from date palm fruit after appropriate fruit treatments with steaming,

digestion/maceration and pressing.

(ii) Steaming vessel: It was used to hydrate dry date palm fruit using steam at atmospheric pressure in order to facilitate the digestion or maceration of the fruit. The maceration process of the fruit promoted solubilization of nutritive constituents of the fruit.

(iii) Prime mover: This was an 8 horse power diesel engine used as a prime mover to drive the mechanical extractor.

2.1.3. Instrumentation

(i) Digital weighing balance: A weighing balance of a maximum mass of 15 kg with a precision of 0.001 g was used for the determination of mass.

(ii) Thermometer: A digital temperature probe with a range of $-50\text{ }^{\circ}\text{C}$ to $750\text{ }^{\circ}\text{C}$ was used for temperature measurement.

(iii) Tachometer: This was a digital microprocessor which was used to measure the speed of machine shaft and prime mover in revolution per minute (rpm).

(iv) Rotary evaporator: This was used to separate the extracted juice into solvent (water) and solute (soluble solid).

(vi) Stopwatch: This was used for measuring time of experimental runs.

2.2. Methods

Model development was based on the principle of continuity which is the law of conservation of mass. The law stated that “materials and momentum lost are equal to

materials and momentum gained in a transformation process” [16-18]. The vector form of equation of continuity was given by Eq. (1). The principle of continuity was used earlier by other researchers [19-22] for the development of models to predict extraction of substances from agricultural produce. It was on this basis that some factors involved in the extraction of date juice from date palm fruit using a mechanical extractor that the present model was developed. The extractor is a two-in-one-machine comprising a horizontal mechanical digester and a horizontal mechanical press. The digester was used to macerate steam-treated date palm fruits and subsequently transferred to the mechanical press where date kernel and other solid particles were removed to give date palm fruit juice (date juice).

$$\partial_t \rho + \text{div}(\rho v) = 0. \quad (1)$$

2.2.1. Model Development

Figure 2 is the physical model of the extractor. The following assumptions were made for model development.

Assumptions:

- Material moved as a bulk.
- No radial movement between particles.
- Axial pressure considered.
- Radial pressure neglected.
- Force was applied to overcome friction at the walls.
- Net change in mass was zero.

