Influence of the time-temperature-profile during convective and microwave assisted roasting on physical properties of cocoa

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ABSTRACT. The roasting of cocoa is essential for flavor generation and physical properties of manufactured products. Focus of the presented research was to investigate the influence of convective and microwave assisted roasting on physical properties (moisture content & color) of cocoa as well as energy consumption. The investigations were carried out with nibs and beans from Nacional cocoa (Ecuador) roasted with a modular lab roaster. An increase of final cocoa surface temperature during convective roasting and an increase of microwave power at constant final cocoa surface temperature resulted in a decreasing moisture content and an increasing color difference compared to raw cocoa. It was possible to achieve the same physical properties with both roasting types. A simplified calculation of the energy consumption at the different roasting conditions revealed a potential energy reduction by about one third using microwave assisted roasting at slightly lower cocoa surface temperature while obtaining the same physical properties as during convective roasting. Maintaining the physical properties is presumably promoted by the effect that microwave assisted roasting can result in a more homogeneous heating of the whole cocoa.

KEYWORDS: cocoa roasting, convective, microwave, water content, color, energy consumption

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1 Introduction

During the processing of cocoa, roasting is essential for the generation of cocoa flavor and other quality characteristics: Unwanted volatile acids are removed, desired flavor components are formed by the Maillard reaction, water content of cocoa is reduced and color of cocoa darkens (Afoakwa, 2010). The roasting conditions, especially temperature and time, influence the color of the cocoa (Krysiak, 2006; Kendari et al., 2012). The roasting conditions including the type of roaster have also a significant impact on the flavor profile of the roasted cocoa (Hernandez and Rutledge, 1994). Especially for the Maillard reaction the water content is relevant. The desired final water content of the cocoa is about 2 % (Afoakwa, 2010). A systematic flavor profile design by the roasting process based on scientific knowledge is not yet reported in literature.

Cocoa is commonly heated during roasting by convective or contact heating which consumes high amount of energy. The application of microwaves for roasting has been investigated by several researcher groups: Using an especially designed roaster it was demonstrated that the required energy can be reduced by up to 30 % in comparison to a conventional roasting processes despite a low loss factor of cocoa microwaves (Rother et al., 2009b; Rother, 2010). With focus on the product quality, it was shown that the use of microwaves for roasting promotes lipid oxidation in cocoa butter but the physicochemical quality of roasted cocoa beans was desirable (Krysiak, 2011). It is assumed that the more homogeneous heating by microwaves is a favorable aspect for the quality.

The presented results focus on the impact of the time-temperature-profile, the type of energy input (convective & microwave) and the cocoa size on its changing physical properties (moisture content & color) due to roasting and the corresponding energy consumption of the process. Resulting perceivable sensory flavor profiles and the corresponding flavor key substances in roasted cocoa are under investigation by our project partner. Based on this knowledge potential improvements of the roasting process concerning cocoa quality, energy consumption and throughput can be identified.

2 Materials and Methods

2.1 Cocoa used for experiments

For investigation of the impact of particle size, Nacional cocoa from Ecuador in the form of whole beans and broken beans without the shell – so called nibs – were used. Both were taken from the same batch. The initial moisture content and color are displayed in Table 1. The measurement methods are described in chapter 2.3. The raw beans have a higher moisture content than the raw nibs which is most likely due to the required heat treatment in the industrial breaking of the beans. The heat treatment is likely to be responsible for the slight color difference as well.

Table 1. Moisture content and color of raw cocoa beans and cocoa nibs.

cocoa type	moisture content w / %	Color		
		L* / -	a* / -	b* / -
beans	6,21 ± 0,24	17,61 ± 0,20	12,00 ± 0,05	15,39 ± 0,10
nibs	4,49 ± 0,16	18,65 ± 0,14	12,30 ± 0,23	15,85 ± 0,20

2.2 Cocoa roasting

A modular lab roaster (Rother et al., 2009a; Kraus et al., 2011) was used for the roasting process. It allows combining convective and microwave energy input. For process control and subsequent analysis, the temperature, the water content and the volume flow rate (at room temperature) of the inlet and outlet air flow, the surface temperature of the sample, the induced and reflected microwave power are measured and recorded. For roasting, the desired surface temperature of the cocoa samples was defined. It was determined by online infrared measurement. Maximum inlet air temperature, air volume flow rate and maximum induced microwave power P_{MW} was configured for control of the energy input. The sample is placed into a rotating PTFE drum which allows simultaneously the throughflow of air, the application of microwaves, the mixing of the sample and the measurement of the sample surface temperature. For pasteurization, steam was injected after 40 minutes of roasting.

