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Quality optimisation of combined osmotic dehydration and microwave assisted air drying of pineapple using constant power emission

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ABSTRACT

Combination of osmotic dehydration with microwave assisted air drying offers increased flexibility for process control and product quality. Osmotic dehydration (55°Brix solution at 40 °C for 90 min) combined with microwave assisted air drying (MWAD) was tested on smooth cayenne pineapples. The influence of the four most relevant processing parameters (osmotic treatment time, microwave power, air temperature and air velocity) was studied using a 2^4 circumscribed central composite experimental design. The product quality was evaluated in terms of charred appearance at the surface, moisture content, soluble solids content, water activity, firmness, colour and volume. Microwave power and air temperature were the two most important processing parameters that influenced the quality of the dehydrated pineapple, with the parameters most affected by the operating conditions being water content and percentage of charred pieces. Only in the latter was a significant quadratic effect found, all others were approximately linear. There was also a significant interactive effect between microwave power and air temperature affecting the percentage of charred pieces. Model predictions using a quadratic surface for water content and % charred pieces were validated with an additional experiment. Quadratic models were used to indicate optimum drying conditions for various targets.

Keywords: Combined technologies; Drying rate; Microwave drying; Osmotic dehydration; Overheating

1. Introduction

Microwave energy offers several advantages compared to conventional heating methods, including speed of operation, energy savings, precise process control and faster start-up and shut down times (Meredith, 1998; Datta and Anantheswaran, 2001). However, as microwaves penetrate within a food and generate heat internally, their greater processing interest is the capacity to deliver energy within the product. In thermal processing this means accelerated and more uniform internal heating and thus substantially decreased processing times, which leads to higher product quality as the detrimental effects of high temperatures are minimised. Other benefits include that microwave processing can also help control energy costs, since heating takes place only in the food material being processed and not in the surrounding medium (Nijhuis et al., 1998; Zang et al., 2006; Pereira et al., 2007).

Supplying microwave energy to a product while drying would have the added benefit of delivering energy fast and efficiently to the point of the structure where evaporation is occurring even when it moves inside the product, and could therefore increase drying rates substantially (Maskan, 2000). However, as water strongly influences the dielectric properties of the food, the electromagnetic field and consequent internal generation of heat in the product will vary substantially during the drying process. Several researchers have applied and studied the concept of applying microwave energy in air drying, which is sometimes referred to a microwave drying, but should properly be called microwave assisted air drying, MWAD (e.g. Al-Duri and McIntyre, 1992; Krodida and Maroulis,

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1997; Funebo and Ohlsson, 1998; Hao-Feng et al., 1999; Maskan, 2000; Erle and Schubert, 2001; Prothon et al., 2001; Zang et al., 2006; Pereira et al., 2007; Vadivambal and Jayas, 2009).

A further benefit to the drying process could be obtained by using osmotic dehydration (OD) as a pre-treatment. The process consists in a pre-drying by immersion of the food in an isotonic solution, typically composed of sucrose. From a MWAD process perspective, it could offer more flexibility because the isotonic solutes may influence the dielectric properties of the material; therefore, controlling the extent of the solute infusion could influence the intensity of MW heating and hence its impact in the drying process. Also, the infusion of solutes increases the glass transition temperature and collapse temperature of the structure which lead to a better appearance (minimised shrinkage) and porosity (improving rehydration properties). Quality is also affected by the higher water content of the pre-osmotically treated products being higher (for the same water activity and hence shelf life), which provides interesting properties for use of such products in their dried state. Several authors reported improved product quality when using this technique (e.g. Funebo and Ohlsson, 1998; Venkatachalapathy and Raghavan, 1998; Raghavan and Silveira, 2001; Prothon et al., 2000; Erle and Schubert, 2001; Prothon et al., 2001; Contreras et al., 2006). The most common benefits mentioned compared to simple air drying are reduced shrinkage and improved microstructure due to the influence of osmotic solutes, and faster drying due to the use of microwave heating.

However, authors have generally considered product quality by analysing successfully dried pieces and discarded damaged ones (Funebo and Ohlsson, 1998; Venkatachalapathy and Raghavan, 1998; Raghavan and Silveira, 2001). The most usual cause of damage is overheating at or near the surface, as the microwaves continue heating the already dried crust in the latter stages of drying, which can cause significant charring and a burnt appearance. Due to the heterogeneity of the electromagnetic field and its interference with the food pieces themselves (which depends strongly on the equipment design and thus differs from equipment to equipment), there will be more or less pieces in different parts of the drier that may be affected. From a processing point of view, this is actually a crucial aspect of the process performance quality, as surface burnt pieces are discarded as waste.