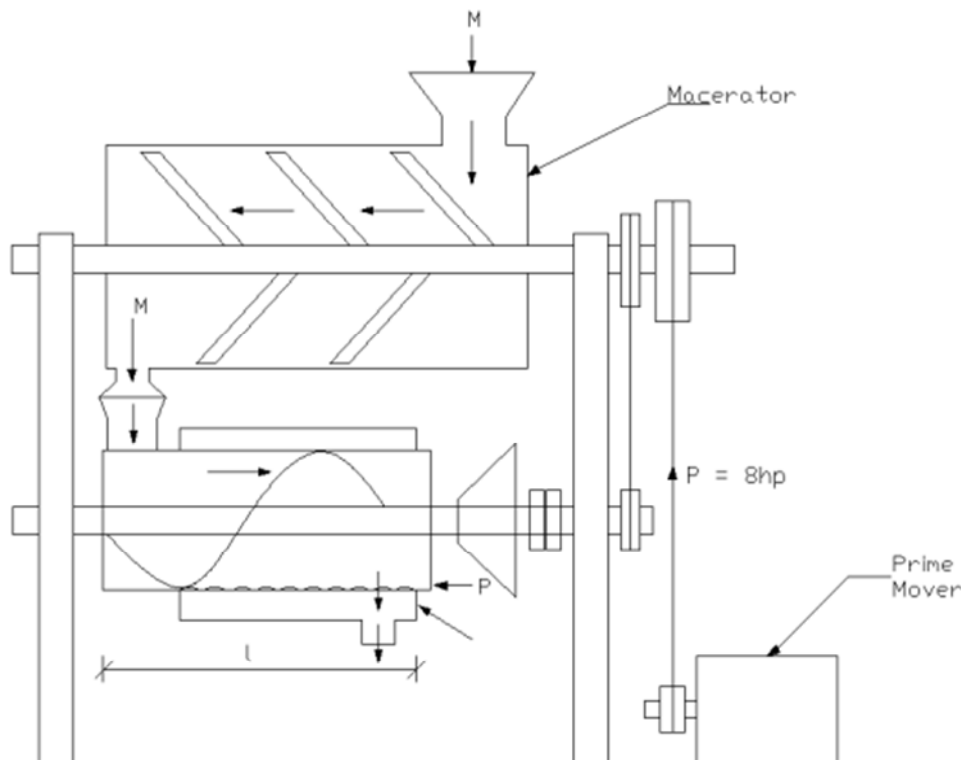


Figure 2. Physical model of the mechanical extractor.

(i) Fruit maceration

Maceration or digestion of date palm fruit of mass, M (kilogramme) at time, t (second) with bulk mass remaining constant was based on the principle of conservation of mass

given by Eq. (2). Changed in mass with respect to time, t , was given as:

$$\frac{dM}{dt} = 0. \quad (2)$$

Assuming that during digestion the change in mass of date palm fruit with mass, M in kg at time, t (seconds) in an area given by A in m^2 with initial and final pressures as P_1 and P_2 , respectively. The change in momentum of the digested mass over area, A with respect to pressure at the digester outlet was given as Eq. (3) which is based on the principle of momentum transport [16-18].

$$\text{Rate of change of momentum at digester outlet} = \frac{dM}{dt} A p_2 \quad (3)$$

(ii) Mash compression

The press chamber consists of an outer cylindrical pipe with radius, r and length, L housing a worm-shaft with an externally positioned choke mechanism. Pressure was developed in the cylindrical pipe during juice extraction. Extraction pressure considered was the axial pressure since radial movement of individual particles was ignored. The analysis of the press chamber was carried out as follows.

$$\text{Surface area (A) of the cylinder} = 2\pi rL, \quad (4)$$

Output material = Input material – Accumulation of material within the system.

$$\text{Driving force (momentum flux) generated by the press} = A\Delta P, \quad (6)$$

$$\text{Force (momentum flux) generated by bulk material} = AMC_f t_s L, \quad (7)$$

The net change in momentum flux within the press chamber was given as:

$$A\Delta P - AMC_f t_s L = 0. \quad (8)$$

The law of conservation of mass stated that a material undergoing some processes in a system could neither be destroyed nor created since change in mass is constant. There may be some transformations but summation of all masses after the process is equal to initial mass. That is material input is same as material output [16-18]. Applying the principle of continuity, Eq. (3) was equated to Eq. (8) to give Eq. (9).

$$\frac{dM}{dt} A P_2 = A\Delta P - AMC_f t_s L = 0, \quad (9)$$

Substituting Eq. (4) in Eq. (9) gives Eq. (10).

$$2\pi rL \frac{dM}{dt} P_2 = 2\pi rL(P_2 - P_1) - M2\pi rL C_f t_s L. \quad (10)$$

Eq. (10) was the mathematical expression for the extraction of juice from date palm fruit. The equation was not suitable to predict juice yield and therefore, needed to be solved by separation of variables and substitutions coupled with differentiation and application of boundary conditions [23-25] to get the desired model.

Taken judgment from experimental observations and systematic combination of the continuity and momentum equations as stated above, Eq. (10) reduced to:

$$\frac{dM}{dt} = \frac{M_0 P_2 - P_1}{t_0 P_2} - \frac{M_0 C_f t_s L}{C_{f_0}^2 t_0 P_2} M \quad (11)$$

where t_0 , M_0 and C_{f_0} were the time, mass and diffusion coefficient. Assuming that $t_0 = M_0 = C_{f_0} = 1$ (dimensionless

Surface area of cylinder = A .

