Microwave assisted air drying of osmotically treated pineapple with variable power programmes

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Abstract

Variable power programmes for microwave assisted air drying of pineapple were studied. The pineapple pieces were pre-treated by osmotic dehydration in a 55 °Brix sucrose solution at 40°C for 90 minutes. Variable power output programmes were designed and run with different inlet air temperatures between 30 and 70 °C. Results indicated that the use of variable microwave power combined with low air temperatures can result in a fast drying process without significant charring of pineapple pieces. High microwave powers need to be reduced quickly, faster than the decrease in water content would suggest, to minimize charring. In this study inlet air temperatures of 70 °C were found to be excessive when combined with microwave energy (5W/g), resulting in fast temperature increase. Microwave power was found to be most effective in the first hour to 1.5 hr of processing, and afterwards should be reduced to 0.1 W/(g initial product weight) in the final stages of drying to avoid charring. The best microwave programme tested lead to 20% water content with just 1% losses due to charring, but the results allow to conclude that charring could be completely reduced byswitching off microwave energy altogether after 1.5 hours and then finish off drying with higher air temperatures. The use of low air temperatures (30 – 50 °C) is advantageous with microwave energy in the first stages of drying as it limits the peaks of specific energy absorption, but it slows down drying towards the end probably because of a too low point of equilibrium (saturation humidity of air). Microwave energy did not significantly influence the drying process towards the end, although drying rates showed a “memory effect”, that is, drying rates in processes with the same conditions after a given time depended on the conditions up to that point.

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1. Introduction

Drying foods with hot air is a simple but slow process that can lead to quality products particularly when combined with pre-osmotic dehydration (Prothon et al., 2001). The controlling factor in drying of foods is a combination of the rate at which energy reaches the evaporation surface and the rate at which water diffuses in the wet structure up to that evaporation surface. Providing more energy accelerates the process but high temperature may damage the surface of the product, creating a hard compact crust which will then hinder subsequent rehydration of the dried product. The temperature at which the product is dried should ideally be relatively low in the case of many foods, such as fruits and vegetables.

Foods are poor heat conductors, and a significant thermal gradient exists in the food, which limits the capacity to supply energy particularly when the slowness of the water diffusion causes the evaporation front to progress into the food. Water diffusion is also so slow in solid foods that a constant drying rate period when water evaporates from the surface is barely observable (Pereira et al. 2007): in fact, the evaporation front moves inside the product fairly quickly, and then supplying heat becomes increasingly difficult due to the thermal gradient in the already dried crust. Furthermore, the evaporation of water requires so much energy that all heat that moves from the surrounding air to the surface of the product and from there inside to the evaporation front is used to evaporate the water. The wet core of the product is therefore kept at the wet bulb temperature, not at the air temperature, and this wet bulb temperature should in fact be fairly lower than the air temperature, or the air would have a very poor drying capacity. This means that the temperature in the region where water needs to move (ideally fast) is low, being primarily responsible for the slowness of air drying.

Supplying energy with microwaves accelerates the process substantially for two reasons: it provides more energy directly inside the product (up to a given depth) and therefore boosts the heat supply to the evaporation front, and more importantly, provide heating beyond the evaporation front, so the product core elevates the temperature and water moves faster to the evaporation front.

The most common form of applying microwave energy combined with hot air to accelerate drying is to use a constant power throughout the drying process. In a previous work Lombard-Schlebusch (2008) studied the application of microwave energy at constant power (in pre-osmotically treated pineapple) and concluded that microwave power is the most influential processing factor affecting the quality and performance of a combination drying process involving osmotic dehydration and microwave assisted air drying, followed by the inlet air temperature. It was also found that some pieces may be wasted due to charring and while that can be minimised, in order to achieve a low water content / water activity, the risk of overheating and charring is high, and this is likely to be the major hurdle to develop a successful industrial process.

Microwave energy has been argued to be more beneficial in the early stages of drying by some authors (Zhang et al. 2006 and Orsat et al. 2007) but its usefulness in the later stages has also been clearly shown by others (Pereira et al., 2009, Ahrné et al., 2007). Actually, both are likely to be correct because it will depend on the temperature sensibility of the product and how the evaporation surface moves during drying. High microwave energy will certainly be particularly useful when the evaporation surface is at or close to the actual product surface in terms of the energy that is supplied to accelerate the evaporation rate. If in the limit the heating of the wet core of the product accelerates water movement to the point where evaporation is the controlling step and so occurs always at the product surface (constant drying rate period), there would likely be few losses due to overheating. As the evaporation front moves inside the product, the dried core may overheat rapidly. This would suggest that changing the frequency to accompany the movement of the evaporation front would be an interesting concept, but there are limits for industrial applications. The only other option is to decrease the intensity of microwave energy to minimise overheating, and/or lower the air temperature to cool down the surface, but this also has a negative impact on the drying rate as it lowers the driving force (a cooler air has a lower water saturation point).

It would seem more appropriate to use a variable microwave power programme, with the electromagnetic radiant energy decreasing in some form along the drying process. Wang and Xi (2005) used a two-step process while Clary et al. (2006) attempted a simple division in 3 steps, for drying grapes with a process combing vacuum as well. Ahrné et al. (2007) showed the advantages of varying microwave power during drying of plant based foods, controlling the power on the basis of the product temperature measured during the drying process, which is a good way to avoid product overheating. However, there is no established strategy to develop microwave assisted air drying programme with variable power that could be used when the product temperature cannot be measured during processing. The objective of this work was to analyse the application of microwave energy with a variable power programme and identify the most suitable strategy to accelerate drying while eliminating losses due to overheating (charring).

2. Materials and methods

2.1 Sample preparation

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.

The samples were treated osmotically at a 55 °Brix solution at 40° C for 90 minutes (Lombard et al, 2008). After the osmotic dehydration (OD) process, the samples were removed, momentarily rinsed, blotted with tissue paper and then placed in the microwave equipment.

2.2 Microwave prototype

The microwave hot-air prototype drier was designed 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 has a maximal output power of 1000 W operating at a frequency of 2450 MHz. The drying area is suitable for about 1kg of fruit pieces. The system instrumentation provided continuous monitoring and computerized data logging of product temperature, product weight (accuracy of ± 2g) and microwave power during drying. Product temperature was measured in the center 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. Temperature was measured in four samples placed in different locations in the cavity. Air temperature and velocity were set up and controlled by a separate console. The inlet air flow was located in the middle of the chamber and distributed in the cavity. The quality assessment was made after the pineapple samples have cooled down to room temperature.

2.3 Experimental procedure

The OD time and air velocity were fixed at an OD time of 90 minutes in a solution of 55 ^{o}Brix at 40 ^{o}C and an air velocity of 3.4 m/s for all experiments. A total of 1000g (approximately) of pineapple pieces were placed in the microwave for each experiment – this allowed the mesh to be evenly covered with samples without juxtaposition – the number of pieces was also recorded.

