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Research article

The dehydration kinetics, physical properties and nutritional content of banana textured by instantaneous controlled pressure drop†

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ABSTRACT: Texturing by instantaneous controlled pressure drop is used to modify texture of banana slices, which was aimed to improve properties of banana flour. Texturing step is inserted between initial and final hot air drying steps. The aim of this research is to investigate the effect of the texturing on the dehydration kinetic, physical properties and nutritional characteristic of banana. Some impacts of the texturing have been identified. The results of this work showed that the texturing increased the effective moisture diffusivity and the water holding capacity, but reduced the oil holding capacity of banana. This work also showed that the banana texturing inhibited the transformation of banana starch to reduction of sugar that might be attributable to enzyme deactivation during the texturing process. © 2011 Curtin University of Technology and John Wiley & Sons, Ltd.

KEYWORDS: banana; effective diffusivity; oil holding capacity; water holding capacity; nutrition

INTRODUCTION

Banana flour is produced from fresh banana fruit through dehydration (drying) process. Basically, the dehydration process is the removal of water from the banana fruit to a certain level at which microbial spoilage is avoided. In Indonesia, the dehydration method mostly used to produce banana flour is sun drying. Because this method needs much time exposure, significant deterioration will occur during the drying process, which can result in very low quality of the banana flour product. In this work, a new process of texturing by instantaneous control pressure drop, called the déetente instantanée contrôlée (DIC), was introduced between initial and final hot air drying. The purpose of the texturing step is to modify the material texture to improve the product quality including the product physical properties.

The DIC technology was initially developed by Allaf *et al*., since 1988, in the University of La Rochelle, France.[1–4] It applied instantaneous pressure drop to modify the texture of the material and intensify functional behaviour. The DIC treatment usually starts by creating a vacuum condition, followed by injecting steam to the material, which keeps contact for several seconds, and then proceeds to apply sudden pressure drop toward vacuum (about 5 kPa with a rate higher than 0.5 MPa/s). This treatment is also categorised as a high temperature short time (HTST) process. By suddenly dropping pressure, rapid auto vaporisation of the moisture from the material will occur, the material will swell and lead to texture change, which results in higher porosity.[5] It increases the material porosity as well as the specific surface area and reduces the diffusion resistance of moisture during the final dehydration step. Such a thermo-mechanical treatment also induces microbiological decontamination.[6]

This research was aimed to apply the DIC technology in the production of banana flour. The variation of the process variables, i.e. steam pressure/temperature and time of treatment in DIC reactor, will be studied in accordance with the kinetics of dehydration, the physical properties, which include water and oil holding capacity and the nutritional characteristics.

MATERIALS AND METHODS

Raw material

Freshly harvested banana fruit (*Musa sp*) were purchased locally and used in all experiments. After peeling, the banana fruit were cut into pieces of $16 \times 16 \times 2\ mm^3$.

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Dehydration method

The banana pieces were subjected to a stream of hot air at 50 °C in a convective hot air dryer (Memmert UFE 600, Schwabach, Germany). The banana pieces were dried until the residual moisture content of about 20% (wet basis). This condition was maintained before DIC treatment. The same hot air dryer and conditions were used for initial as well as for final dehydration.

The DIC reactor

The DIC reactor is shown schematically in Fig. 1. The reactor consisted of four major components, i.e. (a) the processing vessel ($1.5 \times 10^{-3}\,m^3$ volume), where samples were placed and treated, (b) the vacuum system, which consisted mainly of a vacuum tank with a volume 60-fold greater than the processing vessel, (c) the adequate vacuum pump, and (d) the pressure-dropping system, which is a pneumatic valve, separated by the processing vessel from the vacuum tank and could be operated after a high steam pressure treatment, and if required, before the injection of steam to establish an initial vacuum in the processing vessel.

The experimental procedure

The general experimental protocol is detailed in Fig. 2. After preparing the raw food material, an initial partial dehydration, was carried out. This pre-treatment is required before the DIC processing. The food material was then treated in the processing vessel in which a vacuum of 5 kPa was established by a brief connection to the vacuum tank [Fig. 3(b)]. The initial vacuum treatment facilitated the diffusion of steam into the sample. Consequently, the time necessary for the sample to reach the steam temperature was reduced. Saturated steam was subsequently introduced into the processing vessel at a fixed pressure level [Fig. 3(c)] and maintained for a predetermined time [Fig. 3(d)]. This step was followed by a sudden pressure drop [Fig. 3(e)]. The rapid pressure drop inside the processing vessel induced a rapid cooling of the sample, which passed in less than 1 s from 100–144 °C (depending on the steam pressure conditions) to about 30 °C. The treatment was ended by contacting the sample to the atmospheric pressure [Fig. 3(f and g)]. As the atmospheric air injection occurred under vacuum condition, the air expansion decreased the treated food temperature further.