The purpose of this work was to analyse the effect of a combination drying process (osmotic-microwave-hot air drying) on the quality characteristics of pineapple and determine the optimum processing conditions for high quality products, considering also the extent of damage due to overheating. Very little information is available in literature on MWAD drying of pineapples, with or without osmotic pre-treatment. Four processing parameters were varied, namely, osmotic treatment time, microwave power, air temperature and air velocity. The experimental design included the option of no osmotic treatment. For this analysis, it was intended to use a constant power emission of MW only. As the product dries, this means that the intensity of energy generation (energy per mass of product) actually increases with time. On the other hand, drying changes the dielectric properties of the material and internal energy generation generally decreases with the loss of water. Therefore, whether MW influence increases, decreases, or fluctuates, depends on various factors, including the composition of the food itself. Constant microwave power has been the most common way of applying microwave energy. As the operation conditions of a microwave drying processes are also commodity dependent (Orsat et al., 2007) and further studies are necessary for optimisation of microwave related drying (Zang et al., 2006).

2. Materials and methods

2.1. *Sample preparation and processing*

Anana comosus—smooth Cayenne type pineapples were sourced from East London in the Eastern Cape province of South Africa. Pineapple cylinders of 2 cm in diameter and 1 cm thick were cut using a cork borer. Samples were osmotically dehydrated and then placed in the MW drier. The same osmotic process parameters, other than time, were used for all samples, consisting in immersion at 40 °C in a 55°Brix sucrose solution at 40 °C for different time intervals. This eliminated eventual differences that temperatures or osmotic strength of the OD process could cause in the food structure, with different processing times then corresponding roughly to a different infusion of solutes (sucrose) and water content/water activity prior to the MWAD process. The temperature and sucrose concentration were selected from previous research to achieve a good balance between water loss and solids gain (Lombard et al., 2008).

The combined microwave/hot-air drier used was a prototype designed within the EU-funded CombiDry project (INCO-DEV programme) by P.O. Risman in collaboration with SIK, and constructed by TIVOX machine AB (TIVOX Maskin AB, Sweden). The dryer had a maximum output power of 1000 W operating at a frequency of 2450 MHz. The size of the cavity was optimised by modeling the microwave field distribution in the drier for fruit pieces having variable water content. The drying area was suitable for about 1 kg fruit pieces. The tray consisted of a net of Teflon, suitable for microwave applications, and the frame was made of polyethylene. The microwave power was controlled by a software program. The system instrumentation provided continuous monitoring and computerized data logging of product temperature, product weight (accuracy of ±2 g) and microwave power during drying. Product temperature was measured in the centre of the pineapple pieces using optical fiber temperature measurements (Luxtron 790 Fluoroptic Thermometer, Santa Clara, California, USA or Neoptic, Canada). Temperature was measured in four samples placed at different locations in the cavity. Air temperature and velocity were controlled by a separate console. The inlet air flow was located in the middle of the chamber and distributed in the cavity.

Fruit pieces were distributed evenly in a circuit shape of 3–5 rows. No samples were placed around the antenna as the power density was too high there. Microwave hot air experiments started with 500 g of osmotically treated pineapple pieces and the number of pieces was counted. Experiments with pineapple were carried out for 3 h. The quality assessment was made after the samples cooled down to room temperature.

2.2. *Analytical methods*

The quality parameters determined were percentage of pieces that had a charred appearance, moisture content, water activity, soluble solids content (°Brix), firmness, colour and volume. As charred pieces are not sellable, they represent a loss to the process, which should be minimised. Water and soluble solids content and water activity are basic composition prop-

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erties, the latter having a crucial role in defining the shelf life of the product (for a stable dried product, it must be less than 0.6). The Brix measurement is also likely to be related to sensory properties, namely sweetness. Colour and volume are two other quality parameters that relate to sensory value of the product, as well as firmness, which relates both to tactile sensation when handling and to biting/chewing.

Consistency is an important component of quality, and therefore the spread (variability) between samples is also an important parameter, some drying conditions could lead to greater consistency than others. Therefore, the standard deviation of the water content measurements of the various samples analysed in each experiment was also considered as a response, to verify whether any of the factors would contribute to a greater homogeneity or heterogeneity of the batch.

Six of the samples were marked so that the same samples were monitored for weight change (in OD and subsequent MWAD). The number of charred pieces was counted at the end of the drying period. The moisture content was determined using the oven drying method described in AOAC (2000), Method 934.06. Soluble solid content (°Brix) was measured with a refractometer (ABBE ATAGO 3T). Colour was analysed by the L,a,b scale with a Hunter Colorquest-0145. Texture was analysed with an Instron Universal Testing Machine (Model 4301) at a crosshead speed of 50 mm/min with a 3 mm diameter punch—penetrating the entire sample. Water activity was determined with a Novasina Thermoconstanter (TH2/RTD-33/BKS).

Volume was determined by the Archimedes principle using n-heptane. A hook was attached to an analytical balance and weighed in air and immersed in n-heptane. A pineapple sample was placed on the hook and weighed in air and when immersed in n-heptane. The volume was then given by the weight of the displaced n-heptane being equal to the buoyancy force.