Five different variable microwave power programmes were tested, using different air temperatures. Pereira et al., (2007) have studied the difference of MW programmes in the latter stages of drying and the programmes chosen here focus on differences in the earlier stages of drying. The MW are used initially at higher energies to speed up drying, and progressively decrease, which should also have the benefit of minimising overheating and losses due to charring at or near the surface. In all cases, the microwave power was reduced by 15% at set time intervals, the programmes differing in the length of these timings. The microwave power programmes are shown in Figure 1. The outline of the programmes is easy to follow from the starting point that in preliminary experiments it was found that samples should not be exposed to the highest microwave power (1 W/g initial product weight) more than 600 s. This being the first of the 7 stages, in programme P1 the other 6 divide the remaining drying time (total of 3 hours) in equal periods (giving 1700 s for each), while in programme P3 the next periods have the same duration of the first (600 s), thereby leaving a last period of 7200s, and programme P2 provided an intermediate falling rate (1150 s for periods 2 to 6, leaving the last period with 4450 s duration). A programme of 2 hour duration was also used, providing a more concave fall of the energy emitted, using steps of unequal duration. Runs were performed with different air temperatures, between 30 and 70 ^{o}C, as specified in Table 1. Two replicate runs with a constant microwave power of 0.35 W were also performed, with 70 ^{o}C air temperature, for comparison, to previous work.

2.4 Analytical methods

Six of the samples were marked so that the same samples were monitored for weight change. Additionally, the total weight of the samples was monitored continuously by a scale onto which the sample tray was placed inside the oven. The number of charred pieces was counted - as charred pieces are not sellable, they represent a loss to the process, which should be minimised.

The moisture content was determined using the oven drying method described in AOAC (2000), Method 934.06.

Volume was determined by the Archimedes principle using n-heptane. A hook was attached to an analytical balance and weighed in air (W_h) and immersed in n-heptane ($W_{h,n\text{-}h}$). A pineapple sample was placed on the hook and weighed in air (W_{s+h}) and when immersed in h-heptane ($W_{s+h,n\text{-}h}$). The volume was then given by the weight of the displaced n-heptane being equal to the buoyance force.

The rehydration capacity and volume were measured by placing 4 samples in 100 mL of distilled water at room temperature for 4 hours, and then carefully blotting in tissue to remove excess water, weighing and measuring the volume.

A thermocouple was also inserted inside a pineapple piece in each run to record its centre temperature.

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

3. Results and discussion

3.1 Drying curves

Some of the drying curves obtained with the continuous weighing system are shown in Figure 2. It is assumed that the weight loss is exclusively due to water loss.

Fig. 2a shows clearly the influence of inlet air temperature on the drying rate, which increases significantly with temperature. The speeding up of drying achieved with the variable power programmes is also evident by comparing the constant curves with that of P3 at the same air temperature of 70^{o}C, although the constant power programme uses much lower energies in the earlier stages of drying. It is also noteworthy that the variable power programmes seem to lead fairly quickly to a plateau where water content then decreases very slowly. This likely implies that the final microwave powers were too low to cause any significant benefit. The use of higher microwave powers in the earlier times therefore seemed to speed up significantly the drying process, being the inlet air temperature the limiting factor.

It can be seen that if the microwave power of the P3 programme at 70 ^{o}C and P1 at 30 ^{o}C had been switched off at around 4000 s this would not have affected the drying process, as there was virtually no more drying taking place after the first hour of the process at these two conditions, as the plateau of water content reached indicates.

Figure 2b shows clearly that the faster the microwave power falls (P3), the slower the drying. During the first hour of the process, programme P2 provided a very similar drying curve to the constant power programme (which used lower microwave energy in this period but a higher air temperature). The increased microwave power therefore roughly compensated for the lower inlet air temperature (70 to 30 ^{o}C). P1 was insufficient to achieve this result, while P3 provided an even faster drying than that at constant conditions. After 4000 – 6000 s, the variable microwave powers have a slower drying, but as mentioned before, this was likely due to the lower air temperature equilibrating the drying process at an higher moisture content due to the humidity of saturation of air being much lower, and the microwave power being low.

In order to analyse the similarities between the drying curves better, the random effect of variability was smoothen out by fitting the experimental data to a smooth mathematical function. It was found that the Weibul model provided a very good fit of the data, as shown in Fig. 3 for the drying curves used in this analysis. The model is:

$$\frac{w - w_{eq}}{w_o - w_{eq}} = e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \qquad (1)$$

Where w is the weight of all samples measured by the scale with the subscripts o and eq meaning initial and of equilibrium, respectively, α is the system time constant and β the shape factor.

The parameters of these fits are shown in Table 2. It can be seen that the model fits are excellent, with very high coefficients of determination (R^2, percentage of the variance of the data that is explained by the model). With these functions, the derivatives were calculated in order to determine the drying rates, and these are shown in Fig. 4 in a logarithmic scale. Table 2 shows that the shape factor of the Weibul model fits were not statistically different from 1 except in one case, which means that almost all drying curves were close to exponential decays. Under those circumstances, drying rates fall approximately linearly with drying, and the logarithmic graph shows the drying rates very clearly.

It is evident that the processes with initially higher drying rates also have a faster fall of these rates as time progresses. This is simply due to the samples drying faster, with the drying rates approaching zero (it must be noted that Fig. 4 has a log scale). The crossover occurs in a relatively narrow window, around 1800 – 2200 s. The drying rates for programmes P1 with 30 ^oC air temperature and P3 with 70 ^oC were very similar after this time, as were those of programmes P2 with 30 ^oC air temperature and P3 with 50 ^oC. This shows that it can be considered that the effect of lowering the inlet air temperature from 70 to 50 ^oC can be compensated by changing the programme from P3 to P2, and that of the effect of lowering temperature from 70 to 50 ^oC can be compensated by changing the programme from P3 to P1. This shows well that it is possible to adjust the inlet air temperature and the microwave power programme to provide similar drying rates.

It is also very interesting to note that a “memory effect” can be observed in the drying rates. Programmes P1, P2 and P3 all come eventually to the same (low) microwave power, and from that moment, the runs at 30 ^oC are effectively the same, exposing the samples to this air temperature and to 10% of the maximum microwave power. However, the drying rates do not tend to become the same; they therefore depend on the drying conditions up to that point. This can be due to specific conditions like actual sample temperature and water content, but it is not uncommon in drying, where it is attributed to differences in the product microstructure caused by the different previous drying conditions.

3.2 Temperature and specific microwave energy in the samples

One problem that constant microwave programmes have is that the samples dry and therefore lose weight, so the microwave energy emitted may be constant, but it is being absorbed by a smaller weight in each sample. Therefore, the specific microwave energy absorbed will increase with drying. Combining the drying curves with the microwave programmes leads to the specific microwave power, that is, the power per unit of weight delivered (not absorbed) to the fruit pieces, which is shown in Figure 5.

It can be seen that with the constant programme the specific power increases steadily to about 1.6 W/g product, which is 4.5 times the initial energy applied. With the variable programmes at 30 ^oC, the specific power barely increases for P2 and P3 and actually starts falling after about 3600s (or 1 hr), and the levels of energy per g of product are actually very similar in these two programmes. With P1, which is the programme with higher levels of microwave power being used, the specific energy does increase significantly, reaching the same level as in the constant programme, but much earlier, at around 3600 s (or 1 hr), and then falls.