A roasting process with convective energy input was defined as reference. It is based on an industrial roasting process and was modified to achieve the target moisture content of 1.5 to 3.5 %. The time-temperature-profile of the reference roasting process is displayed in Figure 1 left (black continuous line with final cocoa temperature T_{final} = 125 °C). The process was split into five steps:

1. Heating to 90 °C (10 min).
2. Keeping at 90 °C (10 min).
3. Heating to T_{final} = 125 °C (15 min).
4. Keeping at T_{final} = 125 °C (20 min) and injecting water steam for pasteurization (0.5 min) indicated by a temperature drop at 40 min.
5. Cooling with air at 30 °C (10 min).

The maximum inlet air temperature was set in step 1, 2 and 4 to a temperature 45 °C higher than the desired surface temperature and in step 3 30 °C higher, respectively. The air volume flow rate was set to 52.0 m^3/h in all steps. The breaks of 1 min and the temperature drops between the steps 2 to 5 (at 21, 37 and 58 min) are due to weighing of the drum which causes an incorrect temperature measurement. Each batch of beans or nibs had a mass of 250 ± 2 g.

In further experiments, the settings in steps 1 to 4 were changed. The corresponding time-temperature-profiles (t-T-profiles) are shown in Figure 1. For investigation of the influence of T_{final} during convective roasting, it was set in step 3 and 4 to 90, 110 and 140 °C. For all microwave assisted (MWA) roasting experiments, microwave energy input was only activated in steps 1 to 3 as the faster and more homogeneous heating of the cocoa is of interest. P_{MW} was set to 205, 410, 615 and 820 W and T_{final} was kept constant at 125 °C. In order to minimize the effect of the convective energy input while retaining the removal of water and other volatile substances, the air volume flow rate was reduced to 21.5 m^3/h in steps 1 to 3. The maximum inlet air temperature was set in steps 1 to 2 to 90 °C and in step 3 to 125 °C. Settings of step 4 and 5 were according to the reference roasting process. At 205 W the heating was slower than at reference process conditions; at 615 and 820 W the heating was faster. Therefore, the time of steps 1 to 3 was reduced by 10 min for additional roasting experiments at 615 W. The core temperature of some beans was measured with fiber optic temperature sensors (Neoptix T1 Temperature Probe & Reflex Signal Conditioner).

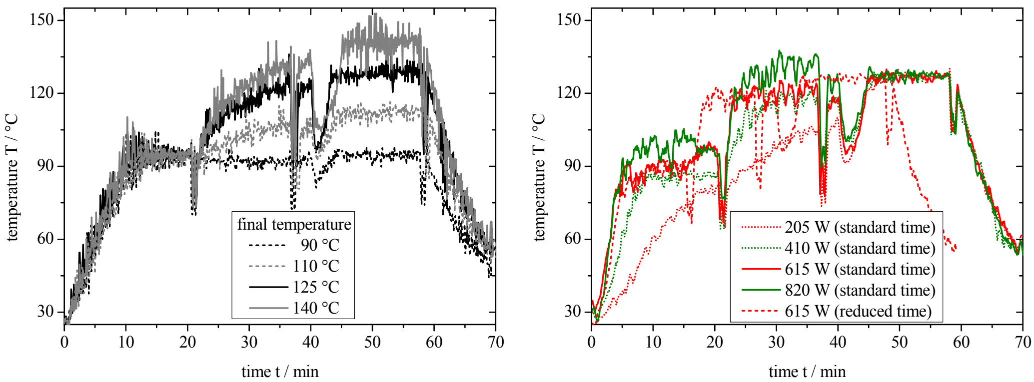

Figure 1. t-T-profiles during convective roasting at standard heating rate and different T_{final} (left). t-T -profiles during MWA roasting at different P_{MW} and different treatment time (right). Moving average of 0.5 min in case of MWA roasting.