Driving force (F) in the cylinder when date palm fruits were in motion was given as:

Driving force = Pressure (P) x Area (A), that is

$$F = 2\pi rL \times P. \quad (5)$$

The force responsible for motion and extraction of juice was influenced by pressure, machine/shaft speed, area of cylinder, diffusion coefficient of biomaterial, mass of biomaterial and volume of solvent (water) in the cylindrical element. These factors are defined as follow.

Area of cylindrical element (m^2) = A ,

Diffusion coefficient of biomaterial (m^2/s) = C_f ,

Volume of water/solvent (litres) = Q ,

Pressure (MPa) = P .

Applying the principle of continuity being the law of conservation of mass which stated that materials and momentum lost are equal to materials and momentum gained in a process:

quantities), then the above linear first order differential equation was written as:

$$\frac{dM}{dt} + \frac{C_f t_s L}{P_2} M = \frac{P_2 - P_1}{P_2}. \quad (12)$$

By the integrating factor procedure,

$$\frac{d}{dt} \left[M \exp\left(\frac{C_f t_s L}{P_2} t\right) \right] = \frac{P_2 - P_1}{P_2} \exp\left(\frac{C_f t_s L}{P_2} t\right), \quad (13)$$

which on integration became:

$$M = \frac{P_2 - P_1}{C_f t_s L} + A \exp\left(-\frac{C_f t_s L}{P_2} t\right), \quad (14)$$

where A was a constant of integration. The value of A was determined using the initial conditions given as: $M = 0$ at $t = 0$,

$A = -\frac{P_2 - P_1}{C_f t_s L}$, then

$$M = \frac{P_2 - P_1}{C_f t_s L} \left[1 - \exp\left(-\frac{C_f t_s L}{P_2} t\right) \right]. \quad (15)$$

The model for the extraction of juice from date palm fruit was therefore, given as:

$$M = K \frac{P_2 - P_1}{C_f t_s L} \left[1 - \exp\left(-\frac{C_f t_s L}{P_2} t\right) \right]. \quad (16)$$

Note that the presence of the constant k in the model, was to tune the model in order to adjust predicted yield to experimental yield.

A programme for simulation of model to generate yield was developed using Matlab 7.9 (R2009b).

2.3. Validation of the Model

The model was validated by applying the method [26] which was based on determination of standard error of difference (S_d) between predicted and experimental yield. The expression for the standard error of difference was given as:

$$S_d = \left(\frac{\sum(\hat{x}_p - \hat{x}_e)^2}{(n_p + n_e)} \right)^{0.5} = \sqrt{\left(\frac{S_p^2}{n_p} + \frac{S_e^2}{n_e} \right)} \quad (17)$$

3. Results and Discussion

3.1. Evaluation of Factors Involved in Extraction of Date Palm Fruit Juice

Tables 3 and 4 show the yield obtained from a 2⁴ factorial experiment and the analysis of variance (anova), respectively. The effect of all the factors on yield were significant (P < 0.01).

3.1.1. Optimum Quantity of Water for Date Juice Extraction

The optimum quantity of water needed for extraction of juice from 1 kg date palm fruit was found to be 8 litres at 8.7° Brix. When the quantity of water fell below the required water to fruit ratio, the extraction process became ineffective since bulk of the water-soluble-nutrients were not be released. On the other hand, if the water to fruit ratio (8:1) was exceeded, most of the water-soluble-nutrients were released but the concentration of the yield in terms of

nutrients were low. Figure 3 shows the increase in yield (soluble-nutrient) with the corresponding increase in water. From Figure 3 it could be seen that maximum yield of soluble-nutrient was achieved at optimum quantity of water which was 8 litres. There was a steady decrease in soluble-nutrient beyond the optimum quantity of water. The graph also shows that the concentration of the juice in terms of sugar in Brix was maximum at quantity of water at 2 litres and decreased gradually with increased in water.

Table 3. Yield obtained using a 2⁴ factorial experiment.

