Convective drying of potatoes assisted by microwave and infrared radiation – process kinetics and quality aspects

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Summary
This article presents the results of experimental studies on hybrid drying of potatoes (tubers of *Solanum tuberosum* L.). Six different drying schedules, being a combination of convective, microwave and infrared drying methods, were arranged and tested to find the best drying kinetics by minimum energy consumption and assuring good quality of products. Kinetics of the process was assessed on the basis of drying curves (evolution of moisture ratio), drying time and drying rate. Quality was judged through sensorial analysis (appearance, odour, tactile) and colorimetric measurements. Chroma meter was used to measure the colour of the samples. On the basis of obtained results, overall colour change between fresh and dried material was calculated. The specific energy consumption was measured with the use of electrical network analyser. The combination of several drying methods at once positively influenced the time of drying, quality of the products as well as the energy consumption. Obtained results proved that crucial was to identify the proper period of microwave or infrared enhancement, with a suitable power of radiation. The novelty of the research presented in this paper is the combination of three different drying techniques in one process, taking into account their advantages and disadvantages.

Keywords
hybrid drying; microwave; infrared radiation; kinetics; energy consumption; colour; potato

Potato chips are a popular snack and a predominant part of the snack food market [1]. Potato, a tuber of *Solanum tuberosum* L., is also a source of many valuable nutrients such as carbohydrates, high-quality proteins, vitamin C, vitamin B6, vitamin B3 and minerals [2]. In addition to these basic nutrients, coloured potato varieties contain significant amounts of phytonutrients, such as polyphenols, which can be used as novel sources of natural colourants and antioxidants for the food and human health industries [3].

Currently, the demand for healthier foodstuffs, such as low-fat or fat-free products, is a major driving force in the snack food industry [4]. Drying provides an alternative method for producing low-fat or fat-free potato chips [5]. Unfortunately, the most popular, convective drying (so-called hot air drying) influences the products quality in terms of nutritional value, colour, texture, shrinkage etc. [6–8]. Due to long operation time, high temperature and atmosphere rich in oxygen, quality of dried products is considerably affected. Caramelization, enzymatic and non-enzymatic reactions (e.g. Maillard reaction), pigments degradation, ascorbic acid or lipids oxidation constitute are deteriorative processes that proceed during drying and affect final appearance and nutritional value of products [9–11]. Moreover, drying has been identified as one of the most energy-intensive operations. Several authors reported that it utilizes up to 25 % of all industrial energy usage [12, 13]. Because of recent environmental and power engineering problems, including greenhouse gasses emission, depletion of fossil fuels etc., it has become extremely important to reduce consumption of energy in all industrial sectors [14].

The disadvantages and problems described above were an incentive to search for alternative methods of pre-treatment and drying. The primary objective of the modern food processing technologies, including drying, is the production of high-quality products at the possibly minimum

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capital and operating costs. For this reason, special emphasis is placed on shortening the operation time, reducing electricity consumption and minimizing the negative effects of the processing [15–19]. Several innovative processes for drying potato chips were reported in the literature, such as microwave-freeze drying [20], vacuum-microwave drying [21], low-pressure superheated steam drying and hot air drying [6].

The research presented in this paper was aimed at elaboration of a drying process for potatoes using convective – hot air drying (CV), microwave (MW) and infrared (IR) techniques applied separately (simple drying) as well as in different combinations (hybrid drying). Six drying schedules with a different combination of the mentioned techniques were tested experimentally to find the most effective drying of potatoes. Each schedule was assessed in terms of drying kinetics, quality of products and specific energy consumption. As an efficient drying operation, the one characterized by high drying rate, good quality of dried products and minimal energy consumption was meant. The product quality was judged on the basis of sensorial analysis (appearance, odour, tactile), shrinkage and colour measurements.

