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Microwave Drying of West Indian Bay Leaf (*Pimenta racemosa*)

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Abstract: *The effect of microwave power (200, 500, 700 and 1000W) on the drying behaviour of West Indian Bay leaf (Pimenta racemosa) was investigated. Leaves were dried in a commercial digital microwave oven until there was virtually no change in weight. The initial moisture content and water activity (a_w) values of fresh leaves averaged 0.85 g H_2O/g DM (46.0 % wb) and 0.912, respectively. Although a decrease in moisture content, water activity and drying time increased with microwave power level, the most noticeable changes were seen as microwave power increased from 200 to 500W. Overall, drying time to equilibrium moisture values decreased from 48.8 to 5.2 minutes for leaves dried at 200-1000W, respectively. The final moisture content values of leaves dried at 200, 500, 700 and 1000W averaged 0.22, 0.05, 0.04 and 0.02 g H_2O/g DM (18.7 to 2.0 % wb), respectively. Corresponding water activity values for microwave-dried leaves averaged 0.756 for leaves dried at 200W power and 0.326 for leaves dried at 1000W. Drying rates at the start of drying averaged 0.02 g H_2O/g DM/min for leaves dried at 200W power, compared with 0.63 g H_2O/g DM/min for leaves dried at 1000W. Drying of all leaves occurred in the falling rate period. Drying rate constants (k) ranged from 0.0410 to1.0930 1/min, with the corresponding diffusivity values averaging 0.62 and 16.69 x 10^{-9} m^2/s, for leaves dried at 200-1000W, respectively. Rehydration ratios were found to increase with rehydration temperature ($p \leq 0.05$). Significantly lower rehydration ratios were seen in leaves dried at 200W when rehydration was carried out at ambient temperature. Leaves experienced changes in colour and texture during drying, with undesirable changes occurring during drying at 200W and 1000W power levels. Drying at 500W and 700W was favourable and found to be similar with respect to the colour attributes and equilibrium moisture content of dried leaves, as well as energy consumption. The chlorophyll content was higher in leaves dried at 500W while the odour of leaves dried at 700W was stronger. Of the nineteen thin layer models applied to the MR data, the Verma model best fit the data for leaves dried at 500W power level and the Jena and Das model best fit the data for leaves dried at 700W. The results show the clear potential for microwave drying as a rapid drying method of drying bay leaves.*

Keywords: *Microwave drying, West Indian Bay leaf, thin layer modelling*

Nomenclature

A	Drying constant		
a_w	Water activity	MR	Moisture Ratio $(M-M_e)/(M_o-M_e)$
D_{eff}	Diffusion coefficient (m^2/s)	P	Microwave power (W)
DM	Dry matter (g)	R^2	Coefficient of determination
E_t	Energy consumption (W.h)	RMSE	Root Mean Square Error
k	Drying rate constant (1/min)	RR	Rehydration Ratio
L	Half thickness of leaf (m)	W	Watts
L^*,a^*,b^*	Colour attributes	$K, K_0, K_1, a, b, c, g, n$	Model constants
M	Moisture content (g H_2O/g DM) at time = t	t	Time (min)
M_o	Initial Moisture Content (g H_2O/g DM)	wb	Wet basis (g H_2O/100g FW)
M_e	Equilibrium Moisture Content (g H_2O/g DM)	χ^2	Chi-Square

1. Introduction

West Indian bay leaves (*Pimenta racemosa*) are dark green, shiny, evergreen leaves that emit a potent spicy aroma that is also comparable with the smell of lemon (Paula *et al*., 2010; Ogundajo *et al*., 2011). The leaves derive from a large tree (15-25 metres), are also known as West Indian Bay, Bay Leaf, Bay Tree, Bay Cherry, Bois d'Inde, Matagueta and Wild Cinnamon (Seaforth and Tikasingh, 2008). The tree is native throughout the Caribbean region, but is predominantly grown in the West Indies, Mexico, Indonesia, Guyana, Puerto Rico, Venezuela, Jamaica and Africa (Seaforth and Tikasingh, 2008; Ogundajo *et al*., 2011). Traditionally, West Indian bay leaves (*Pimenta racemosa*) are used in the production of bay rum which is made by distillation of the leaves with rum, and these leaves are purported to have soothing and antiseptic properties (Seaforth and Tikasingh, 2008). The essential oil, commonly known as “bay oil” or “Myrcia oil” is obtained by steam distillation (McGaw *et al*., 2016). Bay oil is used in aftershaves, hair growth and hair loss lotions, perfumes and as a commercial flavouring in food. In Caribbean folk medicine, bay oil is used to treat rheumatism and toothaches and for its painkilling and anti-inflammatory effects (Jirovetz *et al*., 2007; Alitonou *et al*., 2012).