S/N	Q _w	S _t	D _c	M _t	Yield		
					Y ₁	Y ₂	Y ₃
1	5	60	3.36578	10	0.12319	0.11931	0.12853
2	8	60	3.36578	10	0.15582	0.15877	0.15472
3	5	90	3.36578	10	0.16854	0.16972	0.16192
4	8	90	3.36578	10	0.17954	0.17549	0.17752
5	5	60	4.37552	10	0.16576	0.16084	0.16491
6	8	60	4.37552	10	0.20157	0.20967	0.20755
7	5	90	4.37552	10	0.22485	0.21415	0.23195
8	8	90	4.37552	10	0.25881	0.24650	0.24756
9	5	60	3.36578	15	0.14569	0.14951	0.14209
10	8	60	3.36578	15	0.17455	0.17884	0.17195
11	5	90	3.36578	15	0.19139	0.19834	0.19614
12	8	90	3.36578	15	0.22756	0.23179	0.22692
13	5	60	4.37552	15	0.25886	0.24709	0.25049
14	8	60	4.37552	15	0.29119	0.28569	0.24682
15	5	90	4.37552	15	0.35257	0.34719	0.33519
16	8	90	4.37552	15	0.42964	0.40538	0.41853

Note: Q_w - Quantity of water; S_t - Steaming time; D_c - Diffusion coefficient; M_t - Maceration time; Y - Yield;

Table 4. Analysis of variance showing effect of factors on yield.

Source	DF	Type III SS	Mean square	F Value	Pr > F	Effect
Q _w	1	0.01381007	0.01381007	212.67	<.0001	++
S _t	1	0.04837447	0.04837447	744.94	<.0001	++
D _c	1	0.10972275	0.10972275	1689.7	<.0001	++
M _t	1	0.05994154	0.05994154	923.07	<.0001	++
Replicate	2	0.00023808	0.00011904	1.83	0.1774	NS
Q _w *S _t	1	0.00005716	0.00005716	0.88	0.3556	NS
Q _w *D _c	1	0.00064511	0.00064511	9.93	0.0037	++
Q _w *M _t	1	0.00037673	0.00037673	5.8	0.0224	+
S _t *D _c	1	0.00563316	0.00563316	86.75	<.0001	++
S _t *M _t	1	0.00546045	0.00546045	84.09	<.0001	++
D _c *M _t	1	0.01971576	0.01971576	303.61	<.0001	++
Q _w *S _t *D _c	1	0.00053007	0.00053007	8.16	0.0077	++
Q _w *S _t *M _t	1	0.00157542	0.00157542	24.26	<.0001	++
S _t *D _c *M _t	1	0.00160725	0.00160725	24.75	<.0001	++
Q _w *S _t *D _c *M _t	2	0.00029963	0.00014981	2.31	0.117	NS

Note: ++ - Significant @ 1%; + - Significant @ 5%; NS - Not significant.

3.1.2. Optimum Steaming Time for Date Juice Extraction

Studies showed that optimum steaming time for extraction of juice from date palm fruit was 90 minutes (5,400 seconds). Figure 4 shows the increase in steaming time with the corresponding increase in moisture absorption. Moisture absorbed by date palm fruit increased gradually to a maximum point of 0.74 kg which corresponded to 5400 seconds (90 minutes) steaming time and fell to 0.71 kg at 7,200 seconds (120 minutes) steaming time after the

maximum point of 0.74 kg and remained fairly constant with further increased in steaming time. This implies that at 90 minutes of date palm fruit steaming, the equilibrium moisture content was achieved. At this point any moisture available for absorption would not be absorbed since the intercellular voids of the fruit became saturated with moisture that any excess moisture would be rejected due to lack of accommodation. It could therefore, be said that from the data here obtained, that the optimum steaming time for extraction

of juice from date palm fruit was 90 minutes. This is an improvement over 180 minutes steaming time [27]. In a research conducted by Owolarafe, O. K [28] on micro-structural characterization of oil palm fruit, a steaming/sterilization time of 60 minutes was recommended for oil palm fruit. The disparity in steaming time of date palm fruit and oil palm fruit was in line since they are different crops. Prolong steaming time was required for date palm fruit in order to break up cell bearing nutrients of the fruit.