The equilibrium after the pressure drop depended on the operating conditions: the higher the steam pressure level, the higher the equilibrium pressure. The steam generated by flash vaporisation after the decompression produced microtexturing, which was closely linked to a complex process of micro-alveolation. This process depended on the difference in temperature between the two thermodynamic equilibrium states, before and after decompression. After treatment, the sample was air-dried at 50 °C in convective hot air dryer to around 7% (w. b.) moisture content. The dried banana pieces were then ground using a commercial grinder (Philips Grinder, Philips, Amsterdam, The Netherlands) to pass a 200 mesh sieve and stored at 25 °C in sealed plastic containers prior to further analyses.

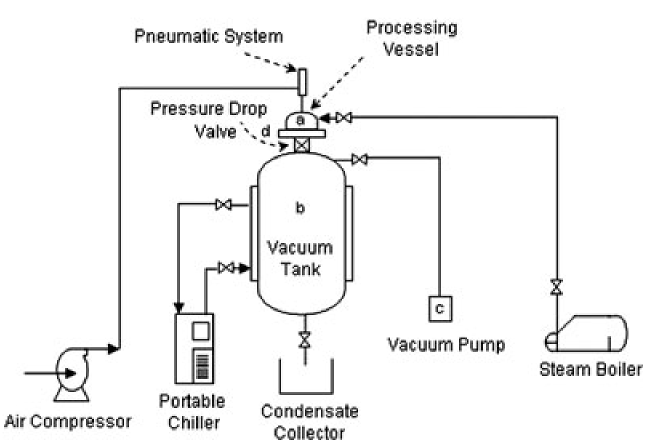

Figure 1. Schematic diagram of the DIC reactor: (a) treatment vessel with heating jacket; (b) vacuum tank with cooling liquid jacket; (c) vacuum pump; (d) instant pressure-drop valve.

FUNDAMENTALS

There are four transfer mechanisms, which usually intervene during the drying process; they are as follows: 1) Heat transfer from outside towards the product surface; the energy can be generally brought by contact, convection or radiation, 2) Heat transfer within the product; the energy is transmitted by conduction, 3) Water transfer within the product; it is carried out either in liquid (by various process including capillarity and molecular diffusivity; the driving force is the gradient of water content) and/or vapour phase (the driving force is the gradient of the partial pressure of vapour), 4) Vapour transport from the surface towards outside. Energy exchange to the product surface result in constant rate drying period and proceed in very short time.[7] Then, especially for biomaterials, during almost overall drying process, the water transfer takes place within the product that results in falling rate of drying.

By assuming that external heat and mass transfers do not limit the overall rate operation, and that there are adequate air flow temperature and velocity, only internal transfers are considered as controlling the processes. Mounir and Allaf assumed that, when mass transfer is much slower than conductive heat transfer within the product, the drying kinetics is controlled

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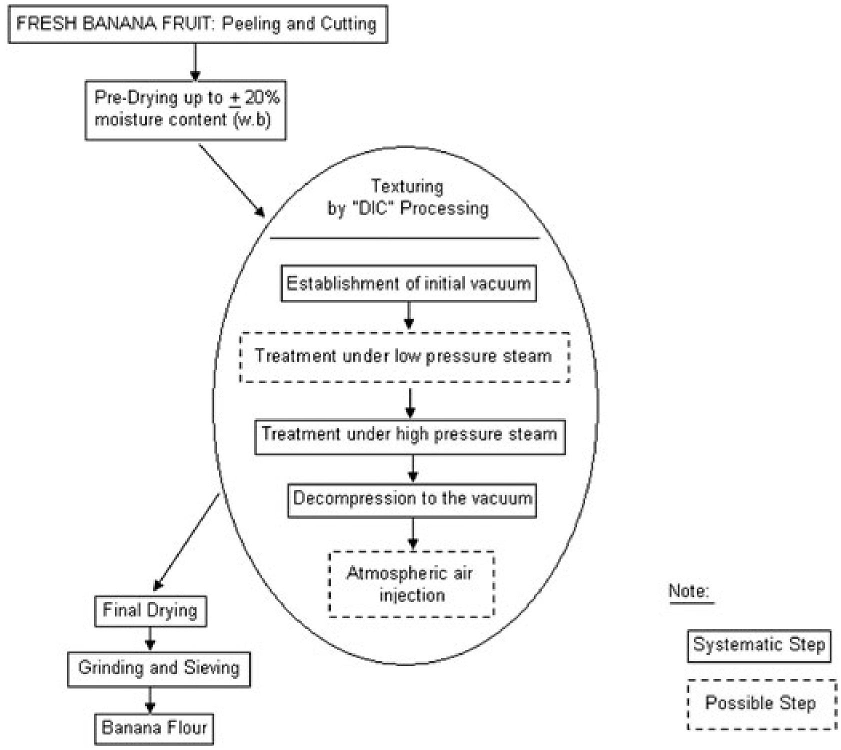

Figure 2. Schematic diagram of global processing.