MATERIALS AND METHODS

Fresh potatoes (tubers of *Solanum tuberosum* L.), variety Bryza, from local market in Poland were used for experimental tests. Each potato tuber was washed, cleaned and dissected with a ceramic knife. Then, samples in the form of slices (diameter 53 mm, height 8 mm) were cut and placed in the dryer chamber on a special perforated scale pan. For each experiment, 10 slices of potato were taken, so that the mass of a single batch was about 50 g. Several techniques of drying were tested, both separately (schedules No. 1 and 2) and in different combinations (schedules No. 3 to 6). Detailed description of the individual schedules is presented in Tab. 1.

Drying was carried out in the laboratory hybrid dryer, constructed by Ertec (Wrocław, Poland), which enables CV, MW and IR drying separately as well as in different combinations. A scheme of the hybrid dryer is presented in Fig. 1.

Hot air for CV drying is provided by an air heating system consisting of the electric heater and fan. Microwaves at 2450 MHz (wavelength about 0.12 m) were produced by a magnetron, which works under the continuous wave mode. The power of microwaves was adjusted by the anode voltage. The IR electric heater, located about 150 mm above the rotatable ceramic pan, supplies the IR radiation directly to the sample surface. Standard IR heater with Ni-Cr filament in a translucent quartz tube was used. For this type of heater, the peak wavelength was approximately 4.3 μm. The whole drying system was controlled by an industrial driver model ST10 produced by Frisko (Wrocław, Poland).

All tests were carried out with the following settings of drying parameters:
- airflow velocity $v_a = 1.2$ m·s^{-1},
- air temperature $T_a = 55$ °C (if used),
- power of microwaves $P_{mw} = 100$ W (if used),
- power of infrared radiation $P_{ir} = 250$ W (if used).

Tab. 1. Description of the drying schedules.

Schedule	Code	Description of the process
1	CV	Solely convective drying
2	MW	Solely microwave drying
3	CV-MW	Convective drying enhanced with microwave radiation during the whole process
4	CV+MW_{30}	Convective drying enhanced with microwave radiation during the first 30 min of drying
5	MW+IR_{per}	Microwave drying enhanced with infrared radiation periodically
		This process consisted of 8 phases. In phases 1, 3, 5 and 7, the process was enhanced with infrared radiation. The length of phases was controlled through the temperature of the sample surface. If temperature rose above 70 °C, the phase was terminated and the process went to the next phase. In phases 2, 4 and 6 (10 min each), only microwave drying was supplied.
6	CV-MW+IR_{per}	Convective drying enhanced with microwave radiation in the whole process and periodically with infrared radiation
		This process consisted of 8 phases. In phases 1, 3, 5 and 7, the process was enhanced with infrared radiation. The length of phases was controlled by the temperature as described above. In phases 2, 4 and 6 (10 min each), convective drying enhanced with microwave drying was performed.