For evaluation of the energy consumption in the lab roasting process, a simplified energy calculation has been conducted. According to equation 1, the total energy required for a roasting process in the modular lab roaster $E_{roasting}$ is calculated from the difference of the energy transferred by the air $Q_{air,in/out}$, the energy required to heat and evaporate the water of the cocoa $\Delta H_{water,cocoa}$ and the difference of the microwave energy $E_{MW,in/out}$. $Q_{air,in/out}$ is calculated assuming dry air from measured temperatures, measured air volume flow rate at room temperature, air density at room temperature of 1.1885 kg/m^3 and an average heat capacity of 1.015 kJ/(kg·K). To take into account the increasing water mass fraction in the air flow, $\Delta H_{water,cocoa}$ is calculated from the respective moisture content change with a temperature change from 20 °C (average room temperature) to 100 °C (average outlet air temperature) with an average heat capacity of 4.200 kJ/(kg·K) and an evaporation enthalpy of water at 100 °C of 2257 kJ/kg. The simplifications for the calculation of $\Delta H_{water,cocoa}$ are expected to cause an underestimation of the required energy but it will be demonstrated that the water mass fraction in the air can be neglected in this process. $E_{MW,in/out}$ is derived directly from measured data.

$$E_{roasting} = Q_{air,in} - Q_{air,out} - \Delta H_{water,\,cocoa} + E_{MW,in} - E_{MW,out} \quad (1)$$

The heating of the roaster between the air inlet and air outlet (temperature measurement points) is neglected. For basic comparison of the data, this can be neglected if the overall t-T-profile of the cocoa is similar assuming the t-T-profile of the process chamber is similar as well.

2.3 Characterization of cocoa

The cocoa was milled in a cutting mill (Vorwerk Thermomix) in two steps for measurement of the moisture content and color. Prior to milling, the whole cocoa beans were broken (CPS Limprimita Cocoa Breaker) and winnowed (CPS CC-1 Catador Winnower) to remove the shells – only the resulting nibs were analyzed. The nibs were milled for 10 s (roasted) or 25 s (raw) to less than 2.0 mm without significant melting and release of cocoa butter which would cause a caking of the powder. The powder was classified by sieving and the fraction 0.5 to 1.0 mm was used for measurements with the moisture analyzer (Kern MLS-A Moisture Analyzer). The moisture content of 4.5 ± 0.1 g was determined at 105 °C and a maximum mass change of 0.001 g per 90 s as stability criterion. The measurements were performed in triplicate.

The remaining cocoa was milled for 300 s at a maximum temperature of 50 °C to prevent further thermal exposure. Due to the use of a cutting mill, the cocoa mass contained some larger particles (up to 2.0 mm) but was overall reduced to smaller particles dispersed in the melted and released cocoa butter. The color of the mass was measured at 40 °C with a colorimeter (Konica Minolta CR-300 Chroma Meter) and characterized with the coordinates L* (0 black, 100 white), a* (negative green, positive red) and b* (negative blue, positive yellow) within the CIELAB color space (DIN EN ISO 11664-4, 2012). These measurements were performed in quintuplicate. For easier visualization of the color change, the color difference ΔE was used according to equation 2, with index R indicating roasted samples and index 0 indicating unroasted samples.

$$\Delta E = \sqrt{\left(L_R^* - L_0^*\right)^2 + \left(a_R^* - a_0^*\right)^2 + \left(b_R^* - b_0^*\right)^2} \qquad (2)$$

3 Results and discussion

3.1 Influence of the energy input on the time-temperature-profile of cocoa

Figure 2 shows the t-T-profiles during step 1 of convective (0 W) and MWA (615 W) roasting for the surface and the core of exemplary beans. The increase of the surface temperatures starts almost simultaneously but the MWA roasting. In contrast to this, the core temperature of MWA roasting is increasing earlier (≈ 1.0 min offset) and faster than the core temperature of convective roasting (≈ 2.5 min offset). This demonstrates that application of microwave energy input results in more homogenous heating of cocoa beans.