2.3. Experimental design and data analysis

A 2^4 circumscribed central composite experimental design was used, with a two stage analysis: a first subset of data corresponds to a full two-level factorial design, which allows to analyse the influence of each factor and interactions between factors without assuming any model. A second subset of data is obtained for three other levels of values of the factors, where each is fixed at a maximum and at a minimum while all others are fixed at the middle point. The full set provides a better analysis of the type of influence of the factors, with a higher certainty as to the relevance and shape of curvatures (estimated by quadratic effects) then with 3-level designs, and is fitted by a full quadratic model which can then allow to estimate regions of optimum operation. The factors (processing variables) considered were: osmotic drying time, microwave power, inlet air temperature and inlet air velocity. Table 1 shows the levels of the processing variables that were selected. It is noted that the experimental design includes the option of no osmotic treatment.

The results of the 2-level factorial design subset of data were first analysed with an ANalysis Of VAriance (ANOVA), which quantifies the variability of the data with its sum of squares (sum of squared residuals to the average), and then determines the portion of this sum of squares that can be attributed to the influence of each factor and each two-way interaction between pairs of factors. The remaining sum of squares left unexplained is attributed to the error (natural variability or white noise, influence of uncontrolled factors and error of the method of measurement), and permits calculating the statistical significance of the influence of each factor and interaction to a chosen level of confidence (90% was considered).

Table 1 – Experimental design (circumscribed central composite design). Experiments were performed in randomised order. MW Power refers to the energy density at the initial conditions (500 g of pre-OD treated samples).

	OD time (min)	MW Power (W/g)	Air temperature (°C)	Air velocity (m/s)
1	45	0.35	40	1.4
2	45	0.35	40	3
3	45	0.35	60	1.4
4	45	0.35	60	3
5	45	0.65	40	1.4
6	45	0.65	40	3
7	45	0.65	60	1.4
8	45	0.65	60	3
9	135	0.35	40	1.4
10	135	0.35	40	3
11	135	0.35	60	1.4
12	135	0.35	60	3
13	135	0.65	40	1.4
14	135	0.65	40	3
15	135	0.65	60	1.4
16	135	0.65	60	3
17	0	0.5	50	2.2
18	180	0.5	50	2.2
19	90	0.2	50	2.2
20	90	0.8	50	2.2
21	90	0.5	30	2.2
22	90	0.5	70	2.2
23	90	0.5	50	0.6
24	90	0.5	50	3.8
25	90	0.5	50	2.2
26	90	0.5	50	2.2

The full results of the experimental design were then analysed by fitting a response surface model, which divides the influence of a factor in two effects, a linear and a quadratic, in addition to including the interactive two-way effects between factors:

$$Y_i = a_o + \sum_{j=1}^{4} a_j F_{ij} + \sum_{j=1}^{4} \sum_{k=1}^{4} a_j a_k F_{ij} F_{ik} \quad (1)$$

where a are the model parameters and F are the coded values of the factors (−1 for the minimum value, 1 for the maximum, 0 of the centre point and 0.5 for the so-called star points of the design). a_o is therefore simply the model offset (value at centre point), a_j is half of the linear effect of factor j, $a_j a_k$ is half of the interactive effect between factors j and k, and a_{jj} (when $k = j$) is half of the quadratic effect of factor j. The statistical significance of the model parameters reveals the type of influence of a factor. If a quadratic effect is not statistically significant, then the influence of the factor is roughly proportional in the range of values tested, while if the quadratic effect is significant, then there is either a region of low influence and another of high influence, or there is a point of maximum or minimum in the range of values studied. To verify whether linear, quadratic and interactive effects are statistically significant, a Pareto diagram can be plotted, with the standardised effects (ratio between the parameters and their respective 95% con-

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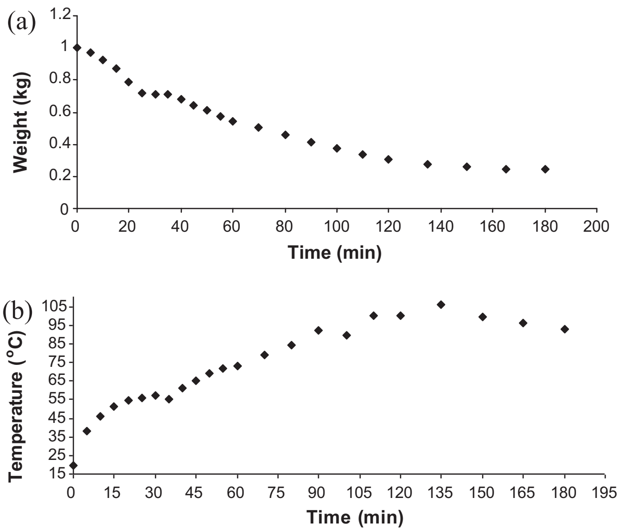

Fig. 1 – Typical drying curve (a) and temperature (b) in a drying pineapple in the microwave dryer (osmotic dehydration at 40 °C in 55% °Brix sugar solution for 120 min, microwave power 0.35 W/g initial weight, 70 °C inlet air temperature and 2.9 m/s inlet air velocity).

fidence interval) represented as bars from the bigger to the smaller, against a vertical line indicating the limit of significance (t-Student value for 95% confidence level). The bars that cross the line correspond to statistically significant effects and the bigger the bar, the more important is the effect.