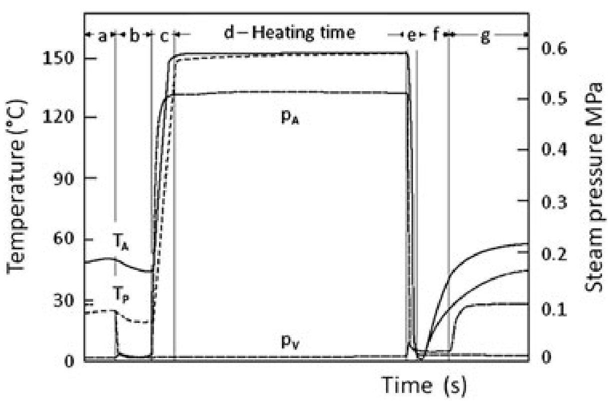

Figure 3. DIC temperature and pressure history: P_A and T_A are the steam pressure and temperature respectively in the processing vessel, P_V the vacuum tank pressure, T_P temperature of product: (a) sample at atmospheric pressure; (b) initial vacuum; (c) saturated steam injection to reach the selected pressure; (d) constant temperature corresponding to saturated steam pressure; (e) abrupt pressure drop towards vacuum; (f and g) releasing to the atmospheric pressure.

by mass transport of water within the granule; this is the case of numerous biopolymers.[8] The process is then described by a first stage of superficial interaction followed by a diffusion Fick's-type law within the material; Allaf's formulation is generally used:[9]

$$\frac{\rho_w}{\rho_m}(\vec{v}_w - \vec{v}_m) = -D_{eff}\, \vec{\mathrm{grad}}\, \frac{\rho_w}{\rho_m} \tag{1}$$

where:

ρ_w apparent density of water in the material (kg m^{-3})
ρ_m apparent density of dry material (kg m^{-3})
v_w absolute velocity of water flow within the porous medium (m s^{-1}).
v_m absolute velocity of solid medium (m s^{-1}).
D_{eff} effective diffusivity of water within the solid medium (m² s^{-1}).

Mounir and Allaf assumed neglecting effects of possible shrinkage, and with the hypothesis of constant effective diffusivity during drying, Fick's second law becomes for 1-D:[7]

$$\frac{\partial \rho_w}{\partial t} = \left[D_{eff}\frac{\partial^2 \rho_w}{\partial {L_o}^2}\right] \tag{2}$$

Where L_o is the thickness of the material (m). At the temperature and moisture content ranges studied in the present stage of the research work, drying process was considered as having insignificant impact on the banana structure because of the absence of shrinkage; the effective diffusivity D_{eff} was assumed to be constant. Different mathematical solutions have been

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proposed for this equation, depending on the initial and boundary conditions;[10] in our study, we can adopt the solution given by Crank, according to the geometry of the solid matrix;[11] by expressing the amount X of water in the solid, Eqn (2) becomes:

$$MR = \frac{X - X_e}{X_0 - X_e} = \sum_{i=1}^{\infty} A_i \exp\left(-q_i^2 t\right) \tag{3}$$

Where MR is moisture ratio, X is the water content dry basis at t, X_e, is the amount of X at equilibrium ($t \rightarrow \infty$) and X_0 the value of X at $t = 0$. For a slab geometry form, Eqn (3) becomes:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L_0^2}\right) \tag{4}$$

Where D_{eff} is the effective diffusivity (m^2/s). For long drying period, Eqn (4) can be further simplified to only the first term of series.[12,13] Thus Eqn (4) could be expressed in linear logarithmic form as follows:

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L_0^2} \tag{5}$$

Water and oil—holding capacity determination

Method proposed by Larrauri was used with slight modification.[14] Five millilitres of distilled water or commercial olive oil were added to 0.2 g dry sample, which was then incubated at 40 °C for 1 h. After centrifugation, the liquid phase was separated and the residue was weighed. The water holding capacity (WHC) and the oil holding capacity (OHC) were calculated as the ratio of water or oil weight absorbed in gramme to that of dry sample in gramme.

Determination of nutritional characteristics

The protein content was determined using Kjeldahl method (AOAC method 988.05). The fat content was analysed according to AOAC method 920.39. The ash and raw fibre content were determined by gravimetric method accoding to AOAC method 942.05, and 962.09, respectively. The Luff–Schoorl method was used to analyse the reduction of sugar content. The calcium, sodium, potassium and magnesium content was analysed using atomic absorption spectrophotometer according to AOAC method 988.35. High performance liquid chromatography analysis was used to determine the concentration of vitamin C, BHA, BHT and TBHQ.

Experimental design and statistical analysis

Interaction effect betwen the design variables was analysed by response surface methodology (RSM). A two-variable central composite rotable design was used. This design needs at least 13 experiments including four-repetition runs at the centre point. The experiments were run in random to minimise the effects of unexpected variability in the observed responses because of extraneous factors. For each factor, the experimental range and the central point were based on the results of other preliminary experiments. Table 1 lists the independent variables, their symbol, the coded and real factor level. The objective was to observe the influence of the process variables, i.e. steam pressure/temperature and time of treatment in DIC reactor on the dependent responses, which consisted of banana flour physical properties, including WHC and OHC. The processing pressure (ξ_1) and the treatment time (ξ_2) were set as the design variables. The dependent variables (referred to as responses), η, which were experimentally measured, were assumed to be affected by the two independent variables ξ_i and was formulated as follows:

$$\eta = f(\xi_1, \xi_2) \tag{6}$$

The obtained experimental data were analysed by RSM to fit to the following second-order polynomial model:

$$\eta = \beta_0 + \sum_{i=1}^{2} \beta_i x_i + \sum_{i=1}^{2} \beta_{ii} x_i^2 + \beta_{12} x_{12} \tag{7}$$

where β_o, β_i, β_{ii} and β_{12} are regression coefficients and

Table 1. Experiment runs expressed in coded and real values.