West Indian bay leaves are used as a spice and share equivalent culinary uses as *Laurus nobilis*, also called “bay leaves” and bay laurel leaves, but which is a completely unrelated species and differs botanically from the West Indian bay (McHale *et al*., 1977; Alitonou *et al*., 2012). *Laurus nobilis* is mainly produced in Turkey and prepared for market by process of drying; usually sun drying (Demir *et al.*, 2004). Drying is usually fully achieved over a period of up to ten days in optimal climatic conditions, however, due to the external exposure to the environment, losses in quality as well as contamination result (Demir *et al.*, 2004).

The drying of leafy herbs is an important operation in value addition and extending the shelf life. Herbs are dried prior to extraction of essential oils and other compounds, and dried herbs are also used extensively in many food preparations. Because of the importance of the drying step, the oven-drying behaviour (40-70°C) of *Laurus nobilis* leaves has been investigated by some researchers (Demir *et al*., 2004; Gunhan *et al*., 2005; Doymaz, 2014; Cakmak *et al*., 2013). The oven drying behaviour of the West Indian bay leaf was investigated by the authors of this work (Mujaffar and Bynoe, 2019). Leaves were dried in a single layer for 300 min in a cabinet oven set at 60°C and the moisture content of the leaves declined from 45.9% (wb) to an equilibrium moisture content value of 5.7%. There was a corresponding decline in water activity value from 0.912 to 0.496. Drying was found to occur in the falling rate period only and the effective moisture diffusivity averaged 0.32 x 10^{-9} m^2/s. The drying data was best described using the Logistic model. Rehydration ratios for oven-dried leaves averaged 1.10 and 1.44 for leaves rehydrated at 30°C and 60°C, respectively.

There has been an interest in the microwave drying of herbs such as mint, basil, parsley and celery leaves as a viable alternative to the conventional hot air oven-drying method (Di Cesare *et al*., 2003; Soysal, 2004; Ozbek and Dadali, 2007; Demirhan and Ozbek, 2011; Seyedabadi, 2015). Microwaves are a form of electromagnetic radiation that effect heating of foods by a process of dielectric heating (Decareau, 1985; Zhang *et al*., 2006). While conventional heating occurs by convection followed by conduction where heat must diffuse into the material, materials can absorb microwave energy directly and internally convert this energy to heat (Vadivambal and Jayas, 2007). The advantages of microwave drying are reduced drying time, less energy use with less impact on product quality (Zhang *et al*., 2006).

The microwave-drying kinetics of bay laurel (*Laurus nobilis*) leaves was explored by Cakmak *et al*. (2013) at a power level of 180W, with favourable results with regard to drying time and quality attributes. Sellami *et al*. (2011) noted that drying method impacted on the yield of essential oil from *Laurus nobilis* leaves and reported that microwave drying (500W) gave an oil yield similar to that of fresh leaves, while oven drying at 45°C and 65°C resulted in the lowest essential oil recovery. Previous work by the authors (Mujaffar and Bynoe, 2019) showed the potential for microwave drying at 500W power as a rapid drying method for West Indian bay leaves. Compared with oven (hot-air drying) at 60°C, drying time was reduced from 300 min to 15.6 min with minimum negative effects on the colour and odour of leaves, compared with oven drying.

This study was undertaken to further explore the microwave drying of the West Indian bay leaf, specifically to investigate the effect of microwave power level (200-1000W) on the thin-layer drying behaviour and selected quality attributes.

2. Materials and Methods

Fresh West Indian bay (*Pimenta racemosa*) leaves were harvested from a single large bay tree. Unblemished leaves were gently wiped with paper towels to remove any adhering dust before drying and drying done on the same day as harvesting. The length, width and thickness of leaves averaged 0.065±0.005 m, 0.044±0.004 m and 0.0030±0.00 m, respectively. Preliminary experiments revealed that blanching of leaves, as recommended by Ahmed *et al*. (2001) for coriander leaves, did not result in any noticeable improvements in quality of microwave-dried leaves.

Microwave drying was carried out using a 34L oven capacity Amana MCS10TS Menumaster Commercial digital microwave oven (Accelerated Cooking Products (ACP), Cedar Rapids, IA, USA) with the following technical features: 3.5kV, 1000W, 120V, 60 Hertz. Microwave power levels used were based on the four pre-set levels (200W, 500W, 700W, 1000W). A sample size of 10g of leaves was selected as the amount could be spread in a single layer onto the sample plate. The total weight of the plate with the leaves was recorded before placing into the oven. At 30s intervals the plate with the leaves was removed from the oven, quickly weighed and returned to the oven. Drying was continued until there was no further change in weight. At the end of drying, leaves were allowed to cool, packaged in re-sealable plastic storage bags and stored in laboratory desiccators until analysis. A total of five (5) drying runs were conducted at each power level.

The rehydration characteristics of dried bay leaves were investigated at ambient temperature (30-35°C) and 60°C using a 26.5L capacity, Precision Reciprocating

Shaker Water Bath (Model 2872, Thermo-Scientific, Ohio, USA) with a stainless-steel chamber and temperature range of ambient to 99.9°C ± 0.1°C. Dried samples (2g each) were placed into beakers containing 200ml of distilled water, then placed into the water bath for 4h (Cakmak *et al*., 2013). The rehydration behaviour of a commercially available sample of dried bay leaf (*Laurus nobilis*) was also checked for comparison.