In addition, the quadratic model can be used to predict a point of optimum (minimum or maximum), and thus, the optimum processing conditions.

All analysis were made using Statistica version 7.0 (StatSoft (Pty) Ltd., Tulsa, OK, USA).

3. Results and discussion

3.1. General issues

Fig. 1 shows typical drying curves and average temperatures during the drying process. Eventual correlations between the different parameters were analysed visually (graphs not shown) and it was concluded that all parameters were fairly independent of others, with some slight exceptions. There was a correlation between moisture content and % charred samples, as there were no charred samples with high water content, but at the lower water contents there was no correlation between it and % charred pieces. Similarly, the higher firmness was found in samples with higher % charred pieces, but there was no correlation between these two factors for the softer samples. There was a fair correlation between volume and water content with higher volumes for the higher water contents, which is not surprising. Similarly, firmer samples also had lower volumes, but there was no correlation between firmness and volume in the softer samples. A correlation between water content and water activity was associated to the sorption isotherm of the product itself.

3.2. *Influence of the processing variables on the quality parameters*

The results of the ANOVAs for all quality factors using the subset of experiments 1–16 were summarised in Table 2.

It can be seen that the osmotic dehydration processing time had no influence on any parameter except the °Brix of the sample, which should obviously be influenced by the sucrose infusion kinetics, and none of its interactions with the drying processing variables were significant. It should be however noted that this subset of data did not include the point with no osmotic treatment, which would allow for the estimation of the effect of applying osmotic drying or not.

Table 2 also shows that volume was not influenced significantly by any of the parameters. Colour was only slightly influenced with statistical significance, the *a* parameter being affected by the microwave power. The *a* values were generally negative (that is, samples were yellow-greenish) and the effect was positive, that is, increasing microwave power generally led to more yellow-reddish colours, which is consistent with overheating (approaching browning before actual charring). The soluble solids content was affected by the osmotic dehydration time and by the interaction between the inlet air velocity and temperature. Water activity was influenced only by microwave power, explained by the fact that increasing the power shortened the drying time and as all samples were dried for the same time, they would be more dried with higher power.

No factor contributed to increase or decrease the variability within the batch, judging by the standard deviation of

Table 2 – ANOVA results of the quality parameters[a], showing the sum of squares explained by each factor or interaction. Statistically significant factors or interactions are denoted in bold.

		% B	WC	σ WC	V	f	L	a	b	°B	a_w
Main effects	OD time (t)	0.008	0.000	0.000	0.049	23.986	222.234	0.218	20.115	**88.689**	0.001
	MW Power (M)	**0.706**	**0.198**	0.000	0.221	**105.04**	420.558	**11.719**	9.986	15.980	**0.086**
	Air temp. (T)	**0.163**	**0.042**	0.000	0.502	**70.871**	109.255	0.000	24.751	23.401	0.022
	Air velocity (v)	**0.025**	0.000	0.001	0.000	2.410	89.634	0.124	12.674	18.041	0.026
Interactions	$t \times M$	0.008	0.009	0.015	0.141	28.164	205.564	0.258	23.184	26.394	0.007
	$t \times T$	0.004	0.011	0.012	0.171	3.019	56.739	0.150	19.803	20.498	0.000
	$t \times v$	0.016	0.032	0.001	0.054	5.483	148.535	0.629	11.868	23.888	0.000
	$M \times T$	**0.118**	0.006	0.001	0.006	**46.023**	293.865	0.745	20.748	25.578	0.019
	$M \times v$	**0.025**	0.008	0.006	0.136	0.026	69.514	0.066	16.000	4.829	0.018
	$T \times v$	0.002	0.014	0.001	0.039	0.485	347.170	0.002	6.076	**106.24**	0.001
Error		0.014	0.030	0.023	0.431	23.692	997.29	5.492	140.82	62.829	0.020
R^2 (%)		98.7	91.5	61.6	75.3	92.3	66.3	71.7	54.0	84.9	89.8

[a] % B—percentage of burnt pieces; WC—water content; σ WC—standard deviation of the water content among samples; V—average sample volume; f—firmness; L, a and b—colour parameters; °B—degrees Brix; a_w—water activity.

the water content, which was not significantly affected by any.

Microwave power was generally the most influential factor, with the inlet air temperature being also relevant for percentage of charred pieces, water content and firmness. The inlet air velocity had a quite negligible effect, except for a slight influence on the percentage of charred pieces.