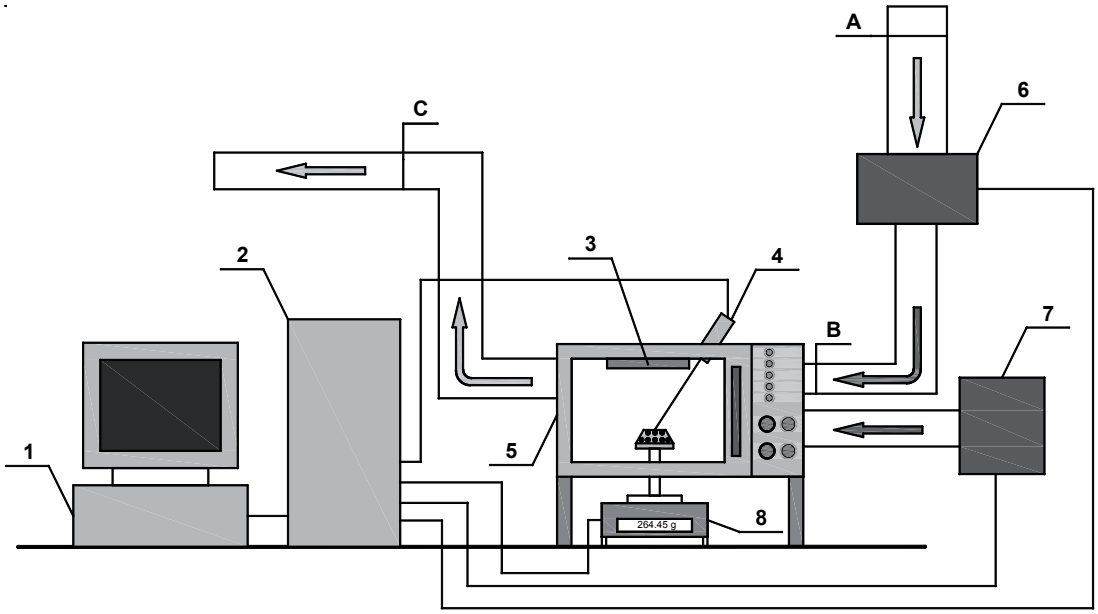

Fig. 1. Scheme of the hybrid dryer.

A, C – air humidity and temperature transmitters, B – hot-wire anemometer, 1 – computer, 2 – driver unit, 3 – infrared electric heater, 4 – pyrometer, 5 – drying chamber, 6 – air heating system, 7 – microwave generation system, 8 – electronic balance.

The powers of MW and IR presented above refer to the energy radiated by the generator (incident radiation). The intensity of radiation, defined as emitted power per volume of the drying chamber, equaled 4.38 kW·m^{-3} and 10.94 kW·m^{-3} for microwaves and IR, respectively. Because these values do not take into account the energy dissipation in the chamber and the losses between the generator and the samples, the effective power utilized during drying was smaller. On the other hand, due to the complexity of propagation, suppression and absorption of radiation by biological materials, it is impossible to simply quantify the losses.

The relative humidity (*RH*) of the air was controlled with the humidity and temperature transmitter model Hygrostats 600 DHT -20/120 (Testo, Lenzkirch, Germany). The air *RH* ranged between 20 % and 22 %, i.e. 21 % on average.

The balance, type WPS 2100/C/1 (precision 0.01 g) produced by Radwag (Radom, Poland), was used for constant measurement of the sample mass reduction. The temperature of the sample surface was measured by the pyrometer, model MI (precision 1 °C), produced by Raytek (Santa Cruz, California, USA), placed in the corner of the dryer chamber. The pyrometer is a non-contact device that intercepts and measures thermal radiation emitted by the material. Air velocity was measured with the use of a hot-wire anemometer, model CTV 100 (precision 0.1 m·s^{-1}) produced by Kimo (Montpon, France). The energy consumed by the whole drying apparatus during the drying process was measured with a standard electricity meter (precision 0.1 kWh) and recalculated to specific energy consumption (EC_a) expressed in kilojoules per kilogram of evaporated moisture.

All of the measured parameters, such as sample mass and temperature, airflow velocity, temperature or humidity, reflected microwave power, were recorded every 5 s during the entire process and stored in the standard personal computer equipped with the data acquisition software.

On the basis of the mass measurement, instantaneous moisture content (MC_t), drying rate (DR_t) and average drying rate (DR_a) were calculated in accordance with Eq. 1–3:

$$MC_t = \frac{m_t - m_s}{m_s} \quad (1)$$

$$DR_t = \frac{dm}{dt} \quad (2)$$

$$DR_a = \frac{m_i - m_{eq}}{DT} \quad (3)$$

where m_t is the mass of a sample at a considered time, m_s is the mass of dry matter, dt is the time at which the change of mass dm took place, m_i is the initial mass of sample, m_{eq} is an equilibrium mass of sample (at the end of drying), and DT is overall drying time till m_{eq} was reached. Mass of dry matter was determined after drying

for 24 h at $T = 75$ °C in a convective dryer model SML42/250/M (Zalmed, Dąbrowa, Poland).