Procedures and instruments used for measuring sample weight, water activity (a_w) and colour were described previously by Mujaffar and Lee Loy (2016), with the following variations: the moisture content of the fresh and dried leaves was measured at 160°C and the dried leaves were blended to create a homogenous sample before colour assessment (Cakmak *et al*., 2013). Chlorophyll determination was carried out spectrophotometrically based on the procedure of Rai *et al*. (2011) and the results expressed in mg/g DM based on the dilution factor and mass of sample used (Looi *et al*., 2019) as well as the sample moisture content. Energy consumption for microwave drying was obtained using Equation 4 (Hebbar *et al*., 2004).

$$E_t = P.t \tag{1}$$

Drying data was analysed using the standard approach to drying studies, that is, the generation of drying curves and drying rate curves as described in detail previously (Mujaffar and Sankat, 2005; 2014; Mujaffar and Lee Loy, 2016). The final moisture content values were used together with the sample weight data to back-calculate the moisture changes in the leaves during the drying process. Moisture Ratio (*MR*) was calculated based on the analytical solution of Fick's Law for an infinite slab assuming uniform initial moisture distribution and negligible external resistances (Crank, 1975), which reduces to the straight-line equation given in Equation (2). The drying rate constant (*k*) was obtained from the slope of the plot of In *MR* versus time (*t*) and effective moisture diffusivity (D_{eff}) values were calculated using 0.003 m as the leaf thickness (Equation 3).

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} exp\left(\frac{-\pi^2 Dt}{4L^2}\right) \tag{2}$$

$$k = \frac{\pi^2 D}{4L^2} \tag{3}$$

Rehydration Ratio was calculated using the following equation (Cakmak *et al*., 2013):

$$\text{Rehydration Ratio} = \frac{\text{Weight of rehydrated bay leaf sample (g)}}{\text{Weight of dried bay leaf sample (g)}} \tag{4}$$

For this study, a total of nineteen (19) empirical and semi-empirical thin layer models (see Table 1) most commonly used in curve fitting studies were applied to the *MR* data (Erbay and Icier, 2010, Ertekin and Firat, 2017). Curve fitting was carried out using Curve Expert Professional software (Version 2.3, Hyams, 2016) and fit assessed through the use of the coefficient of determination (R^2), root mean square error (*RMSE*) and the chi-square statistic (χ^2) (Mujaffar and Lee Loy, 2016). ANOVA was carried out using Minitab 17 Statistics Software (Minitab Inc., PA, USA) (Minitab 2016) and post hoc analysis carried out using "Rapid publication-ready MS-Word tables for one-way ANOVA" (Assaad *et al*., 2015).

Table 1. Thin Layer Drying Models

Model name	Equation
Newton	$MR = exp(-Kt)$
Page	$MR = exp(-Kt^n)$
Modified Page	$MR = exp(-Kt)^n$
Henderson and Pabis	$MR = a\ exp(-Kt)$
Modified Henderson and Pabis	$MR = a\ exp(-Kt) + b\ exp(-gt) + c\ exp(-ht)$
Logarithmic	$MR = a\ exp(-Kt) + c$
Two-Term	$MR = a\ exp(-K_0 t) + b\ exp(-K_1 t)$
Two-Term Exponential	$MR = a\ exp(-Kt) + (1-a)\ exp(-Kat)$
Wang and Singh	$MR = 1+at+bt^2$
Verma	$MR = a\ exp(-Kt)+(1-a)\ exp(-gt)$
Hii	$MR = a\ exp(-Kt^n) + c\ exp(-gt^n)$
Midilli	$MR = a\ exp(-Kt^n) + b\ t$
Weibull distribution	$MR = a - b\ exp(-Kt^n)$
Diffusion approach	$MR = a\ exp(-Kt)+(1-a)\ exp(-Kbt)$
Aghbashlo *et al.*	$MR = -K_1 t / (1 + K_2 t)$
Logistic	$MR = a_0 / ((1 + a\ exp(Kt))$
Jena and Das	$MR = a\ exp(-t + b\ t^{1/2}) + c$
Demir *et al.*	$MR = a\ exp(-Kt^n) + c$
Alibas	$MR = a\ exp(-Kt^n + b\ t) + g$

3. Results and Discussion

3.1 General Observations and Colour

Leaves were initially shiny, dark green in colour and pliable in texture. The aroma of the fresh whole leaves was mild, which became more pronounced when the leaves were torn. Noticeable changes in appearance and texture occurred during the drying process (see Figure 1). Leaves dried at 500 to 1000W power levels became very brittle and were susceptible to tearing during post-drying handling.