Run	Saturated steam pressure		High temperature processing time	
No	Coded level	Real values (MPa)	Coded level	Real values (s)
1	0	0.4	-α	12.3
2	0	0.40	0	30
3	-α	0.26	0	30
4	0	0.40	0	30
5	0	0.40	+	47.7
6	0	0.40	0	30
7	0	0.40	0	30
8	0	0.40	0	30
9	+1	0.50	+1	42.5
10	+	0.54	0	30
11	−1	0.30	+1	42.5
12	−1	0.30	−1	17.5
13	+1	0.50	−1	17.5

$\alpha = \sqrt[4]{2^N}$, N is the number of independent variables. In the present case: $N = 2$ and $\alpha = 1.4142$

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x_i are the coded variables linearly related to ξ_i. The coding of ξ_i into x_i is expressed by the following equation:

$$x_i = 2\left(\xi_i - \xi_i^*\right)/d_i \tag{8}$$

where ξ_i = actual value in original units; ξ_i^* mean of high and low levels of ξ_i; and d_i = difference between the low and high levels of ξ_i.

RESULTS AND DISCUSSION

The texture change

To observed texture change during DIC treatment, an observation was conducted on the surface of the dried banana slices by using a scanning electron microscope, and the results were presented in Figs. 4 and 5. Those scanning electron microscope pictures show formation of micropores within the product. The instantaneous pressure drop and rapid autovaporation of moisture surely became the factor that promotes the formation of such micropores.

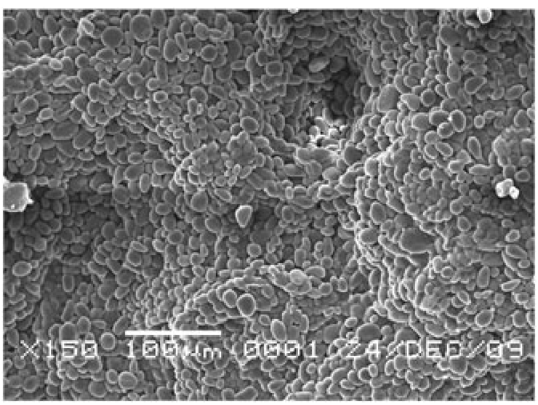

Figure 4. Dried banana before DIC treatment.

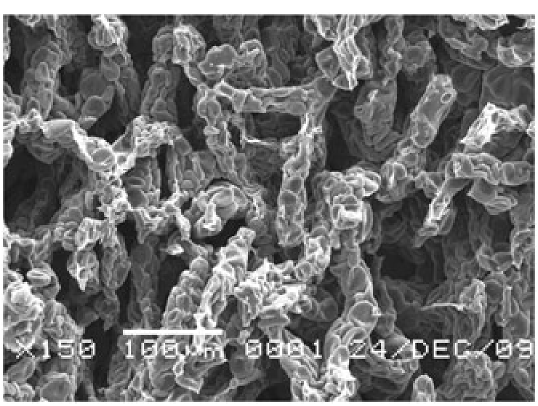

Figure 5. Dried banana after DIC treatment.

Moisture effective diffusivity (D_{eff})

The initial moisture contents of the banana obtained from the several experiments run were in the range of 60–62% (w. b.). The final moisture contents were in the range of 6–8% (w. b.). The observed profile of the moisture content change, that is expressed as moisture ratio (MR) change, is presented in Fig. 6. It showed that the experimental data lied on curvature profile, which indicated that falling rate drying mechanism had occurred during the whole drying period. In such case, water diffusion mechanism would control the process. To investigate the impact of DIC texturing on the drying kinetics, the main parameter had been the water diffusivity within the material. Taking the prerequisite assumption and setting material thickness 2 mm as L_o, then the effective diffusivity (D_{eff}) was calculated using Eqn (5). The results showed that the DIC treatment increased the water effective diffusivity.

The reference D_{eff} obtained with non-DIC-treated drying (drying without inserting DIC treatment) had been $8.11 \times 10^{-10}\,\text{m}^2/\text{s}$, whereas the D_{eff} values obtained from DIC-treated drying was higher, which was $10.01 \times 10^{-10}\,\text{m}^2/\text{s}$. It indicated that the change in banana physical properties, such as capillary and molecular diffusivity, had occurred during texturing by DIC treatment.

This hypothesis was enhanced by the fact that observation using scanning electron microscope, which was taken on the banana slice surface, show formation of micropores within the product. The formation of micropores led to faster moisture diffusion within the product. The higher D_{eff} value attributable to the texture change is one among other advantages of DIC treatment application, especially for biomaterial products.