Comparing the runs with programme P3 at the 3 different temperatures shows a very dramatic effect of the increased drying rate provided by the increasing inlet air temperatures. With 30 ^oC air temperature the specific power is approximately constant for about an hour (3 600s) and then falls, with 50 ^oC air temperature the specific power increases and then falls, in a very similar manner to programme P1 at 30 ^oC, and with 70 ^oC air temperature the increase in specific power is very dramatic, reaching 5 times the initial value at around 5400 s, and then falls, reaching about the same level as initially only after the full 3 hours of drying.

The specific microwave power is a particular concern to the main quality problem - the appearance of charred spots due to scorching. This might also be noticeable by analysing the actual temperature of the product. The temperature of one sample in each run was monitored by placing a thermocouple inside, and the results are shown in Fig. 6. It can be seen that the behaviour of the variable programmes is dramatically different from the constant power programmes. The variable programmes were all able to limit the temperature of the sample to less than 100 ^oC, and it can be seen that the effect of the air temperature is not very significant. In all cases, the temperature increased to about 100 ^oC, somewhat slower or faster depending on the programme, and then decreased, stabilising at a value that depends on the air temperature and programme. With the constant power programmes, however, the temperature rose continuously, reaching values close to 150 ^{o}C in one case. This must be associated to significant scorching.

This analysis indicates that programme P3 with 70 ^{o}C uses excessive energy, and that the levels of microwave energy used in the constant programmes are excessive in the final stages of drying. Both may result in loss of quality due to scorching, and certainly result in energy waste.

3.3 Product quality

The main process performance criteria considered were the water content achieved, and the percentage of charred pieces due to overheating. The latter is a crucial quality factor of the process that variable programmes can improve. The results for the different runs are given in Table 3.

The two programmes that gave no charred pieces (P2 and P3 with 30 ^{o}C air temperature) also resulted in still fairly wet samples, with water contents around 30 %. However, programme P4, even though it worked only for 2 hours, reached those water contents, but with 5% losses due to charring. This shows the importance of decreasing the microwave power early, which is even more evident in the results of P1. However, it is possible to use programme P1, with generally higher levels of microwave energy, provided that the air temperature is just 30 ^{o}C, as at those conditions a water content around 20% is reached with less than 2% losses. This is a similar result to that of programme P3 with 50 ^{o}C air temperature. It is noted that these two programmes were found previously to provide very similar drying rates and also very similar histories of specific microwave energy. Although programme P3 with 70 ^{o}C did not show excessive sample temperatures, it resulted in samples with similar water content (about 10%) and similar losses due to charring (about 6%). It can be concluded that in a programme such as P3 / 70 ^{o}C microwave power would need to be switched off much earlier to avoid charring, and/or that the air temperature is excessive.

The results show that increasing air temperature and microwave power increased charring, as found for constant power by Lombard-Schlebusch (2008). Combining with the previous analysis, it would be concluded that programme P1 is excessive from the point of view of microwave energy, and that 70 ^{o}C inlet air temperature combined with the use of microwave power is also excessive from the point of view of the impact of the air temperature. Of the programmes tested, the best would therefore be to dry to 20% water content with programme P3 at 50 ^{o}C air temperature, which have a microwave energy/cost saving benefit advantage over P1.

However, the conclusions taken so far permit to suggest more complex programmes, using high microwave power with low temperature in the earlier times, and finishing off drying without microwave energy, and in this case, increasing the air temperature (to increase the driving force). The drying curves also suggest that microwave energy is best used only for 1 to 1.5 hours. The ideal programme will depend on business and product objectives, combining cost, productivity, yield and quality issues, and can be sketched from these results in terms of limits of interest for temperature, microwave power, and time.

An issue of particular importance is that of variability within the microwave dryer, as the microwave field is known to be quite heterogeneous. Therefore, it is not only the average water content that would be of interest, but its variability as well. The water content of 6 samples was measured for each run, selecting 3 that visually appeared to be more wet, and 3 that appeared to be more dry, to force to have as much variability as visually observed. The results are shown in Fig. 7. It can be seen that the water content of fresh samples and of samples after osmotic dehydration is very consistent. The dried pieces have much more variability, but it is noteworthy that in the run where the final result was still fairly wet (P3 / 30 ^{o}C), the variability is small, and that in the runs that led to more dried samples (P3 / 70 ^{o}C and constant / 70 ^{o}C), the variability is also smaller than in the intermediate values. This suggests that while the samples are dried to still fairly wet status, the variability is still low, possibly because temperature and water still diffuse with relative ease, alleviating hot spots. As some samples begin to reach a more dried status, the variability increases significantly, as some pieces dry faster and the run-away effect of microwave energy takes those that dry faster to dry even faster (eventually scorching). Temperatures in the samples as high as 150 ^{o}C were recorded, and even with low microwave energy (10% of the maximum), the temperature of the samples recorded was at least 10 ^{o}C above the inlet air temperature, as shown in Fig. 6.

Another quality aspect which also has obvious direct commercial interest is volume, both in terms of the volume of the dried sample and that of a rehydrated sample (considering possible use of the dried pieces as ingredients in other food products). The volumes of samples fresh, after osmotic dehydration, after the drying programme, and after subsequent rehydration (for 4 hours) are shown in Fig. 8. There was some variability in the size of the fresh samples, while that of osmotically dried pieces was quite constant. After drying, there was a fair variation, but interestingly, the volume of the rehydrated pieces was very similar, regardless of the programme, and therefore, regardless of the actual initial volume and water content that the samples had prior to rehydration. Therefore, it can be expected that the rehydration capacity of the dried pieces is not affected by the choice of drying conditions of the microwave programmes.

It can be seen in Fig. 9 that there is a general relationship between water content and volume, but in the range of 10 – 35 % water content, the volume of all samples was roughly equal regardless of the specific programme and resulting water content, at about one quarter of the initial size.

4. Conclusions

The use of a variable microwave power combined with low air temperatures can result in a fast drying process without significant charring of pineapple pieces. High microwave powers need to be decreased fairly quickly, faster than the decrease in average water content would suggest, which probably reflects the fact that at the surface, where charring occurs, the samples dry quickly and the evaporation front recedes into the product.

For pineapple, the inlet air temperatures of 70 ^{o}C were found to be excessive when combined with microwave energy (4-5 W/g), resulting in substantial peaks of specific energy absorption. Microwave power was found to be effective mostly in the first hour to 1.5 hr of processing, and after that it should be reduced. In the case studied 0.35 W in the final stages of drying proved to lead to excessive temperature in samples.

The best microwave programme tested would lead to 20% water content with just 1% losses due to charring, but the results suggested that a better system would lower microwave energy after 1 to 1.5 hours and then finish off drying with much lower microwave powers or higher temperatures. The use of low air temperatures (30 – 50 ^{o}C) is advantageous with high microwave energy in the first stages of drying as it limits the peaks of specific energy absorption, but it slows down drying towards the end probably because of a too low point of equilibrium (saturation humidity of air).