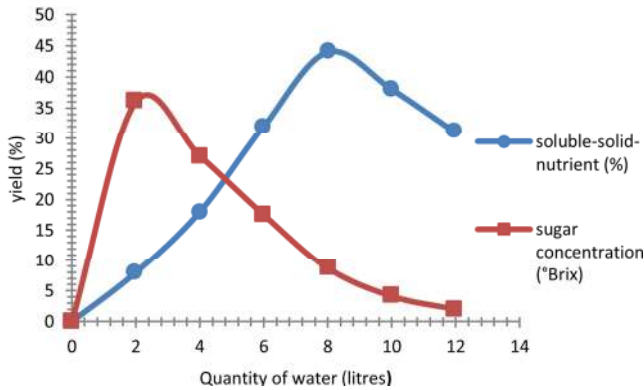


Figure 3. Optimum quantity of water for juice yield.

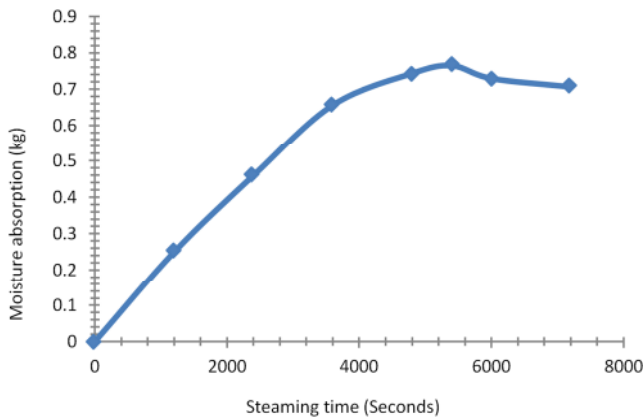


Figure 4. Optimum steaming time.

3.1.3. Optimum Diffusion Coefficient for Date Juice Extraction

Optimum diffusion coefficient was the diffusion coefficient that corresponded to 90 minutes (5,400 seconds) of date palm fruit steaming. The diffusion coefficient at 90 minutes fruit steaming obtained by interpolation was $4.38 \times 10^{-9} \text{ m}^2/\text{s}$ (Table 5). Diffusion coefficient was the driving force responsible for the movement of air and water molecules through the intracellular and intercellular voids of fruit mesocarp during fruit processing. Figure 5 shows increase in yield with the corresponding increase in diffusion coefficient. Maximum yield was achieved at optimum diffusion coefficient of $4.38 \times 10^{-9} \text{ m}^2/\text{s}$. The yield then remains fairly constant beyond the optimum diffusion coefficient since the intra-and-intercellular voids of the fruit mass became saturated with moisture that molecular transfer became stagnated.

3.1.4. Optimum Digestion Time for Date Juice Extraction

Figure 6 shows the increase in yield with the corresponding increase in digestion time. The yield increased steadily from 3 minutes of digestion time until maximum yield was achieved at 15 minutes digestion time. The digestion time of 15 minutes was then taken as the optimum digestion time. Yield obtained from fruit digested beyond 15 minutes remained fairly constant as shown by Figure 6. Optimum digestion time was the most appropriate and economic time taken for digestion of date mesocarp. Table 5 shows the diffusion coefficients of date palm fruit at different steaming time.

Table 5. Diffusion coefficients.