During the drying process, moisture was observed on the surface of the leaves which then evaporated. The higher the power level, the faster this process occurred. Leaves dried at 200W power level developed a damp appearance with the centre of the leaves turning yellow after approximately 4 min of drying. After 12 min, leaves appeared discoloured, with areas of dark green, brown and yellow. After 25 min the leaves were fully yellow/ brown. It is possible that due to the low drying potential at this power level, leaves dried at 200W became "cooked". It took approximately 40 min for the leaves to start losing the moisture and become more brittle.

Undesirable changes were also observed in leaves dried at 1000W. The leaves became severely distorted and curled at the edges after 2 min of drying. After 6 min, the edges of some of the leaves turned brown and

Figure 1. Appearance of fresh (a) and dried (b) 200W (c) 500W (d) 700W (e) 1000W West Indian bay leaves

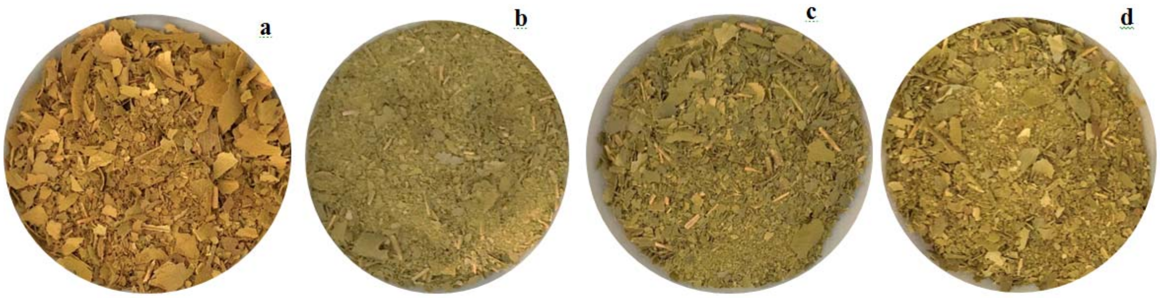

Figure 2. Appearance of ground, dried West Indian bay leaves (a) 200W (b) 500W (c) 700W (d) 1000W

Table 2. Colour attributes and Total chlorophyll content of fresh and dried West Indian bay leaves.

Quality Attribute	Bay Leaf Sample				
	Fresh	200W	500W	700W	1000W
L*	49.58 ± 1.75^{b}	38.65 ± 0.73^{c}	63.97 ± 0.26^{a}	62.64 ± 0.13^{a}	64.36 ± 0.05^{a}
a*	-7.07 ± 0.50^{b}	8.44 ± 0.08^{a}	-8.56 ± 0.07^{c}	-8.48 ± 0.09^{c}	-8.66 ± 0.07^{c}
b*	8.32 ± 0.55^{d}	20.12 ± 0.4594^{c}	37.32 ± 0.26^{a}	35.10 ± 0.33^{b}	36.95 ± 0.10^{a}
Hue (°)	-49.67 ± 0.37^{b}	67.23 ± 0.6468^{a}	-77.07 ± 0.046^{c}	-76.42 ± 0.04^{c}	-76.81 ± 0.08^{c}
Total Chlorophyll (mg/g DM)	5.81 ± 0.09^{a}	3.46 ± 0.02^{b}	1.46 ± 0.02^{c}	0.99 ± 0.002^{d}	0.82 ± 0.04^{e}

Values are means ± SEM. n = 3

$^{a\text{-}c}$ Means in a row without a common superscript letter differ (P<0.05) as analysed by one-way ANOVA and the LSD test.

were very brittle. These undesirable changes could have been the result of overheating and uneven heating in the microwave oven (Zhang et al. 2006). The leaves dried at 200 and 1000W power levels lost their shine.

During microwave drying, the leaves emitted a moderate odour which became stronger near the end and after drying; especially when the leaves were torn or crushed. The odour of the torn, dried leaves was weaker in leaves dried at 500 and 1000W power levels. Leaves dried at 500 and 700W power levels were the most attractive, with the typical bay leaf odour being stronger in leaves dried at 700W. Leaves dried at 700W power level appeared to be visibly greener than the leaves dried at 500W.

The dried leaves were ground prior to colour analysis (see Figure 2). Compared with the leaves dried at 200W, leaves dried at the higher power levels were easier to grind as the leaves were more brittle. Velu *et al.* (2006) reported that microwave drying improved the grinding of maize, with microwave-dried maize showing a decreased Bond's work index, which is a measure of grinding energy. The colour attributes and chlorophyll content (mg/g DM) of the fresh and dried leaves are given in Table 2.

Higher L^* values indicated the lightening of leaves dried at 500-1000W power levels, while darkening of the leaves occurred at 200W. Leaves dried at the higher power levels maintained a dark green colour, as reflected in high negative a^* values, while a positive value of +8.44 was found for leaves dried at 200W power level, indicating reddening/browning. The high positive b^* values indicated the increase in yellowing of all leaves after drying, increasing at the higher microwave power levels. Increasing microwave power from 200 to 500W resulted in a large decline in the chlorophyll content of the leaves.