Moisture ratio at a given time of the process (MR_t) was calculated accoding to Eq. 4:

$$MR_t = \frac{MC_t - MC_{eq}}{MC_i - MC_{eq}} \quad (4)$$

where MC_i, MC_t and MC_{eq} are initial, instantaneous (at a given time of process) and equilibrium moisture content, respectively. Equilibrium moisture content (MC_{eq}) was assumed constant during the study and equaled 5 %. Initial moisture content (MC_i) was determined in accordance with Eq. 5:

$$MC_i = \frac{m_i - m_s}{m_s} \quad (5)$$

The quality of the products was assessed on the basis of sensorial analysis of appearance, tactile feelings, odour and instrumental measurements of colour. The colour of the fresh and dried samples was measured using CR400 colorimeter (Konica Minolta, Tokyo, Japan) using settings illuminant D65, observer 2°, precision 0.01 and expressed in CIE*Lab* colour space. Five spots for colour measurement were randomly chosen for each sample and five measurements of colour parameters (L^*, a^*, b^*) in each spot were done (25 measurements per sample). During measurement, the sample was placed on a white ceramic plate to provide identical measurement conditions and to eliminate the influence of background. Arithmetic means were used for data processing. On the basis of obtained results, the differences in colour of samples (before and after drying) were calculated as an overall colour change parameter (dE_a).

$$dE_a = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (6)$$

where L^*, a^* and b^* are the tristimulus colour coordinates in CIE colour space.

The colour of the products was chosen as a quality marker because, in the case of fresh and processed food, appearance is one of the most important sensory quality attributes. The colour is the first quality parameter evaluated by consumers, and it is critical to product acceptance [22–24]. This follows from the fact that colour is the first sensation that the consumer perceives, thus it has a strong influence on the consumer's opinion about the food quality [25]. In the absence of any other generally available tools, the consumer is willing to either accept or reject the presented food product, based only on visual stimuli associated with the colour of the product [26]. Each food product may be characterized by the acceptable "colour range", but it usually depends on a wide variety of factors, including variability among consumers, their age and ethnic origin, and the physical nature of the surroundings at the time of judgment [27].

Shrinkage and deformation of samples were analysed on the basis of digital images. Samples were photographed on a plotting paper (with 1 mm mesh) from the top and front side. In this way, both shrinkage and deformations of the samples might be estimated. Additionally, radial shrinkage coefficient (*RS*) was calculated in accordance with the following equation:

$$RS = 1 - \left(\frac{A_d}{A_0}\right) \quad (7)$$

where A_d and A_0 are the top surface of the raw (fresh) and dried samples, respectively. Both surfaces were determined with the use of ImageJ software ver. 1.51n (National Institutes of Health, Bethesda, Maryland, USA) [28].

Each of the analysed processes was performed in triplicate. Obtained data were averaged and the standard deviation was calculated with Statistica software ver. 12 (StatSoft, Tulsa, Oklahoma, USA).

RESULTS AND DISCUSSION

Drying kinetics

In Fig. 2, the evolution of moisture ratio (wet basis) versus time is presented for particular schedules of the process. Average drying rate (DR_a) and drying time (DT_a) are presented in Fig. 3. It can be seen that the course of the curves depended strictly on the type of process. Solely, convective drying (CV) was assumed as a control procedure, and each subsequent program was judged in reference to this operation. As expected, CV was the slowest process, lasting up to 220 min (Fig. 2, 3). This surely resulted from ineffective drying at so-called falling drying rate period (FDRP). It was stated that, at the beginning of the drying when the material contains much moisture, the rate of the process depends mainly on the rate of water evaporation from the surface of sample [12]. The internal transport (diffusion of water) in this period is very efficient so it does not influence the overall drying rate. Thus, the speed of the process remains almost constant, and the drying conditions such as temperature, *RH* or velocity of air may effectively influence it. This so-called constant drying rate period (CDRP) lasts

until the first dry regions occur on the surface of the material. Appearance of dry areas on the surface of the sample results from faster evaporation of moisture from the surface than the diffusion of water from the interior to the surface of material. Moisture content (or ratio) at which the first dry regions appear is defined as critical one. During FDRP, the overall rate of the process is fully controlled by diffusion (internal resistance) and operational conditions do not significantly affect the rate of the process [12].