The negligible influence of osmotic dehydration time deserves a better analysis, as it did not validate literature data on apples and berries (Funebo and Ohlsson, 1998; Venkatachalapathy and Raghavan, 1998; Prothon et al., 2001; Raghavan and Silveira, 2001). This is likely due to the more fibrous nature of pineapple, which means that its structure is already protected from collapse by this fibrosity, and hence was less improved by osmotic dehydration. In fact, the experimental data points obtained with no osmotic dehydration (experiment 17 in Table 1) led to fairly average values in all parameters. This is shown in Fig. 2, where all data points for all quality parameters are plotted normalised by the respective range of spread, and where the points for experiment 17 are highlighted from all others. It can be seen that the drying experiment of pineapple pieces that were not osmotically predried is not particularly different from all others, except that it had the highest value of the *b* colour parameter, that is, it provided the samples that were more yellow (the *b* axis indicates colour changes from blue at the − extreme to yellow at the + extreme). As pineapples should be yellow, it may suggest that osmotic dehydration caused some loss of the natural yellowness of the product and hence some loss of natural colour. An improvement in volume or texture with osmotic dehydration was not observed. Fig. 2 also highlights the data points obtained with the same combination of settings for the drier factors (microwave power, inlet air temperature and inlet air velocity), but the extreme of osmotic dehydration (180 min). Comparing the effect of osmotic dehydration just at those levels (centre) of the other 3 factors seems to suggest that indeed osmotic dehydration caused a significant loss of the yellowness (parameter *b*), and also led to some of the lowest values of firmness and percentage of samples that were charred. This would be consistent with a greater plasticity and smoothness of the structure, which could have an effect in preventing hot spots and thus charring. This would be a clear benefit, but the results show that manipulating the drier operating variables could cause an equally suitable effect in adjusting the quality parameters of the product, and the ANOVA indicated that the influence of osmotic dehydration was overall statisti-

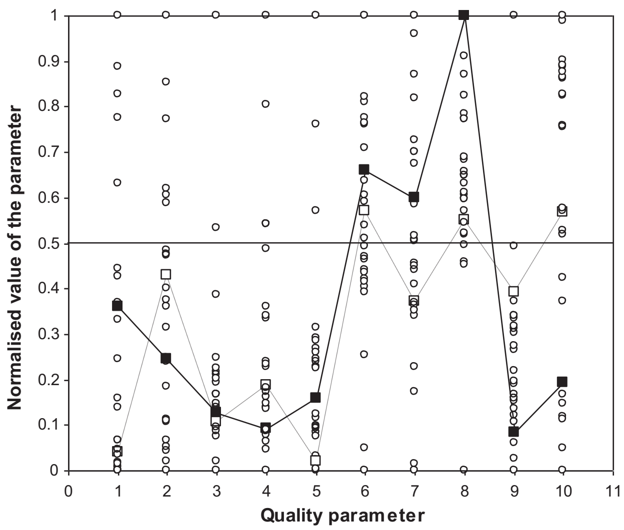

Fig. 2 – Normalised values of the quality parameters for all experiments (0 corresponds to the minimum value measured and 1 to the highest). The experiment performed with no osmotic dehydration is enhanced with a full square and full line, and the one with the same microwave power, inlet air temperature and velocity, but 180 min of osmotic treatment at 40 °C in a sucrose solution of 55°Brix is highlighted with open squares and dotted line. Quality parameters: 1—percentage of charred pieces, 2—water content, 3—standard deviation of the water content in a batch, 4—volume, 5—texture, 6—colour parameter *L* (black → white), 7—colour parameter *a* (green → red), 8—colour parameter *b* (blue → yellow), 9—soluble solids content, °Brix, 10—water activity.

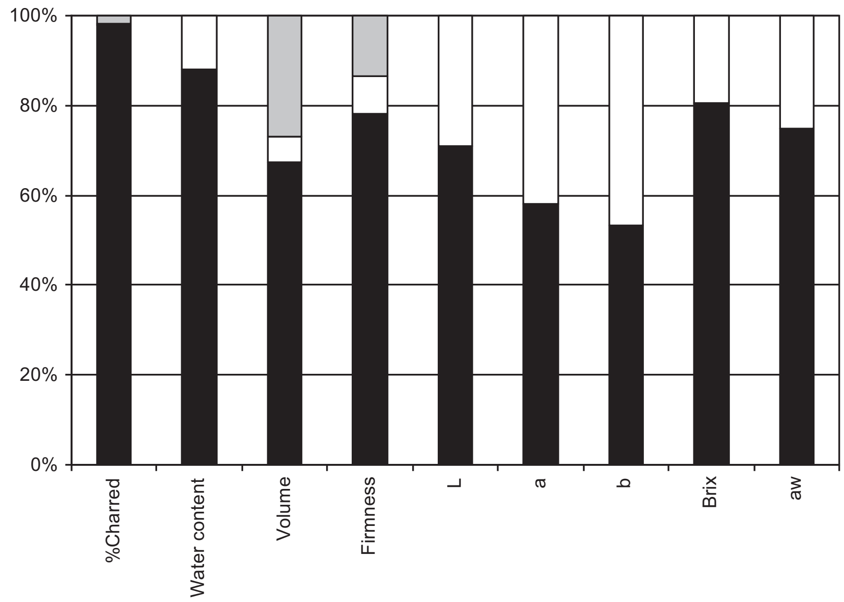

Fig. 3 – Percentage of the sum of squares of the data that is explained by the quadratic models (solid black bar), by the estimate of the pure error (white bar) and by an estimated lack of fit of the model (solid grey bar) for the quality parameters measured.