Mujaffar and Bynoe (2019) found that microwave-dried West Indian bay leaves were greener in appearance with correspondingly lower a^* values than oven-dried (60°C) leaves, which were brown in colour. Cakmak *et al.* (2013) found that microwave-dried (180W) *Laurus nobilis* leaves were greener but with higher b^* values compared with oven-dried leaves. Microwave-dried leaves also showed a smaller colour difference when compared with fresh leaves. Demir *et al*. (2004) found that while the colour attributes of dried *Laurus nobilis* were significantly different from the fresh leaves, the impact of drying method (oven, sun and shade drying) was not significant. Vadivambal and Jayas (2007) noted that microwave-dried products are generally less brown than conventional air-dried products. From the present study, the lowest chlorophyll content (0.82 mg/g DM) was observed in leaves dried at 1000W power level, however, this was higher than the 0.68 mg/g DM reported for leaves dried at 60°C (Mujaffar and Bynoe, 2019).

3.2 Drying Curves

During drying, all leaves experienced a change in weight. The maximum weight loss (% over original weight) experienced by microwave-dried leaves at 500-1000W was approximately 43%, with most of the change in weight occurring at the early stages of the process. The maximum weight loss for leaves dried at 200W was 34%.

The initial moisture content and water activity of fresh leaves averaged 0.85 g H_2O/g DM (46% wb) and 0.912, respectively. The decline in moisture content of the leaves as a function of microwave power is given in Figure 3. Moisture content was significantly affected by drying time and microwave power level, as well as a time-power interaction ($p \leq 0.001$). Increasing the power level from 200 to 1000W resulted in an increase in moisture reduction, with the greatest effect was observed as the power level increased from 200 to 500W. Equilibrium moisture and water activity of dried leaves are given in Table 3. The final moisture content values of leaves dried at 200, 500, 700 and 1000W averaged 0.22, 0.05, 0.04 and 0.02 g H_2O/g DM, respectively (18.7, 5.2, 3.8, 2.0 %wb). The higher the power level, the shorter the drying time to achieve equilibrium moisture content.

The increase in moisture decline and drying time with increasing microwave power has been described for many leafy materials, including celery, basil, parsley, spinach and amaranth (Soysal, 2004; Alibas 2014; Demirhan and Ozbek, 2011; Seyedabadi, 2015; Mujaffar and LeeLoy, 2016). Increasing microwave power increases the rate of energy supply (J/s) to the material, which leads to faster heating. Evaporation of moisture is therefore increased and the movement of internal moisture to the surface of the material occurs at a faster rate.

Mujaffar and Bynoe (2019) reported that oven-dried (60°C) West Indian bay leaves took 300 min to reach equilibrium moisture content. Cakmak *et al.* (2013) found that microwave drying of *Laurus nobilis* leaves at 180W resulted in a four-fold reduction in drying time, compared with leaves dried in an oven at 50-70°C, and that drying could be completed within 25 min. Demir *et al*. (2004) reported that *Laurus nobilis* leaves could be dried to 10-12% moisture in 2.5 to 9h in a convection oven at 40-60°C, respectively. Doymaz (2014) found that drying time for *Laurus nobilis* leaves could be reduced from 170 to 60 min when the drying temperature increased from 50 to 70°C.

The drying energy consumption (W/h) for 10g samples of bay leaves is given in Figure 4. Energy consumption decreased from 9670 to 5200 W/h as microwave power increased from 200 to 1000W. Energy consumption values were not significantly different ($p \leq 0.05$) between 500 and 700W power levels, or 700 and 1000W power levels. Alibas Ozkan *et al*. (2007) also reported higher energy consumption values of leaves dried at lower power levels of 90 to 160W microwave power levels, with similar values at 350 to 1000W power levels.

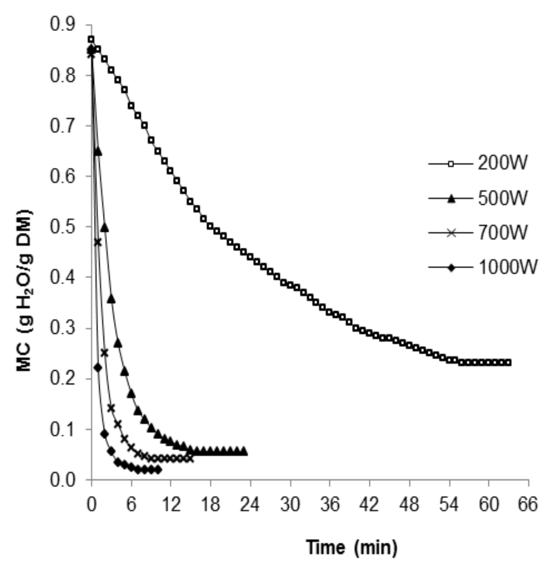

Figure 3. Effect of microwave power level on the moisture content of West Indian bay leaves