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Table 1 Experimental design, showing the combinations of microwave power programmes and inlet air temperatures that were used in the experimental runs. C refers to the constant power programme at 0.35 W and P1 to P4 are defined in Figure 1.

Air temperature (^{o}C)	Microwave power programmes				
	P1	P2	P3	P4	C
30	**X**	**X**	**X**		
35	**X**			**X**	
40	**X**				
50	**X**		**X**		
70			**X**		**X**

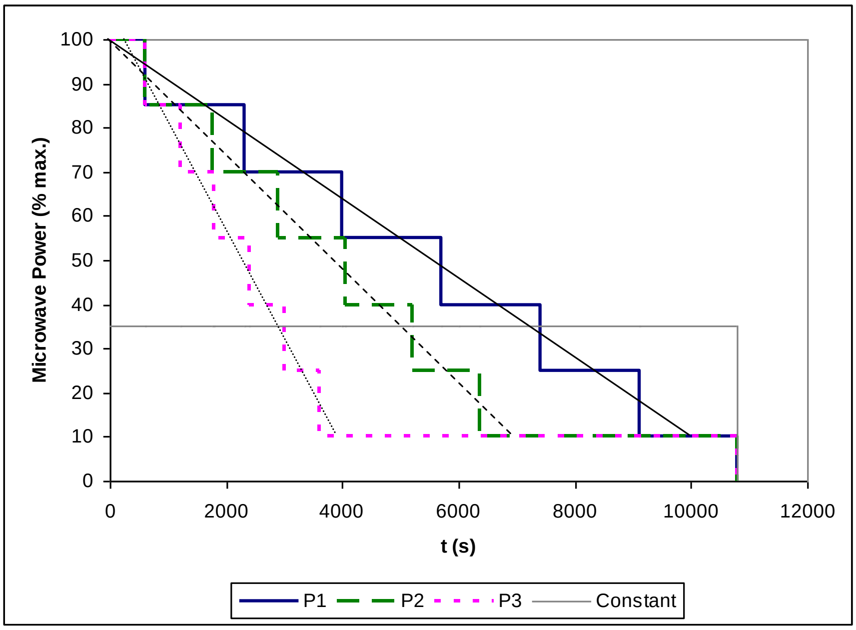
Table 2. Parameters of the fits of the Weibul model to the drying curve data.

Programme	T (^{o}C)	w_o	w_{eq}	α (x10^{-3})	β	R^2 (%)
P1	30	1.01 ± 0.02	0.354 ± 0.009	1586 ± 86	1.07 ± 0.08	99.73
P2	30	0.999 ± 0.008	0.419 ± 0.006	2369 ± 60	1.05 ± 0.04	99.95
P3	30	1.01 ± 0.02	0.379 ± 0.12	5452 ± 2577	0.68 ± 0.11	99.46
P3	50	1.03 ± 0.04	0.300 ± 0.027	1848 ± 211	0.94 ± 0.14	99.07
P3	70	1.01 ± 0.04	0.379 ± 0.018	5452 ± 115	0.68 ± 0.11	99.36
C	70	0.97 ± 0.05	0.167 ± 0.146	4295 ± 1509	1.18 ± 0.22	99.93
C (rep)	70	1.02 ± 0.01	0.131 ± 0.024	4353 ± 215	0.97 ± 0.07	99.75

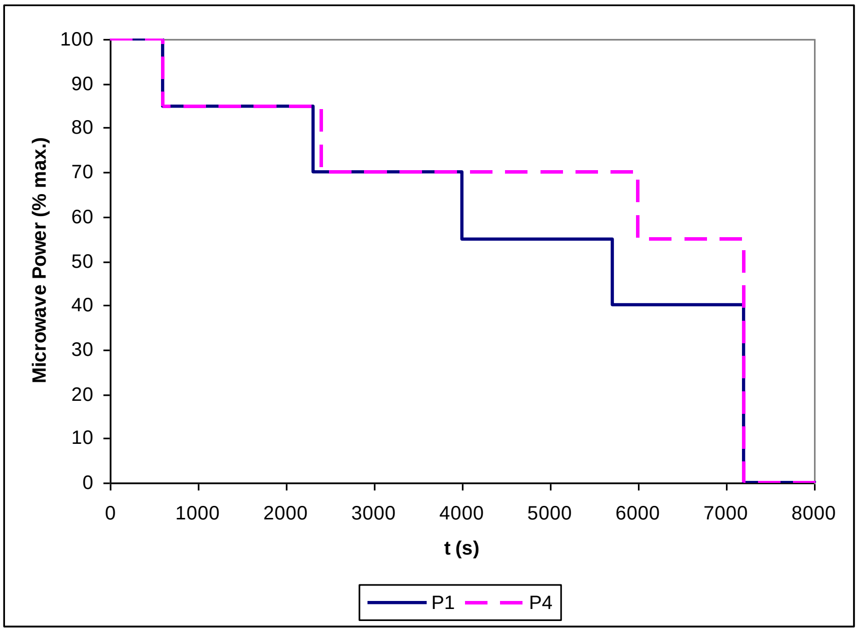
Table 3. Water content, water activity and percentage of burnt pieces in the different runs with different variable microwave energy programmes and air temperatures.

Cells containing two numbers give values of two replicated experiments. n.d. – not determined

Programme	P1	P1	P1	P1	P2	P3	P3	P3	P4	C
air Temperature (°C)	30	35	40	50	30	30	50	70	35	70
percentage of charred pieces	1.3 / 2.0	6.9	15.3	27.1	0	0	1.0	6.0	4.9	6.1 / 6.6
water content (% wet basis)	21.1 / 23.1	20.3	21.9	19.7	29.2	36.0	20.3	10.5	33.8	11.0 / 12.1
water activity	0.76	n.d.	n.d.	n.d.	0.83	0.86	0.76	0.58	n.d.	0.62 / 0.65



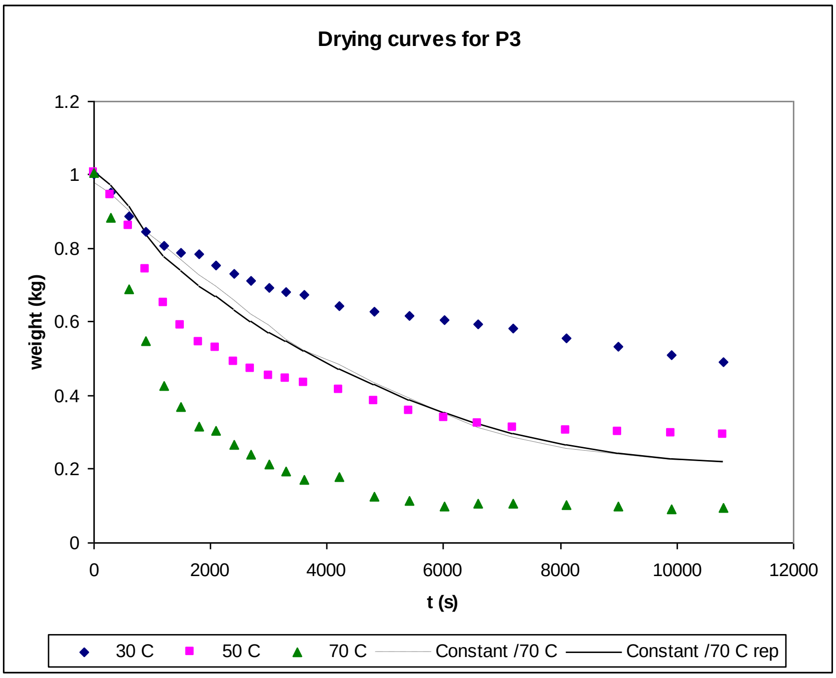
(a)