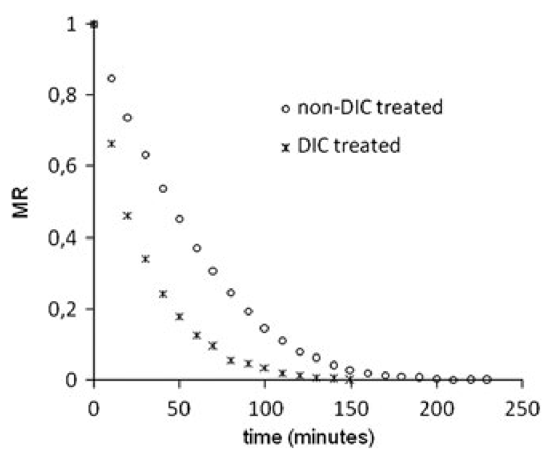

Figure 6. The profile of the moisture content change expressed as moisture ratio (MR).

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The water and the oil holding capacity

The WHC and the OHC are the physical properties that indicate the capacity to hold water and oil, respectively. Both these physical properties to have influent on the further processing of flour or powder food products such as blending to produce a certain final food product. Thus, appropriate WHC or OHC of food raw material becomes an important property. In this work, the effect of DIC treatment on WHC and OHC of the banana flour was studied.

Surface and contour plots for WHC were presented in Figs 7 and 8, whereas those for OHC were presented in Figs 9 and 10. It was found that the WHC of more than 7 g water/g was achieved by DIC treatment at a relatively high steam pressure (more than 4.5×10^{-5} Pa) for DIC treatment time between 30–45 s. It was also found that the WHC will be very low, below 3 g water/g, at the level of steam pressure less than 3.0×10^{-5} Pa, and DIC treatment time less than 15 s. In regard to OHC, OHC more than 1 g oil/g was achieved by DIC treatment at relatively low steam pressure (less than 4.0×10^{-5} Pa) for DIC treatment time less than 25 s. The OHC will be very low, below 0.6 g oil/g, at the level of steam pressure more than 5.0×10^{-5} Pa and DIC treatment time more than 35 s.

It was also found that texturing by DIC resulted in the increase of WHC from 2.0 g water/g dry banana (drying without DIC treatment) to 3.3–7.8 g water/g dry banana. On the other hand, texturing by DIC resulted in the decrease of the OHC from 1.3 g oil/g dry banana (drying without DIC treatment) to 0.6–1.1 g oil/g dry banana. The effect of pressure and treatment time on the WHC and OHC might be correlated with the change in its nutritional composition especially protein, thus reducing sugar and raw fibre content.

The trend result for the WHC indicated that the texture change resulted from the application of instantaneous pressure, and temperature drop has significantly changed the material structure. The formation of micropores during this treatment might have a correlation with the increasing specific surface of the material, which might increase the WHC. Meanwhile, the decreasing OHC might be correlated with the decrease of the fat, protein and sugar content after the material exposure to high temperature during the DIC treatment as shown in Table 2. The decreasing fat, protein and sugar content might correlate with the decreasing hydrophobic character of the material.

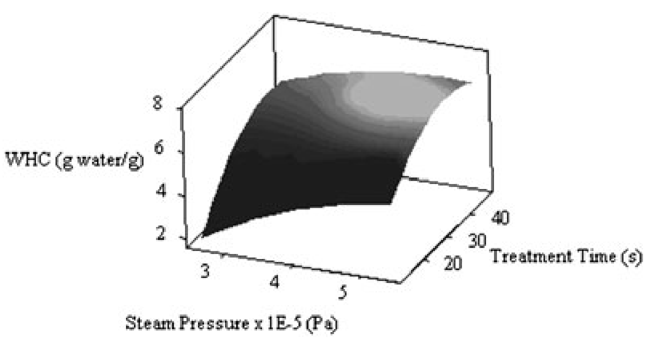

Figure 7. Surface plot of the water holding capacity.

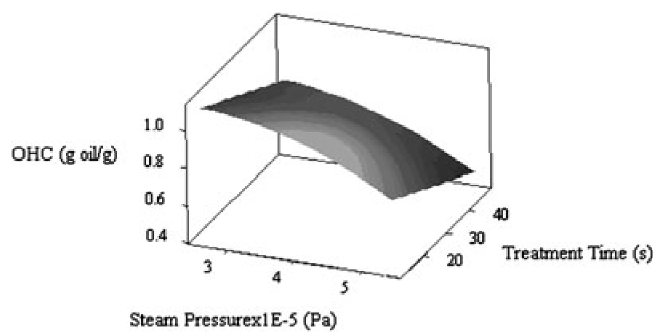

Figure 9. Surface plot of the oil holding capacity.

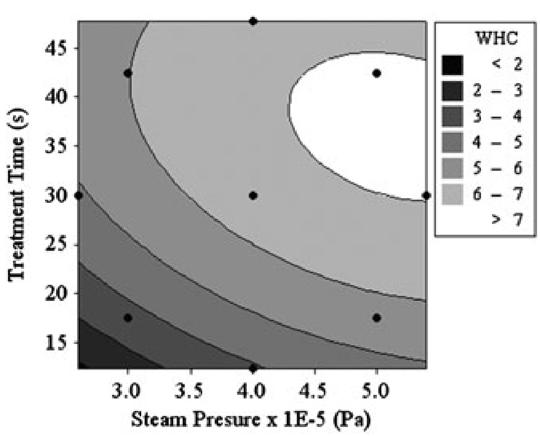

Figure 8. Contour plot of the water holding capacity.