S/No.	Steaming time (minutes)	Diffusion coefficients (C_D) $\times 10^{-9} \text{ m}^2/\text{s}$
1.	0	0
2.	20	1.83536
3.	40	2.99181
4.	60	3.36578
5.	80	3.59591
6.	100	4.86168
7.	120	6.88498
8.	140	6.89534

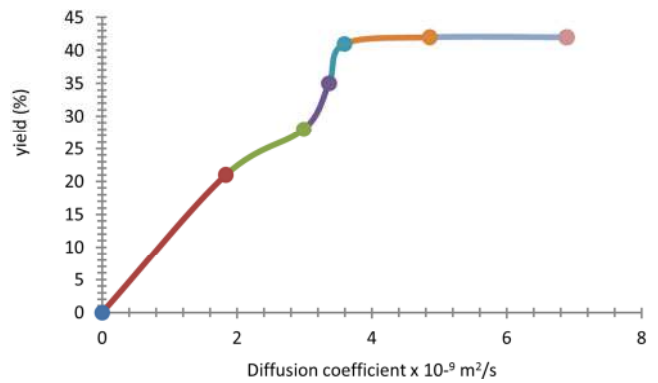


Figure 5. Optimum diffusion coefficient for juice yield.

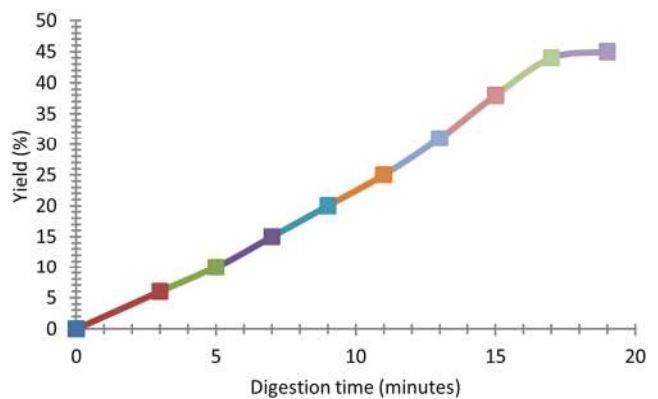


Figure 6. Optimum digestion time for juice yield.

When digestion time was less than the optimum value of 15 minutes, a small fragment of date mesocarp was mechanically digested which did not significantly affect dissolution of water-soluble-nutrients thereby retarding juice yield. In a situation where optimum digestion time was exceeded, dissolution of water-soluble-nutrients was fairly

static and this could lead to losses in energy, time and unnecessary tear and wear of equipment. It was reported by Owolarafe, O. K [28] that appropriate digestion time stimulate cell content disintegration which will eventually results in increasing yield.

3.2. Effect of Variables on Experimental and Predicted Yield

The variables considered here were steaming time and diffusion coefficient. Figure 7 shows the effect of steaming time on predicted and experimental yield. Predicted yield at optimum steaming time of 90 minutes was between 56.72 and 56.82% and remained fairly constant with further increase in steaming time. Experimental yield also followed the same trend.

Figure 8 shows the effect of diffusion coefficient on predicted and experimental yield. Both predicted and experimental yield increased with corresponding increase in diffusion coefficient of $1.84 \times 10^{-9} \text{ m}^2/\text{s}$ to $4.86 \times 10^{-9} \text{ m}^2/\text{s}$ with yield remaining fairly constant after $4.86 \times 10^{-9} \text{ m}^2/\text{s}$. This was because every agricultural produce has critical values of diffusion coefficients at which diffusion of materials remain fairly constant [29-30].

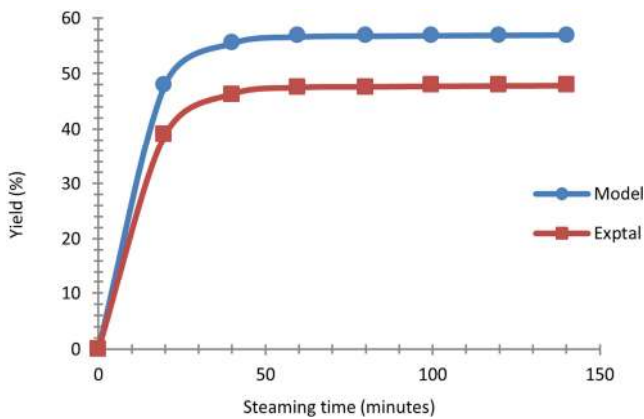


Figure 7. Effect of steaming time on yield.