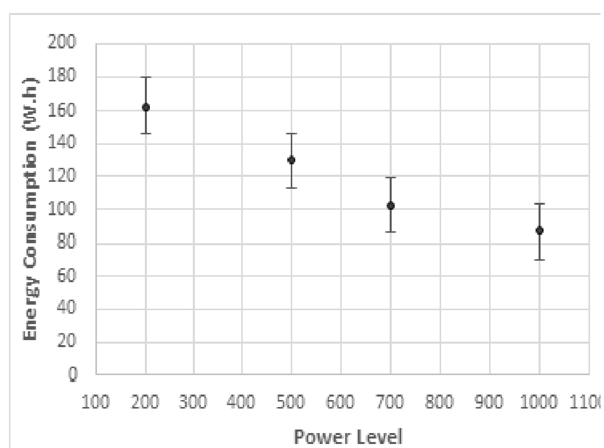

Figure 4. Energy Consumption for microwave drying of West Indian bay leaves at different power levels

Table 3: Moisture and water activity values of fresh and dried leaves

Quality Attribute	Bay Leaf Sample				
	Fresh	**200W**	**500W**	**700W**	**1000W**
MC (g H_2O/g DM)	0.87 ± 0.06[a]	0.22 ± 0.022[b]	0.05 ± 0.005[c]	0.04 ± 0.004[c]	0.02 ± 0.002[c]
a_w	0.912 ± 0.006[a]	0.756 ± 0.016[b]	0.406 ± 0.007[c]	0.331 ± 0.014[d]	0.326 ± 0.008[d]
Time to Equilibrium (min)	NA	48.8 ± 3.5[a]	15.6 ± 0.93[b]	8.8 ± 0.97[c]	5.2 ± 0.58[c]

Values are means ± SEM, n = 5 per treatment group.
[a-d] Means in a row without a common superscript letter differ (P<0.05) as analysed by one-way ANOVA and the LSD test.

3.3 Drying Rate Curves

Drying rates of microwave-dried bay leaves as a function of average moisture content are shown in Figure 5. The higher the power level, the higher the drying rates for most of the drying process. Initial drying rates averaged 0.02, 0.20, 0.37 and 0.63 g H_2O/g DM/min, for leaves dried at 200, 500, 700 and 1000W, respectively. Drying at 200W power level occurred in the constant rate and falling rate period, with the falling rate period beginning at a moisture value of 0.65 g H_2O/g DM (40% wb). Drying at the higher power levels occurred in the falling rate period only, which means that drying was controlled by diffusion of moisture.

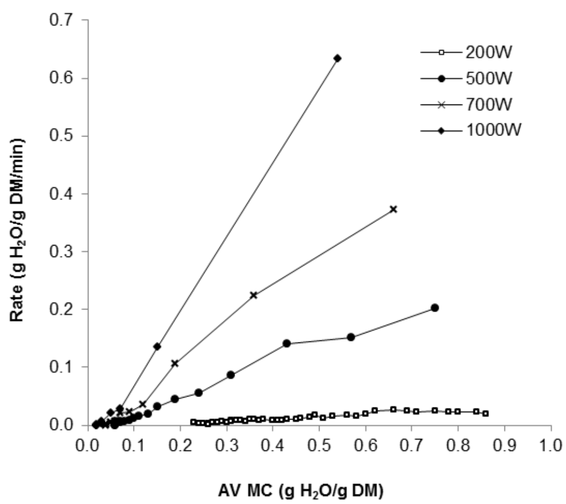

Figure 5. Drying rate curves for West Indian bay leaves at various microwave power levels

With respect to the drying of bay leaves, specifically, Gunhan *et al*. (2005) presented curves of drying rate as a function of drying time for oven-dried *Laurus nobilis L*. leaves dried at 40-50°C. They noted that drying rates were impacted by drying temperature, but not by the humidity of the air, with approximate initial values of 0.18 to 0.80 g H_2O/g DM/min for leaves dried at 40-50°C, respectively. Doymaz (2014) presented curves of drying rate versus Moisture Ratio (*MR*) to support that drying of bay leaves at 50-70°C occurs in the falling rate period only.

Similar changes in drying rate with time and with increasing microwave power levels were reported for celery, mint, parsley, spinach and amaranth leaves (Soysal, 2004; Alibas Ozkan *et al*., 2007; Ozbek and Dadali, 2007; Demirhan and Ozbek, 2011; Sharada, 2013, Mujaffar and Lee Loy, 2016). According to those authors, high moisture values of leaves at the initial stages of drying result in higher absorption of microwave power and higher drying rates due to higher moisture diffusion. Decrease in moisture as drying progresses results in a decrease in absorption of microwaves and a drop in temperature, with a resulting decrease in drying rate. Other authors have reported drying during the falling rate only for the drying of spinach and celery leaves (Alibas Ozkan *et al*., 2007; Demirham and Ozbek, 2011). Demirham and Ozbek (2011) added that the critical moisture content was equal to the initial moisture content of celery leaves which meant that the microwave drying process at 180 to 900W power levels was entirely controlled by mass transfer resistance. It has been suggested that microwave drying is most effective at product moisture contents below 20% (wb), which usually corresponds to drying in the falling rate period (Maskan, 2001). The removal of moisture during this time is therefore more rapid than with oven (hot-air) drying.