In Fig. 4A, an exemplary evolution of instantaneous drying rate (DR_t) during the convective process is presented. Although the experimental points are scattered, both CDRP and FDRP may be distinguished. Furthermore, after the linear regression analysis, it was possible to determine the critical moisture ratio (content) at the intersection of the fitting lines.

In the case of MW drying, the kinetics of process is completely different. Average drying time (DT_a) was visibly shorter (Fig. 3A), and the average drying rate (DR_a) grew almost two-fold compared to solely CV drying (Fig. 3B). Differences between convective and microwave drying result mainly from different mechanisms of heat transfer. In the case of convection, energy required for drying is delivered from the hot air to the surface of material and the evaporation proceeds mainly in the region of so-called evaporation front. Throughout CDRP, this front is located on the surface of material, but in FDRP, it starts to shifts to the interior of the sample (wet core), which hinder heat and mass transport [12].

In contrast, during MW drying, the heat is generated in the whole volume of sample or to a depth of penetration. Thus, moisture is evaporated not only at the surface but also inside of the material and evaporation front cannot be distinguished. Moreover, due to the increase of pressure inside the material, plug flow of moisture both in vapour and the liquid state may occur, which additionally accelerates the drying. In effect, internal moisture transport (diffusion) does not significantly affect the overall rate of drying and neither CDRP nor FDRP may be distinguished on the drying rate curve (Fig. 4B).

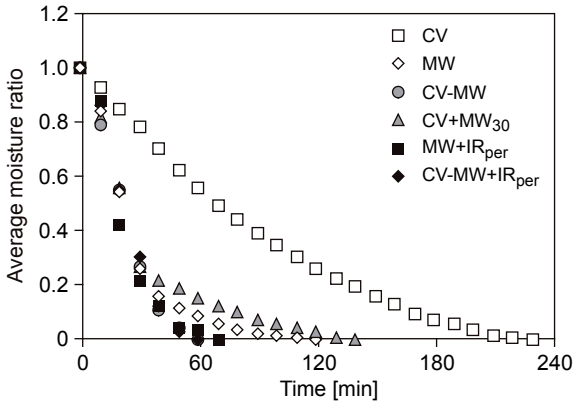

Fig. 2. Evolution of the moisture ratio during the processes.

CV – convective drying, MW – microwave drying, CV-MW – convective-microwave drying, CV+MW30 – convective drying enhanced with microwave radiation during first 30 min, MW+IR_{per} – microwave drying enhanced with infrared radiation, CV-MW+IR_{per} – convective-microwave drying enhanced with infrared radiation.

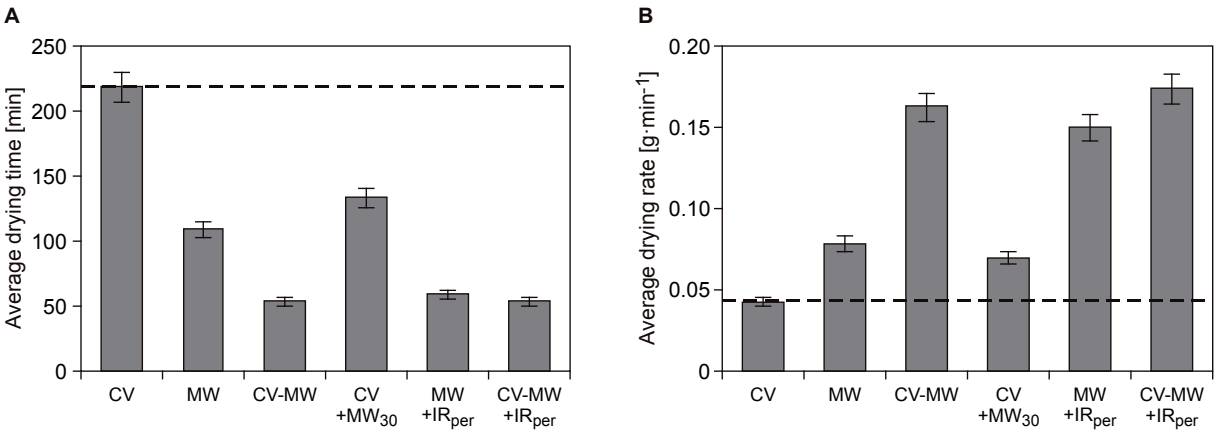

Fig. 3. Kinetic parameters of the processes.