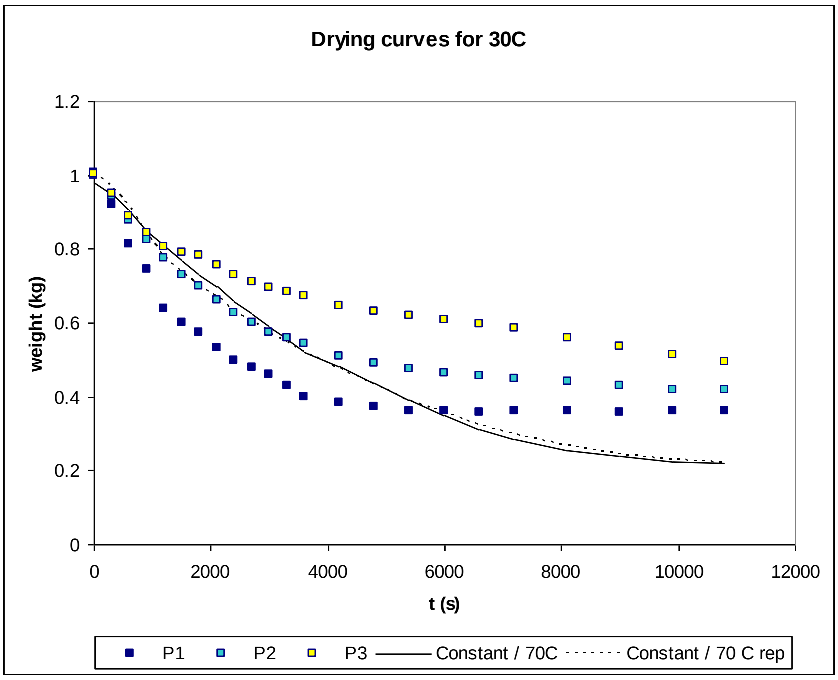
(b)

Fig. 1. Microwave power programmes used in the experiments. (a) 3 hour duration and (b) 2 hour duration.

The maximum power was 1 kW (= 1 W/g initial product weight). The thin lines in fig. a visualise the average rate of decrease of microwave power



(a)



(b)

Fig. 2. Drying curves for (a) programme P3 with 30, 50 and 70 ^{o}C air temperature and (b) programmes P1, P2 and P3 with 30 ^{o}C air temperature, with the two replicates for constant power of 0.35 W and 70 ^{o}C air temperature shown for comparison

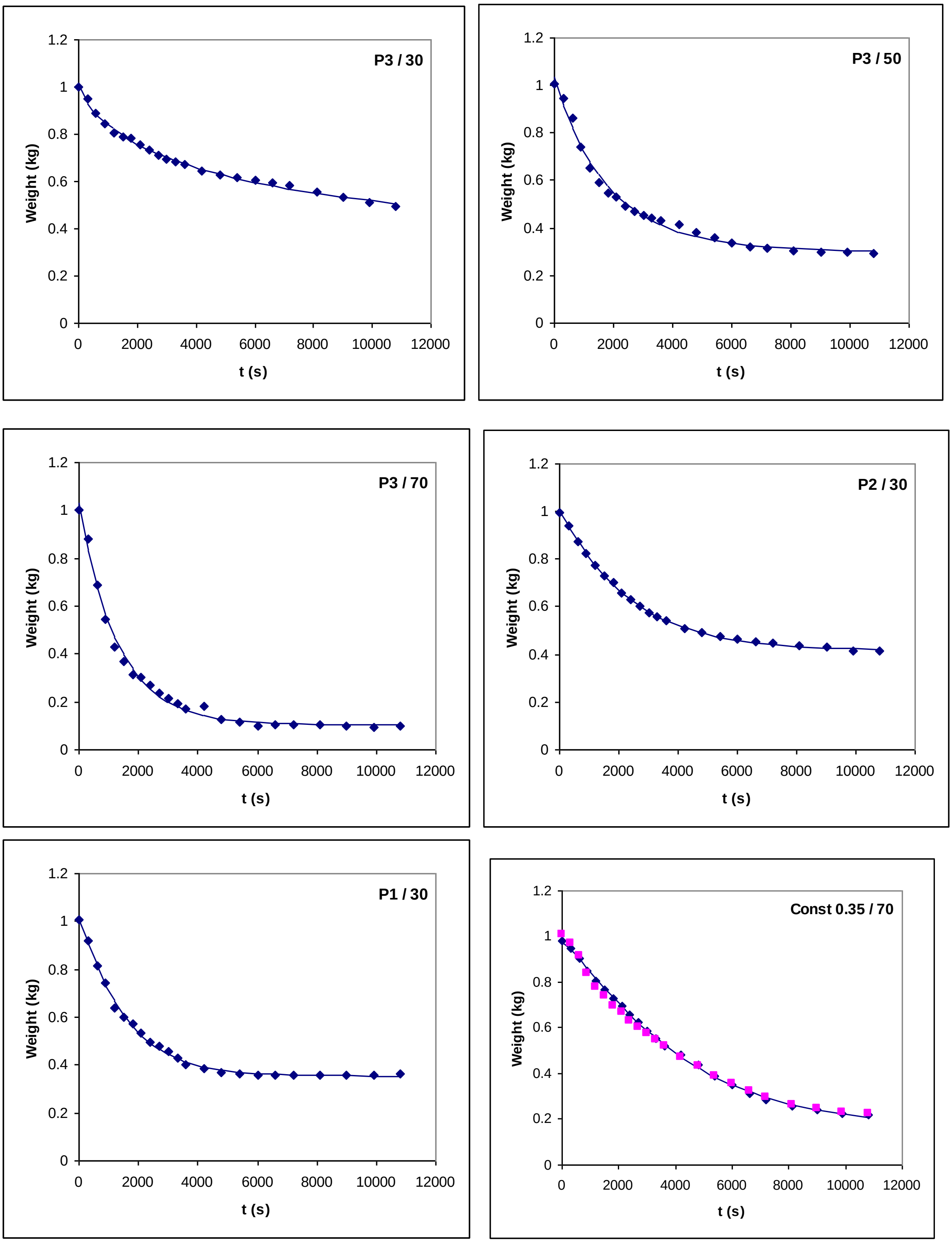


Fig. 3. Fits of the Weibul model to the drying curves.