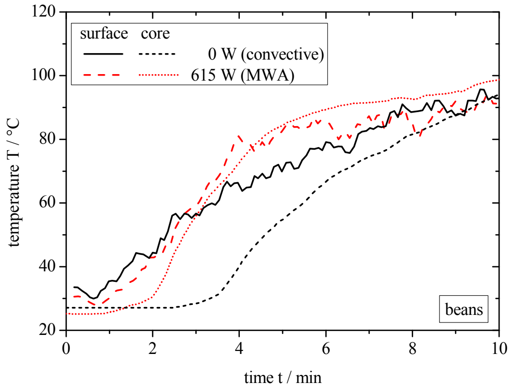

Figure 2. t-T-profile of bean surface and bean core during step 1 comparing convective roasting with MWA roasting at 615 W.

3.2 Impact of roasting conditions on physical properties of cocoa

The change of the moisture content during MWA roasting compared to the reference roasting process (convective) after steps 2, 3 and 5 is displayed in Figure 3 for beans (left) and nibs (right). For all roasting conditions, the highest moisture content reduction rates for each respective experiment are observed in steps 1 to 3. With increasing P_{MW}, the moisture content reduction during steps 4 and 5 is decreasing which is more distinct for beans than for nibs. The energy input level has overall a much higher impact on the moisture content reduction rate of beans than of nibs. Comparing MWA roasting at different P_{MW} to convective roasting, the change in beans during convective roasting is comparable to 205 W while the change in nibs during convective roasting is comparable to 410 or 615 W. As the surface temperature of cocoa at 205 W during MWA roasting was significantly lower than at standard conditions (see Figure 1) the beneficial effect of homogeneous heating is more distinct for larger particles (beans). Additionally, the decrease of the moisture content in the beans is limited at higher levels indicating a limitation of the heat and mass transfer due to the larger particle size.

The trend of highest moisture content reduction rates in steps 1 to 3 is also observed for all convective roasting conditions. In steps 3 to 5, the rates decrease with decreasing final temperature. The lesser impact of the energy input level for nibs compared to beans is seen as well.

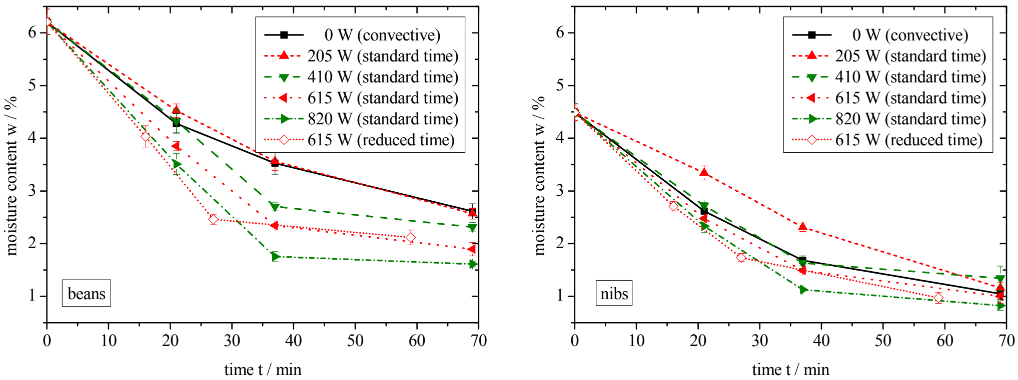

Figure 3. Change of moisture content of cocoa beans during MWA roasting compared to reference roasting process (0 W) for beans (left) and for nibs (right). Standard deviation of three measurements.

In Figure 4, the final values (after step 5) of the moisture content (left) and color difference (right) for all investigated roasting conditions are presented. Increasing T_{final} and increasing P_{MW} result in decreasing moisture content and increasing color difference for beans and nibs. T_{final} has more influence than P_{MW}. At 110 and 125°C, a plateau is observed for the moisture content which can not be explained so far. Considering convective roasting at standard conditions, it can be stated that MWA roasting can achieve comparable physical properties at 205 to 410 W. The MWA roasting at 615 W with reduced treatment time results in similar moisture content but less color difference compared to 615 W with standard treatment time. Besides the above mentioned limitation due to larger particle size, the overall difference between beans and nibs for both physical properties can partially be attributed to the initial difference of the moisture content (1.72 %) and of the color difference (1.18).