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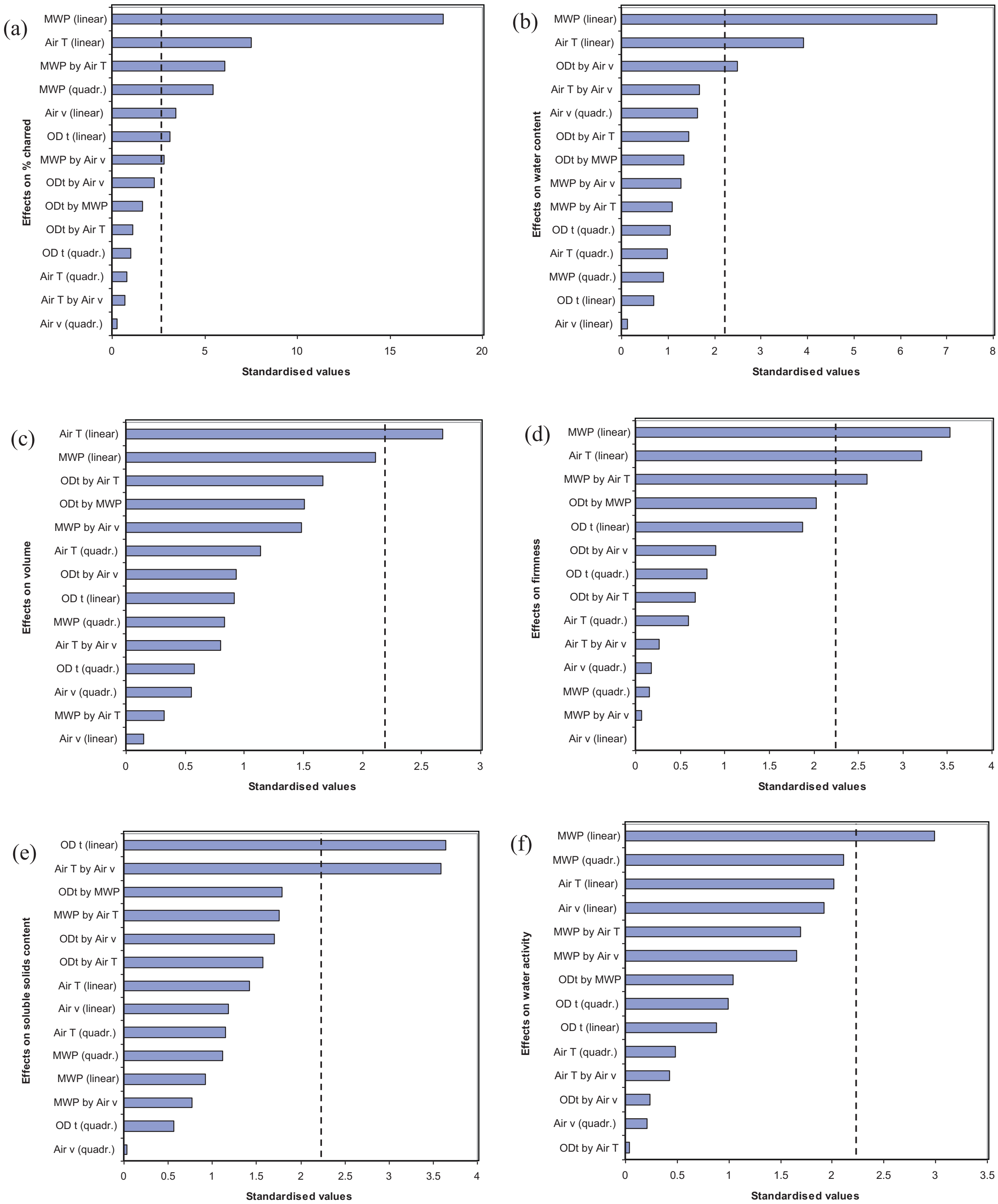

Fig. 4 – Pareto charts of the linear, quadratic and interactive effects of the process variables on the quality parameters most affected. Bars crossing the vertical line are statistically significant at 95% confidence level.

cally weak, while that of the drier parameters was much more influential.