The legend on the top right corner of the graphs gives the conditions indicating first the programme and then the air temperature in ^{o}C

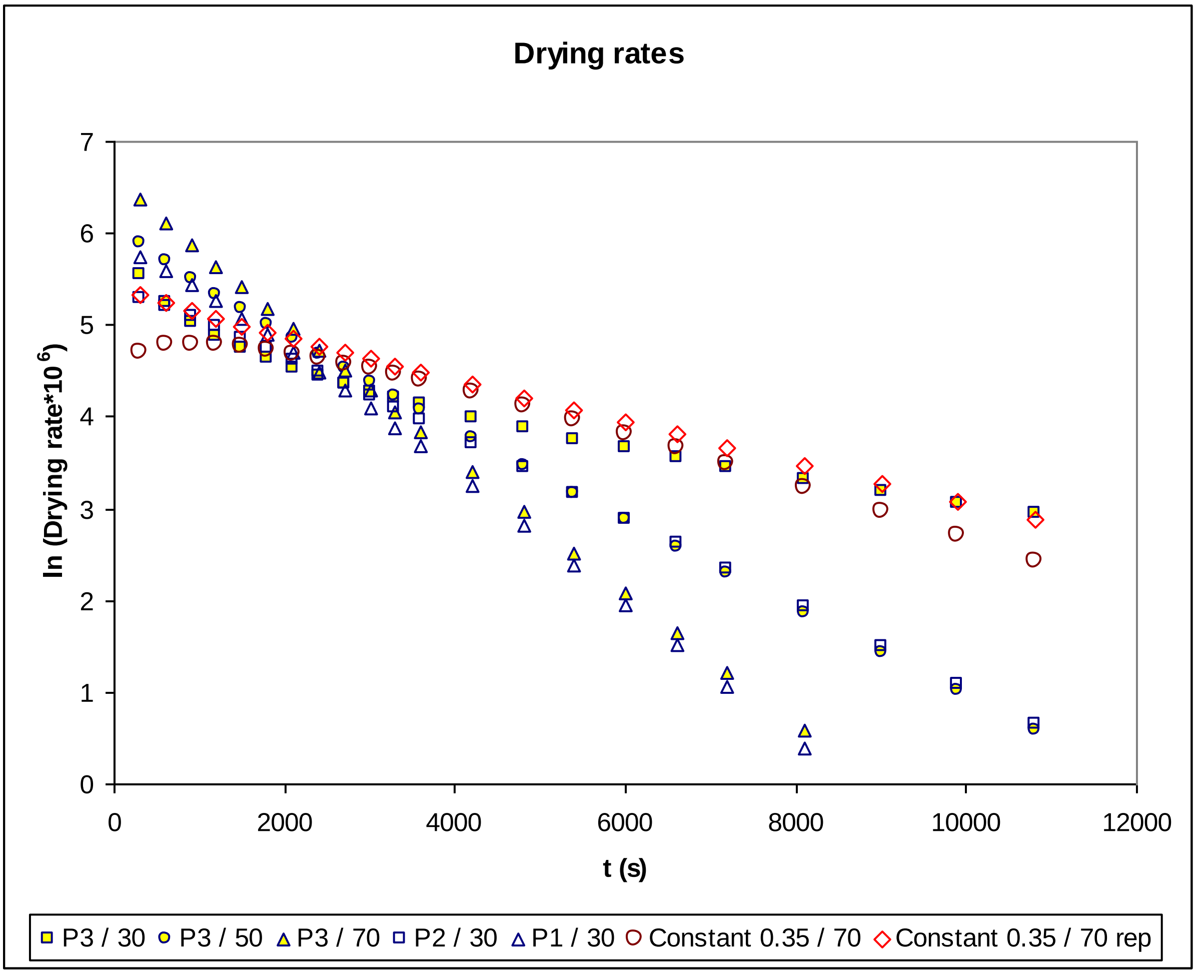


Fig. 4. Drying rates determined by mathematical smoothing of the experimental data with the Weibul models in Table 2.

The caption gives the microwave power programme and the air temperature in °C for each run.

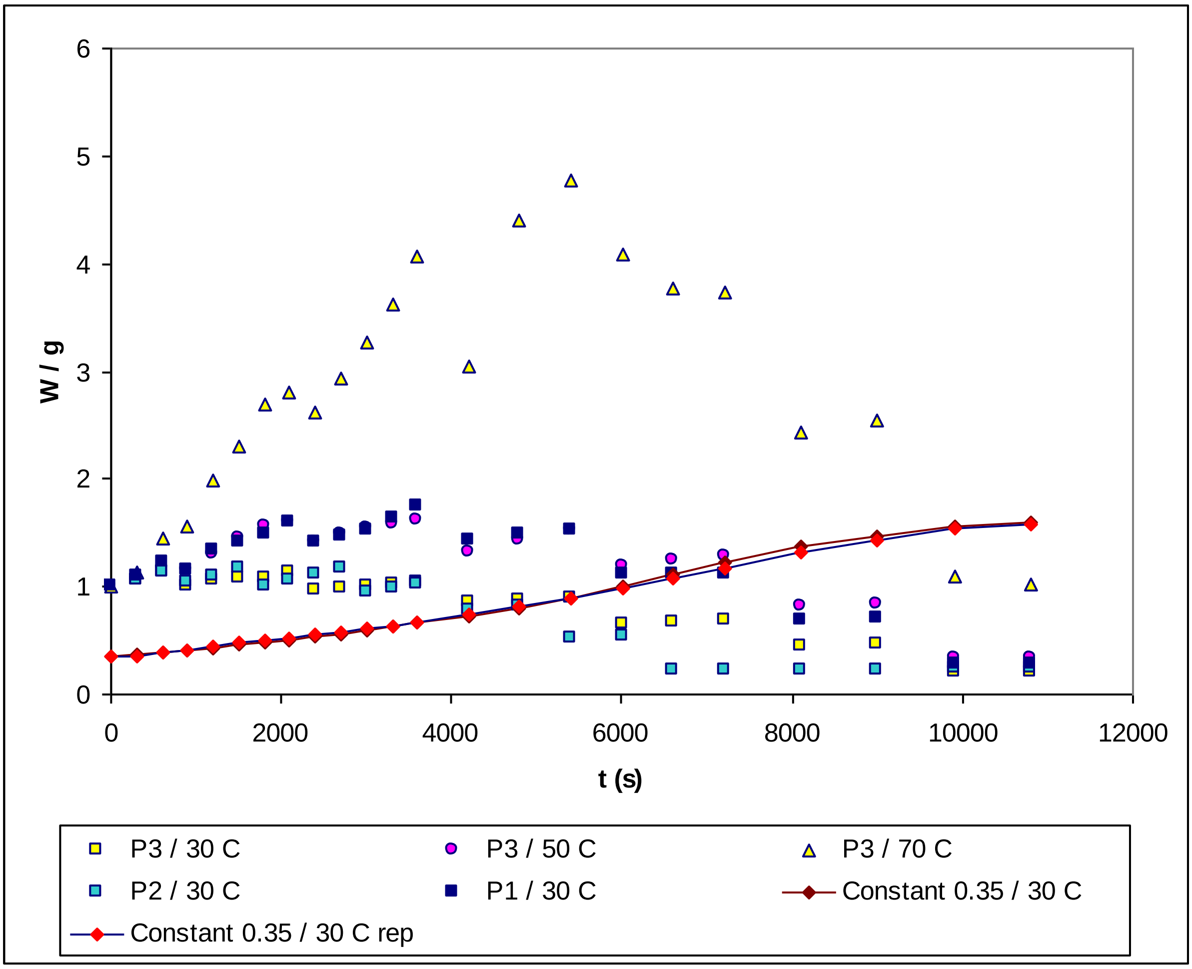


Fig. 5. Specific microwave power during the drying process as W delivered by the magnetron per g of product weight.