3.4 Moisture Ratio (MR), Drying Rate Constants (k) and Diffusion Coefficients (D_{eff})

Plots of Moisture Ratio (*MR*) versus time (min) are given in Figure 6. A similar trend to the drying curves was observed, where increasing the power level from 200W to 1000W resulted in the decline in values, but with the greatest decline occurring when microwave power level was increased from 200 to 500W.

The drying rate constants (*k*) for the initial minutes of microwave drying of bay leaves were determined from plots of the ln free moisture (ln *MR*) as a function of drying time. Drying rate constants (see Table 4) were significantly affected by microwave power level ($p \leq 0.05$). The increase in drying rate with microwave power level could be described by the following relationship ($R^2 = 0.9953$):

$$k = 7 \times 10^{-7}.P^{2.0781}$$

Mujaffar and Bynoe (2019) reported *k*-values of 0.0213 1/min and D_{eff} values of 0.32 x 10^{-9} m^2/s for West Indian bay leaves dried in an oven at 60°C.

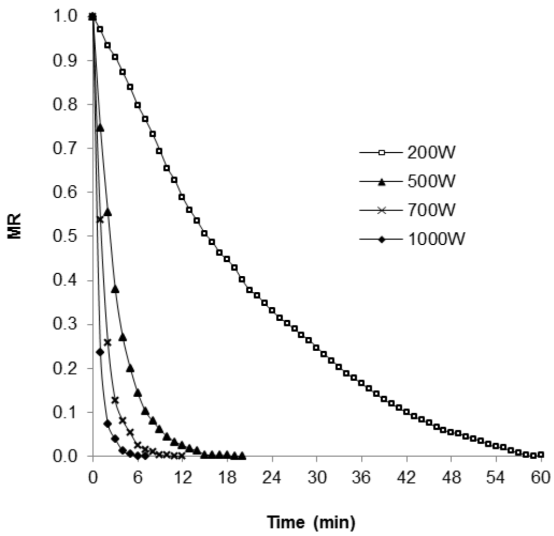

Figure 6. Moisture ratio curves for bay leaves at different microwave power levels

Table 4. Drying rate constants (k) and diffusion coefficients (D_{eff}) for microwave-dried bay leaves

Microwave power level (W)	k (1/min)	D_{eff} (m²/s)	R^2
200	0.0410 ± 0.016[d]	0.62 x 10^{-9}	0.9905
500	0.3115 ± 0.005[c]	4.73 x 10^{-9}	0.9989
700	0.6397 ± 0.030[b]	9.72 x 10^{-9}	0.9939
1000	1.0930 ± 0.028[a]	16.60 x 10^{-9}	0.9706

Values are means ± SEM, n = 5 per treatment group.
[a-d] Means in a column without a common superscript letter differ (P<0.05) as analysed by one-way ANOVA and the LSD test.
[a]D_{eff} = k ($4X^2/\pi^2$) where X = half thickness 0.0015m

With respect to work done on the microwave-drying of *Laurus nobilis* leaves, Cakmak *et al.* (2013) reported D_{eff} values of 1.52 to 3.64 x 10^{-9} m²/s for leaves dried in an oven at 50-70°C, and 8.08 x 10^{-9} m²/s for microwave-dried leaves. Doymaz (2014) reported lower D_{eff} values of 9.38 to 20.70 x 10^{-12} m²/s for leaves dried in an oven at 50-70°C, demonstrating the rapid drying rates achieved through microwave drying in the present study.

With respect to D_{eff} values for other microwave-dried leafy greens and herbs, Demirhan and Ozbek (2011) reported moisture diffusivity values for microwave-dried celery leaves of 0.343 x 10^{-10} to 1.714 x 10^{-10} m²/s as microwave power increased from 180 to 900W using 25g celery leaf samples. Alibas (2014) reported D-values for microwave-dried celery leaves ranging from 1.595 x 10^{-10} to 6.377 x 10^{-12} m²/s at power levels of 90 to 1000W. An increase with microwave power level has been attributed to the increased activity of water molecules at higher power levels.

3.5 Rehydration Ratio

Rehydration ratios for the dried leaves are given in Table 5. Rehydration ratio increased at the higher temperature (60°C). There were no significant (p<0.05) differences between dried leaves at the higher rehydration temperature, but at 30°C, the rehydration ratios of leaves were significantly lower for leaves dried at 200W power level.

Rehydration is an indicator of cellular and structural changes that may have occurred during the dehydration process and Cakmak *et al*. (2013) reported a rehydration ratio of less than 1.2 for microwave-dried (180W) bay laurel leaves. According to Vadivambal and Jayas (2007), enhanced rehydration may be seen in microwave-dried products compared with air-dried samples.