3.3. *Analysis of the significant effects*

The ANOVA results using the model to estimate all contributions to the sum of squares are not shown as it provided very similar results to the one performed in the previous section, showing a very good internal consistency of the experimental data. The main relevant difference was that some effects that previously were not statistically significant now are, although in relative terms they show the same comparative importance in relation to others. Namely, osmotic dehydration time now played a statistically significant (albeit small) influence on the percentage of charred pieces. This was due to the full set of data including a point with no osmotic dehydration, that is, an osmotic drying pre-treatment improves this quality parameter compared to no treatment, but the treatment time was then not relevant.

It was important to analyse the extent to which the error could be due to lack of fit of the quadratic model. The experimental design was not repeated, but there was a repeat point, the centre point. Thus, a rough estimate of the magnitude of the pure error could be obtained from the difference between these two points. If the whole design had been replicated and all points had the same error between them as the one shown by the centre point, then the sum of squares due to the natural error would be equal to:

$$SS_{pure\_error} = 25 \times (y_{c1} - y_{c2})^2 \quad (2)$$

where y_{c1} and y_{c2} are the two experimental values obtained at the centre point (runs 25 and 26 in Table 1). If this sum of squares was not sufficient to explain the portion of the total sum of squares not explained by the model, the remaining can only be attributed to lack of fit of the model. The results, in percentage terms, are shown in Fig. 3. It can be seen that only for volume and texture there could be a lack of fit affecting the conclusions, in the other cases, the low R^2 could be explained by white noise.

All data for all quality parameters were fitted to quadratic surfaces and the resulting Pareto charts of the parameters that were most affected by one or more of the drying parameters (as already seen in Table 2) are shown in Fig. 4a–f.

It was evident that microwave power and air temperature are the two processing conditions that had the most significant effect on the quality parameters. Microwave power had almost twice the effect than that of the air temperature on the moisture content and about two and a half times the effect on the number of charred pieces. It can be concluded that within the range of the present study, controlling the power output was the most important way to control the quality parameters of a MWAD process.

Fig. 4a shows an interactive effect between microwave power and air temperature and a quadratic effect of microwave power that are almost of the same order of magnitude, indicating that the effect of these two operating variables on the percentage of charred pieces was more complex than that on water content. This is not surprising, as the effect of air temperature and of microwave power is likely to be simply additive on water loss (the bigger the intensity, the bigger the effect, without too much interference between one and the other, although temperature influences dielectric properties). On the other hand, low air temperatures can cool down the product and compensate somewhat for hot spots, so low air temperatures and high microwave powers, or low microwave powers and high temperatures, could have lower percent of burnt pieces, while high of both would lead to greater charring. However, the quadratic effect suggested a region of optimum somewhere in the solution space, so this should be visualised in detail.

The response surfaces of the parameters that were more significantly influenced by the drying conditions and better fitted by the curves (% charred pieces and water content) are depicted in Fig. 5. It can be seen that the average moisture content of the dried pineapple decreased as the microwave power and air temperature increased. Fig. 5a shows well the interactive and quadratic effects that were significant in the results for % charred pieces. The quadratic effect of microwave power meant that there is a minimum, that is, an optimum level of microwave power to minimise the percentage of charred pieces, however, it was noted when looking at the data points that the minimum may be a mathematical artefact (noting also that the surface predicted negative values, which were physically impossible). It is likely that there was simply a plateau at low values of temperature and microwave power, but as the quadratic surfaces were parabolic, they would not be able to describe a plateau, and would curve to negative values. The interactive effect with temperature means that this point of (mathematical) optimum occurred for different values of the microwave power as temperature increased, and beyond a certain temperature, there was no more minimum, the best would be the lowest microwave power. The inclination of the gridlines in Fig. 5a shows well the influence of increasing air temperature on increasing charring at a constant microwave power. It was also noticed that with an air temperature of 30 °C it was possible to use up to 0.5 W/g (initial weight) of microwave power, above which charring would occur, even with the lowest air temperature, while the higher air temperature of 70 °C could also be used provided that the microwave power was not higher than about 0.3 W/g.