The legend gives the microwave power programme and the air temperature in ^{o}C for each run.

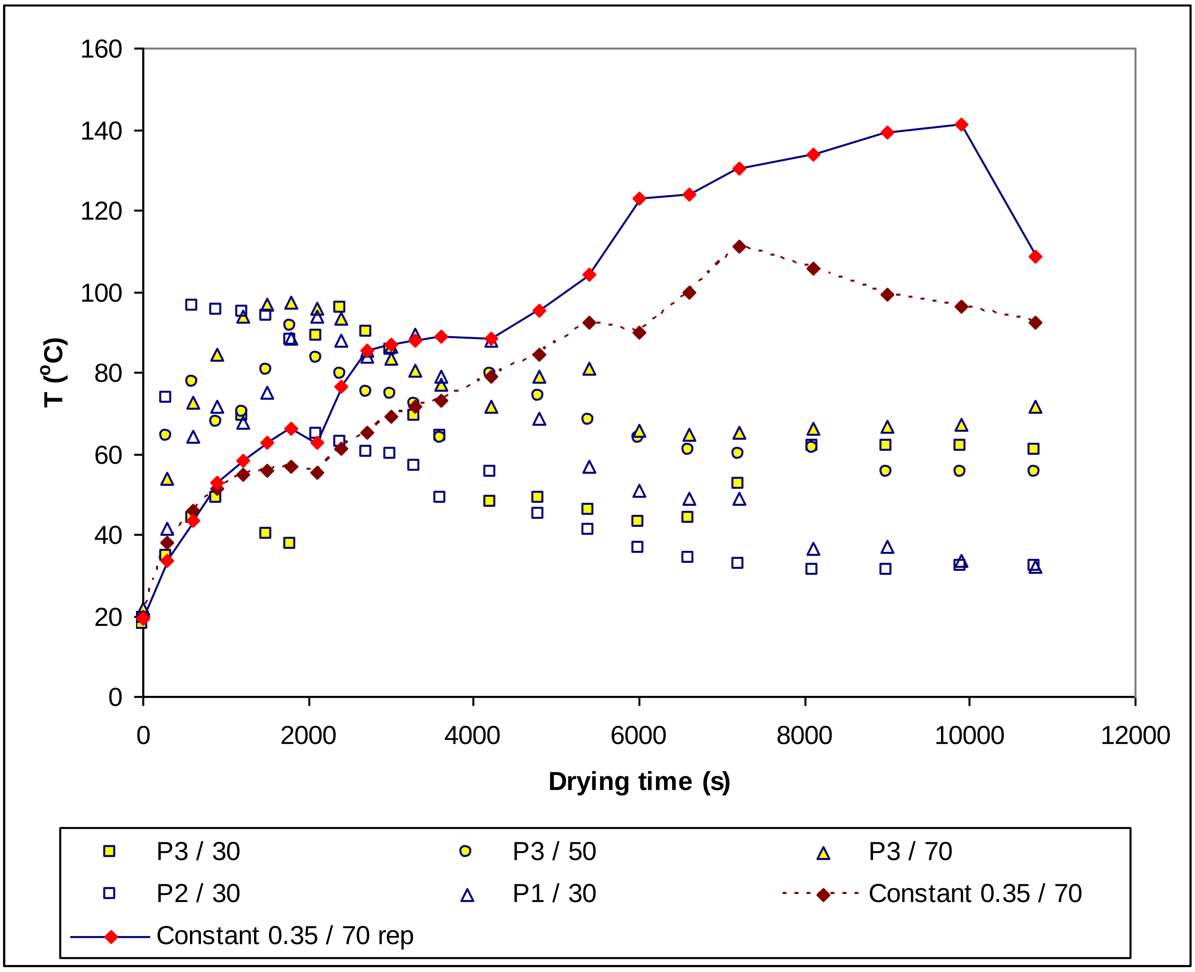


Fig. 6. Temperature measured inside one pineapple piece in each run.

The legend gives the microwave power programme and the air temperature in °C for each run.

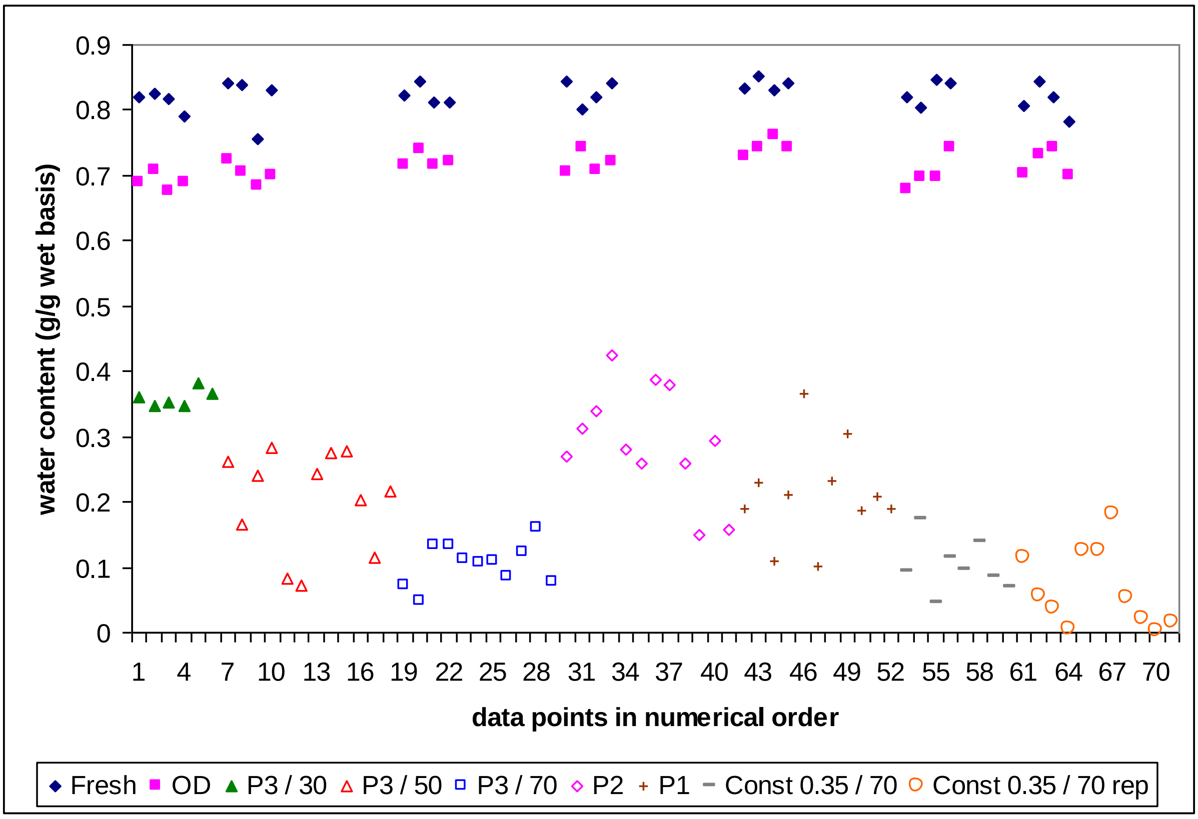


Fig. 7. Water contents of various pineapple pieces processed at different conditions.