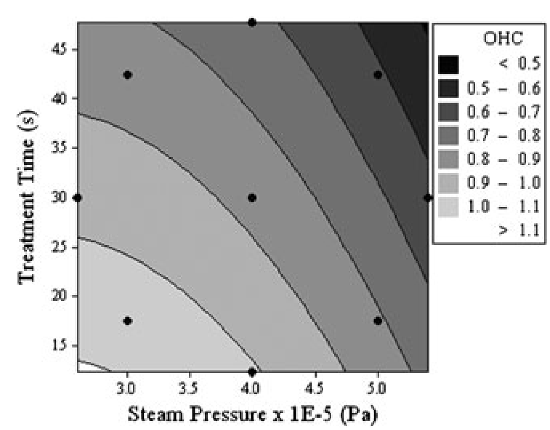

Figure 10. Contour plot of the oil holding capacity.

Table 2. Nutritional characteristics of the banana flour among different processes.

Parameter	Unit	Process Sun dried	 Non-DIC treated	 DIC treated
Protein	%	3.01	3.02	2.76
Fat	%	0.28	0.41	0.34
Ash	%	2.72	2.62	2.74
Raw fibre	%	0.85	0.65	1.40
Carbohydrate	%	86.27	87.20	86.55
Calorific value	kcal/100 g	359.64	364.57	360.30
Reduction of sugar	%	5.86	6.22	1.55
Phosphorus	%	0.09	0.10	0.08
Calcium	%	0.03	0.04	0.06
Sodium	%	0.02	0.02	0.02
Potassium	%	0.99	0.92	1.0
Magnesium	%	0.04	0.04	0.04
Vitamin C	ppm	<0.5	<0.5	<0.5
BHA	ppm	<0.5	<0.5	<0.5
BHT	ppm	<0.5	<0.5	<0.5
TBHQ	ppm	<0.5	<0.5	<0.5

Nutritional characteristics

The nutritional characteristic of sun dried, non-DIC-treated and DIC-treated banana are shown in Table 2. Sun-dried banana was obtained by exposing the banana slices to the sun light outdoor. It needed around 3 days to attain the moisture content of less than 8% (w. b.). Compared to the sun-dried and non-DIC-treated banana, the protein content of DIC-treated banana was lower. Some portion of the protein content of banana might decompose at the high temperature treatment of DIC. The DIC-treated banana also exhibited the lowest reduction in sugar content compared to the other two treatments. This showed that the indigenous enzyme responsible for the hydrolysis of banana starch into the reduction of sugar might be deactivated or decomposed during DIC heat treatment. This was also supported by the fact that the lost protein content might include some indigenous enzymes. The other nutritional contents and caloric values of DIC-treated banana are not significantly different from the two other treatment methods. Compared with the sun drying and the non-DIC treatment, the lower fractions of protein and the reduction of sugar in the DIC-treated banana might also be correlated with the higher fraction of its raw fibre.

CONCLUSION

The impact of the texturing by instantaneous controlled pressure drop on the effective moisture diffusivity, the WHC and the OHC, and the nutritional characteristics of banana have been investigated. The texturing by instant controlled pressure drop has increased the effective moisture diffusivity, increased the WHC and reduced the OHC. It has been found that the banana texturing by DIC inhibited the transformation of banana starch to the reduction of sugar that might be attributable to enzyme deactivation during the heat treatment process.

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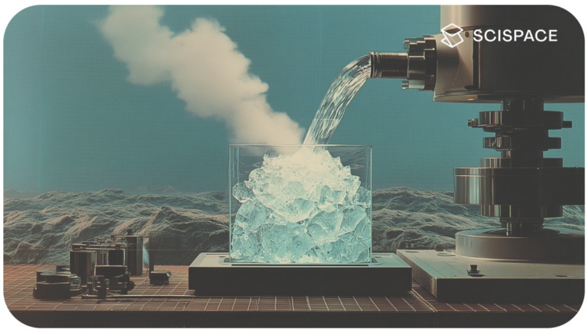

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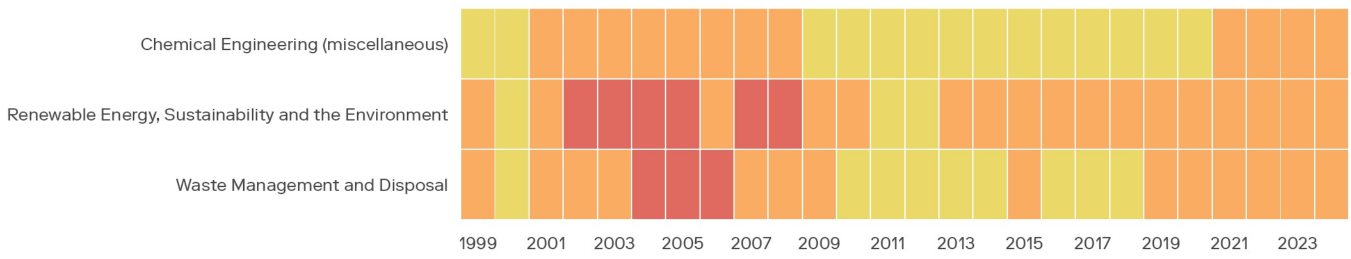