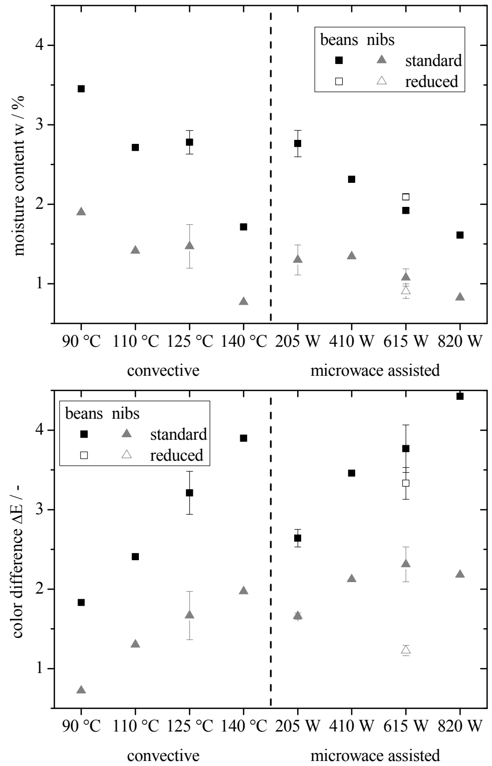

Figure 4. Final moisture content and color difference of roasted cocoa at different T_{final} (left) and at different P_{MW} & microwave treatment times (right). Standard deviation in case of multiple experiments.

3.3 Energy consumption at different roasting conditions

The calculated energy data for beans at all investigated roasting conditions are listed in table 2. The impact of the heating and the evaporation of the water contained in the cocoa can be neglected as the required energy is between 0.018 and 0.030 MJ compared to 1.95 to 3.48 MJ overall energy required for the roasting process. For convective roasting, the energy transferred by the air is increasing with increasing T_{final} as expected. In case of MWA roasting, the required microwave energy increases slightly with increasing maximum P_{MW} while the overall energy required for the roasting process is nearly constant as the required energy transferred by air is reduced. The reduced microwave treatment time reduces the overall energy only slightly. All MWA roasting conditions require less overall energy for roasting than any convective roasting condition. The same trends are observed for nibs. Discussing this data, the above mentioned simplifications of this calculation have to be considered. Nevertheless, it can be concluded that using MWA roasting can result in a reduction of the energy consumption of up to one third at constant T_{final} and a similar t-T-profile.

Table 2. Energy data for bean roasting at all investigated roasting conditions.

	$Q_{air,in}$ / MJ	$Q_{air,out}$ / MJ	$\Delta H_{water,coc.}$ / MJ	$E_{MW,in}$ / MJ	$E_{MW,out}$ / MJ	$E_{roasting}$ / MJ
90 °C	6,33	3,89	0,018	-	-	2,42
110 °C	7,10	4,35	0,023	-	-	2,73
125 °C	7,70	4,40	0,022	-	-	3,27

140 °C	8,38	4,87	0,029	-	-	3,48
205 W	4,77	2,93	0,022	0,42	0,20	2,04
410 W	4,48	2,83	0,025	0,51	0,19	1,95
615 W	4,68	2,88	0,028	0,62	0,25	2,15
820 W	4,67	2,93	0,030	0,69	0,30	2,10
615 W reduced time	4,42	2,64	0,027	0,49	0,20	2,04

4 Conclusions

The same physical properties (moisture content & color) can be achieved by microwave assisted roasting at 205 to 410 W at a slightly lower surface time-temperature-profile and a final cocoa temperature of 125 °C with an energy consumption reduced by about one third compared to convective roasting with the same final cocoa temperature. The use of microwaves in roasting results in a more homogeneous heating of the cocoa, especially when beans are roasted. Reduction of the microwave and overall treatment time at constant maximum microwave power and final cocoa temperature results in the same moisture content compared to standard treatment time but less color change and no relevant reduction of the energy consumption.

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