In the legend, "Fresh" stands for fresh pineapple pieces, "OD" for pieces after osmotic dehydration at 50 ^{o}C in a sucrose solution of 55 ºBrix for 90 min, and the subsequent notation gives the microwave power programme and the air temperature in ^{o}C

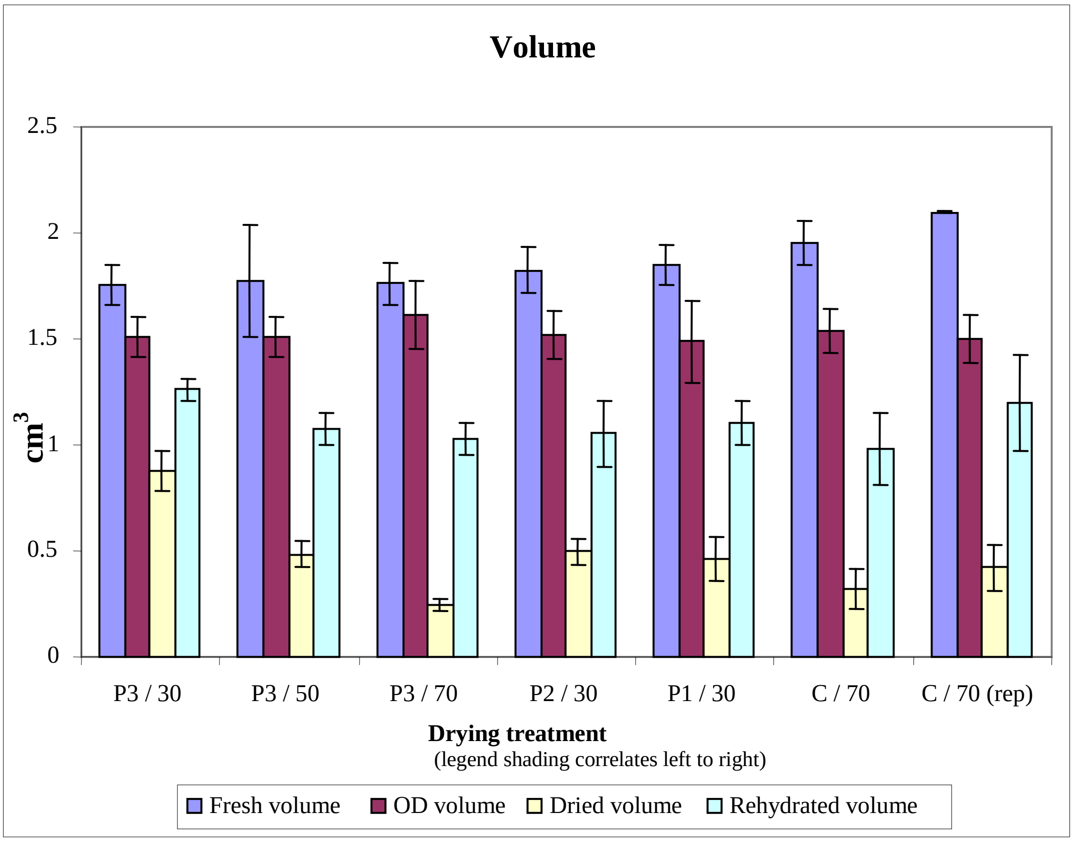


Fig. 8. Volume of pineapple pieces fresh, after osmotic dehydration at 50 °C in a sucrose solution of 55 °Brix for 90 min, after a microwave – air drying process, and after rehydration for 4 hours at room temperature.

The labels indicate the conditions of the drying process, microwave power and air temperature.

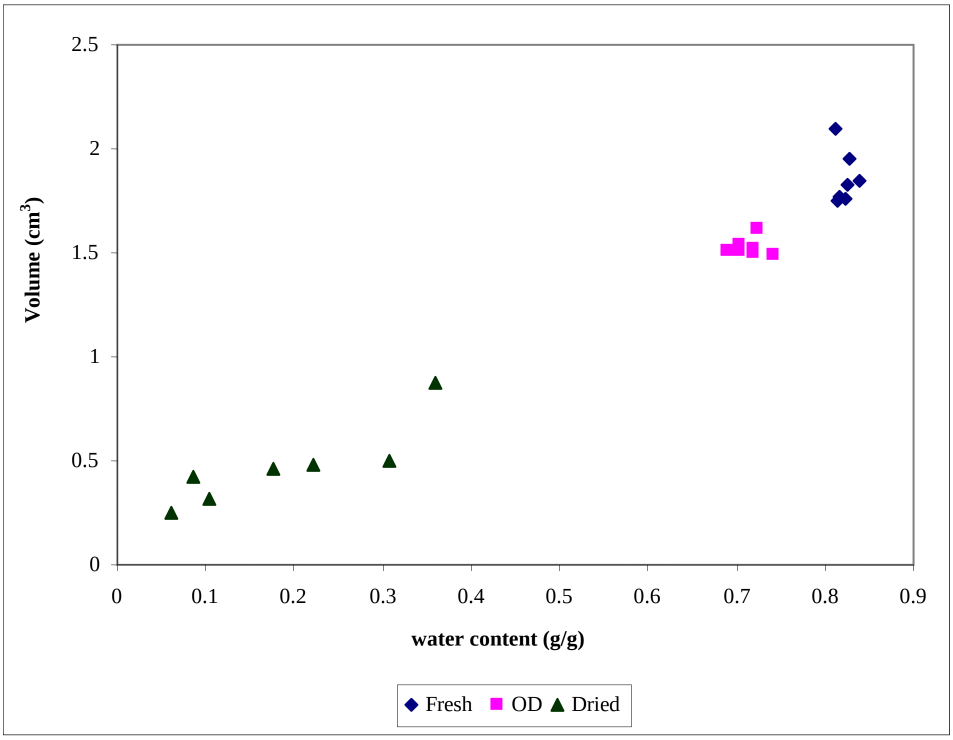


Fig. 9. Volume of pineapple pieces for different water contents from fresh to dried, distinguishing the pieces after osmotic dehydration.

The data points for dried pieces refer to the end values after drying according to 6 different programmes.