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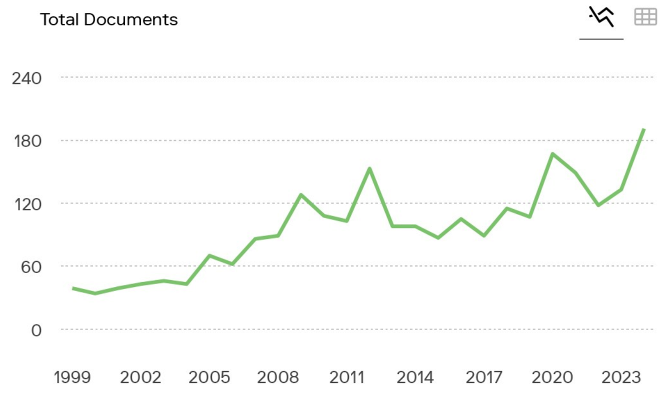

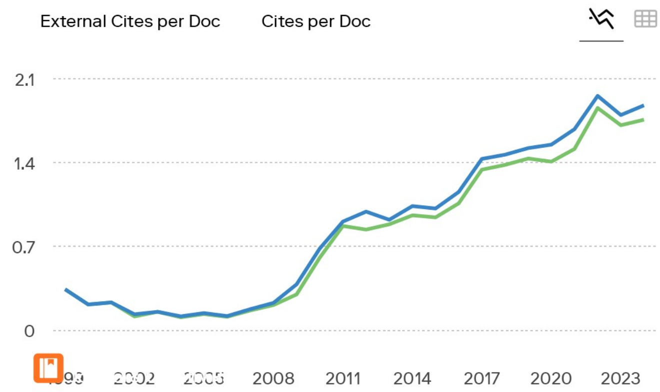

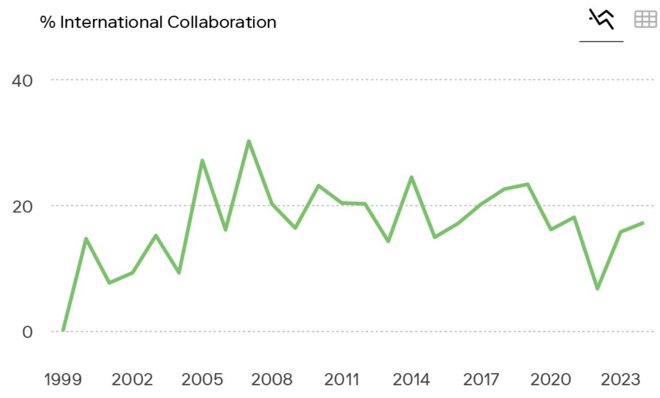

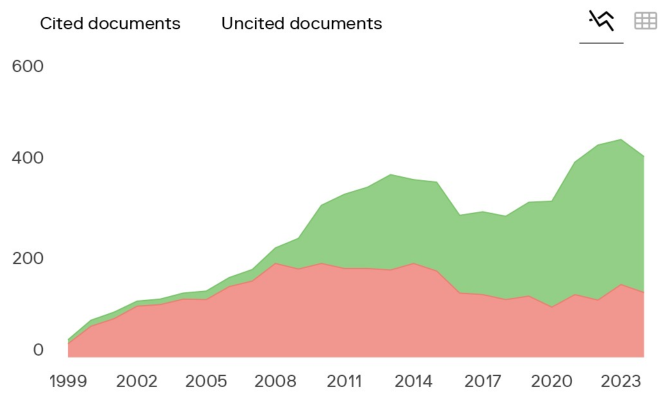

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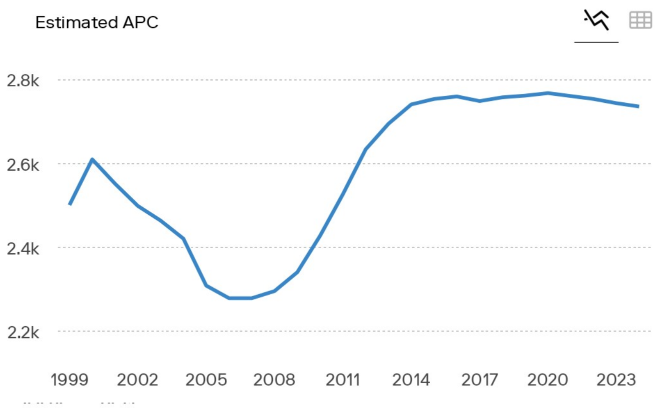
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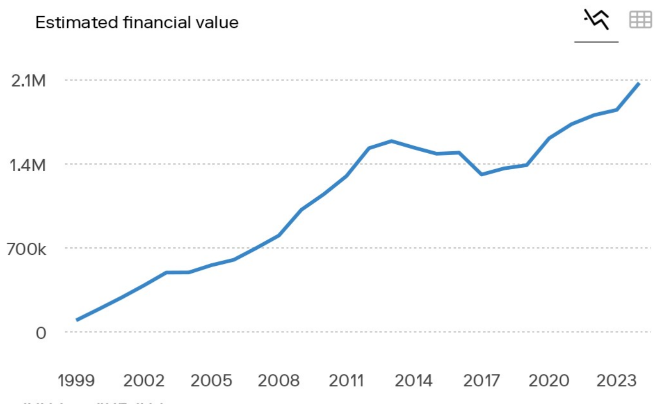