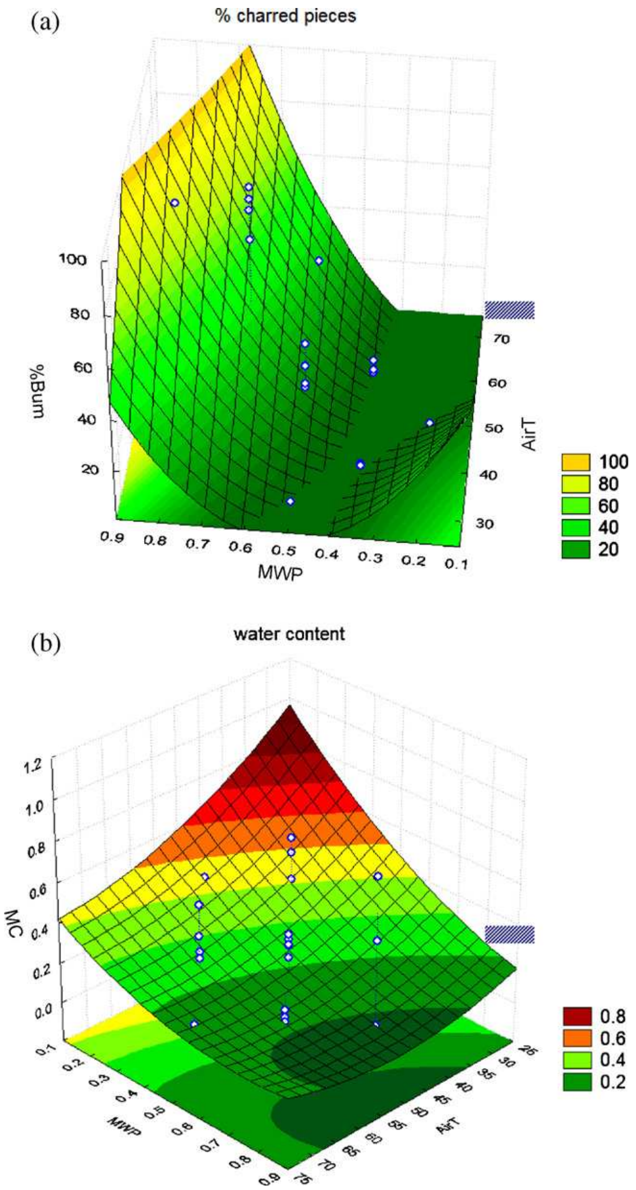

Fig. 5 – Response surfaces of the average % charred pieces (a) and water content (b) of dried pineapple as influenced by microwave power and air temperature. The surfaces were drawn for the middle point settings of air velocity and osmotic dehydration time and the experimental data are shown as circles. Graph (a) for % charred pieces was truncated to physically feasible values (0–100%).

Table 3 – Optimum operating conditions for various optimisation objectives. ODt is osmotic dehydration time in min at 40 °C and 55 Brix, MWP is the microwave power in W/g of initial weight, Air *T* is the inlet air temperature in °C, Air *υ* the inlet air velocity in m/s, % ch. is % of charred pieces, WC is water content in g water/100 g total weight and B is soluble solids content in °Brix.

Target	ODt	MWP	Air *T*	Air *υ*	% ch.	WC	°B
Minimum a_w with no more than 0.1% charred pieces	0	0.2	48.6	1.8	0.1	70	23.4
Minimum water content with no more than 0.1% charred pieces	123	0.30	70.0	2.9	0.1	20	29.3
Minimum soluble solids content with no more than 0.1% charred pieces	0	0.39	67.0	0.6	0.1	82	13.6
Maximum soluble solids content with no more than 0.1% charred pieces	0	0.2	69.9	3.15	0.1	41	46.4
Minimum charred pieces with water content not more than 20%	123	0.3	70.0	2.9	0.1	20	29.3

3.4. *Optimum drying conditions*

The quadratic models could be used to estimate optimum drying conditions, but first the predictive ability of the model should be validated independently. A new experiment was therefore performed with the following conditions.

Osmotic dehydration for 120 min, drying with 0.35 W/g of microwave power at 70 °C air temperature and with an air velocity of 2.9 m/s.

These conditions should result in some charred pieces, so that prediction could be properly tested, and were obtained by determining the minimum water content with a maximum of 5% charred pieces using the response surface models. At these conditions, the models predicted 5% charred pieces and a water content of 18%.

The drying curve and temperature evolution in the pineapple pieces were those given in Fig. 1a and b. The results were a water content of 11% and 6.5% of charred pieces. These were close enough to the predictions, with a slightly higher percentage of charred pieces but lower moisture content. This, together with the measured water activity of 0.6, made this set of conditions actually able to produce shelf-stable dried fruit pieces.

With the main models validated, several optimum conditions could be proposed, which at best depended on business objectives and strategies. Table 3 provides some examples. The models actually showed that it was not possible to obtain both a low water content and low water activity without significant charred pineapple pieces in the equipment used, within the range of process variables tested.

4. Conclusions

Microwave power and air temperature were the two most important factors that influenced the quality of osmotically pre-treated pineapple dried with microwave energy at constant emission power. There were no clear benefits of osmotic dehydration on volume or appearance, likely due to the fibrous nature of the pineapple microstructure, which makes it fairly resistant to water loss already. However, the quality parameters of the process and product that were more influenced by the operating conditions were the water content of the product and the percentage of pieces that are wasted (charred) due to overheating. Regarding the charred pieces, although less reported, it is a very crucial aspect of process performance and slightly better results were obtained with samples that were previously dried osmotically compared to no osmotic treatment–even though time of osmotic treatment did not play a significant role. The predictions of water content and % charred pieces by quadratic surface models were validated with an additional drying experiment, and the use of such models to define multicriteria points of optimum was illustrated.

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