During microwave-drying, the rapid outward flux of water vapour from inside the material can help to prevent shrinkage and collapse of the tissue structure typical of air-drying systems and therefore lead to improved rehydration characteristics (Al-Duri and McIntyre, 1991). Leafy materials such as the bay leaf are very thin (0.003 m), so there may not be noticeable structural differences between oven- and microwave-dried leaves.

3.6 Thin Layer Curve fit

Given that the drying of leaves at 200W and 1000W did not give good results in terms of drying time and or/quality of leaves, the thin layer models were applied only to the data for leaves dried at 500 and 700W. Of the nineteen thin layer models applied to the *MR* data, the Verma model fits the data best for leaves dried at 500W power level and the Jena and Das model fits the data best for leaves dried at 700W (see Table 6).

The comparison of Predicted versus Experimental MR values for leaves dried at 500 and 700W gave straight lines with high R2 values (0.9996 and 0.9994, respectively), an indication of good agreement of values.

With respect to the oven drying of West Indian bay leaves, Mujaffar and Bynoe (2019) found the Logistic model to adequately describe the drying data. With respect to modelling work done on *Laurus nobilis* leaves, Cakmak *et al*. (2013) found the Midilli model to adequately describe the drying data for both oven- and microwave-dried leaves, while the Page and Midilli models were reported to best fit the MR data for

Table 5. Rehydration ratios of West Indian bay leaves dried at varying power levels.

Temperature (°C)	Microwave Power			
	200W	500W	700W	1000W
30	1.04 ± 0.008[a]	1.14 ± 0.004[b]	1.13 ± 0.004[b]	1.14 ± 0.017[b]
60	1.39 ± 0.033	1.50 ± 0.034	1.55 ± 0.006	1.46 ± 0.063

Values are means ± SEM, n = 2 per treatment group.
[a-b] Means in a row without a common superscript letter differ (P<0.05) as analyzed by one-way ANOVA and the LSD test.

Table 6. Thin layer models and constants in order of best fit for West Indian bay leaves dried at different microwave power levels (a) 500W and (b) 700W

Model	(a) 500W - Model constants								R^2	RMSE	χ^2
	K	n	a_o	a	b	c	g	h			
Verma	0.3362	-	-	1.0707	-	-	1.8524	-	0.9998	0.005436	0.000035
Jena and Das	0.3572	-	-	0.9983	0.0735	0.0019	-	-	0.9998	0.005482	0.000038
Modified Henderson and Pabis	0.6419			-15.522	15.9587		0.6301	0.2783	0.9998	0.005215	0.000039
Alibas	1.1650	1.0179	-	0.9986	0.8739	0.5631	0.0032	-	0.9997	0.005805	0.000045
Logistic	0.3527	-	5.7601	4.7340	-	-	-	-	0.9997	0.006380	0.000048

Model	(b) 700W - Model constants								R^2	RMSE	χ^2
	K	n	a_o	a	b	c	g	h			
Jena and Das	0.7457			0.9935	0.1093	0.0070			0.9997	0.007957	0.000099
Newton	0.6500	-	-	-	-	-	-	-	0.9995	0.009643	0.000102
Page	0.6412	1.0201	-	-	-	-	-	-	0.9995	0.009462	0.000109
Weibull distribution	0.6427	1.0502	-	0.0069	-0.9944	-	-	-	0.9996	0.008444	0.000112
Two-Term Exponential	0.6937	-	-	0.7662	-	-	-	-	0.9995	0.009579	0.000112

oven-dried leaves (Demir *et al*., 2004; Gunhan *et al*., 2005; Doymaz, 2014). The Page, Midilli and logarithmic models have all been reported to successfully describe the *MR* data for microwave-dried leafy materials including celery, mint, parsley and basil leaves (Soysal 2004; Ozbek and Dadali, 2007; Demirham and Ozbek, 2011; Seyedabadi, 2015).

4. Conclusions

From the results of this study, microwave drying appears to be a feasible drying method for the rapid drying of West Indian bay leaves. Microwave power level had a significant impact on the drying rates and quality of dried samples. An increase in power level resulted in increased drying rates, with browning and the risk of scorching increasing at 1000W power. Drying at 200W power level was unfavourable in terms of low drying rates and leaf quality.

Drying of leaves at 500W and 700W was favourable and found to be similar with respect to the colour attributes, equilibrium moisture content of dried leaves as well as energy consumption, but with less drying time required at 700W power level (8.8 min versus 16.6 min). Leaves dried at 500W had slightly higher chlorophyll contents while leaves dried at 700W had a stronger bay leaf odour. Leaves dried at 500 and 700W remained intact as whole leaves but could be easily be blended to a powder. Drying at 500 and 700W occurred in the falling rate period only.

The drying data was successfully analysed through the determination of drying rate constants (*k)* and moisture diffusivity values (D_{eff}), and the Verma and Jena and Das models best fit the data for leaves dried at 500W and 700W, respectively. Future work on the optimisation of the microwave-drying process will focus on the impact of power level on the essential oil content of the leaves.

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