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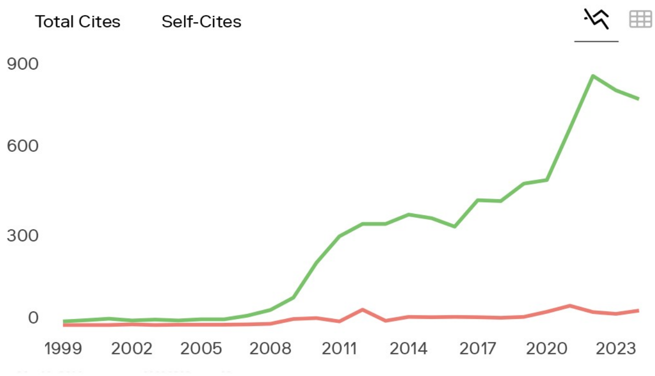
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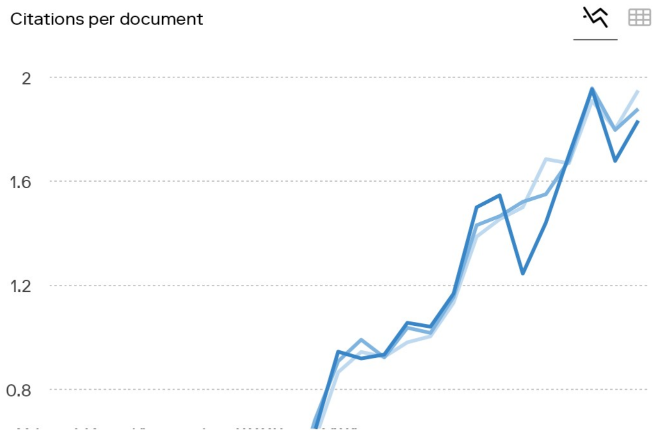
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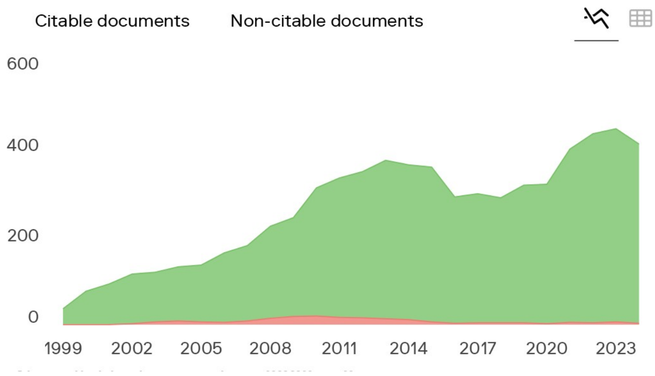

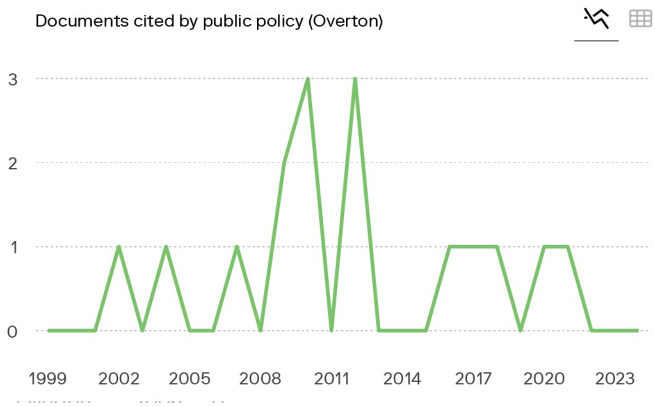

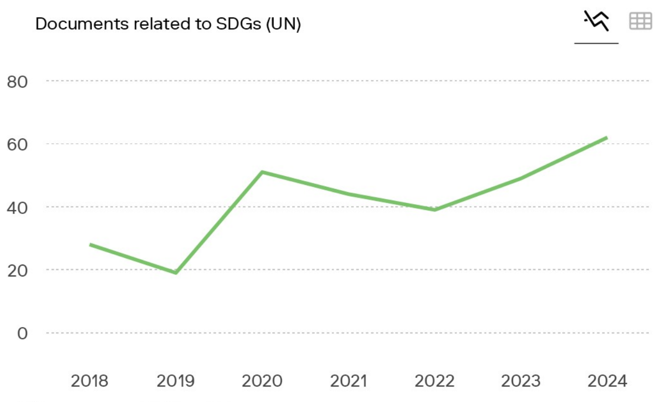

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