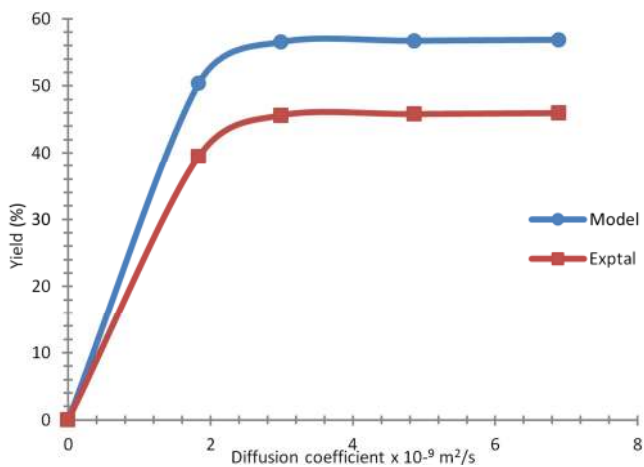


Figure 8. Effect of diffusion coefficient on yield.

3.3. Effect of Pressure on Predicted and Experimental Yield

Figure 9 shows the effect of pressure on predicted and experimental yield obtained at optimum values of extraction factors (steaming time, diffusion coefficient and digestion time). The Figure shows that predicted and experimental yield increased with respect to increase in pressure. This observation was also reported by [21] in the extraction of β -carotene from apricot bagasse. Figure 9 also shows that predicted and experimental yield at a pressure of 16.8 MPa were 53.7% and 44.8%, respectively. It was further observed that a pressure of 32.8 MPa gave 55.6% and 46.7% for predicted and experimental yield, respectively. It was observed from the results obtained in the study that there was no significant difference in yield after 16.8 MPa. Yield increased gradually with increased in pressure until 16.8 MPa and remained fairly constant with further increased in pressure. It could therefore, be inferred from the empirical information got that extraction pressure from 14.8 to 16.8 MPa was sufficient for optimal extraction of juice from date palm fruit.

3.4. Validation of Model

Results on validation of model using error statistics showed a good correlation between predicted and experimental yield. Model predictions using optimum values of extraction factors were accurate at a percentage error of 2.56%. It was reported that percentage error below 10% was assumed to be appropriate for practical purposes [1-31]. Figure 10 shows date palm fruit juice extracted under different conditions.

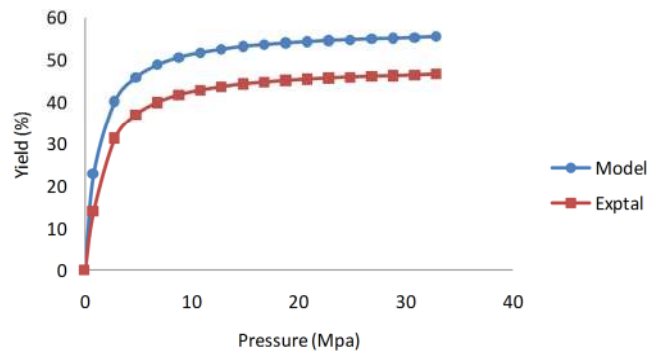


Figure 9. Effect of pressure on yield.



Figure 10. Date palm fruit juice.

4. Conclusion

The model developed in the study accurately predicted the extraction of juice from date palm fruit. The accuracy of model prediction was shown by the results presented. The model can also be applied to predict the extraction of juice and oil from other fruits and oil bearing seeds, respectively. This is possible if the level of each factor required to facilitate extraction is known. This work has provided a road map for either the expression or extraction of juice/oil from agricultural produce. It is worthy to note that when juice was extracted from date palm fruit and subsequently dehydrated by applying heat gave rise to date syrup. Alcohol can also be obtained from date palm fruit juice depending on the handling and treatments applied to the extracted date palm fruit juice. Other part of the date palm fruit of economic importance is the seed or the stone. It was reported in literature that the seed contains oil which is of economic importance. This is an area for future research.

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