A – average drying time, B – average drying rate.
CV – convective drying, MW – microwave drying, CV-MW – convective-microwave drying, CV+MW30 – convective drying enhanced with microwave radiation during first 30 min, MW+IR_{per} – microwave drying enhanced with infrared radiation, CV-MW+IR_{per} – convective-microwave drying enhanced with infrared radiation.

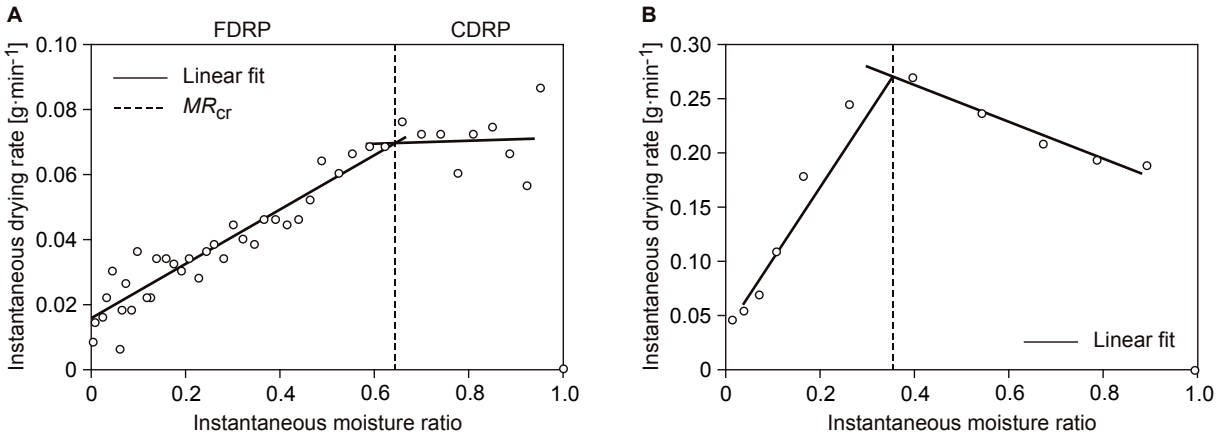

Fig. 4. Dependence of drying rate on moisture ratio.

A – convective drying, B – microwave drying.
MR_{cr} – critical moisture ratio, CDRP – constant drying rate period, FDRP – falling drying rate period.

Because microwaves had been identified as an effective drying agent, this radiation was used during the convective process in the next two drying schedules, to accelerate and shorten the duration of the process. As an expected application of an additional source of energy, it meaningfully influenced the kinetics of the convective process. During convective-microwave drying (CV-MW), the radiation was applied to the material during the whole process, which resulted in significant growth of average drying rate (fourfold compared to CV and two-fold compared to MW) and in a reduction of the drying time to less than 60 min. This positive effect followed from the complementary action of microwaves and hot air. Microwaves are known to easily heat up the material and evaporate the moisture, while dry hot air effectively carries off the vapour to the surroundings. Unfortunately, high speed of drying or excessive irradiation may result in negative effects on products quality. Thus, in the fourth drying program (CV+MW_{30}), microwaves were applied only for the first 30 min of the process. Such modification was aimed not only at reducing the negative effects of radiation on the product quality, but also at lowering the energy consumption. From the kinetics point of view, this change negatively influenced both time of drying (DT_a) and average drying rate (DR_a) in comparison to the previous program (CV-MW). After first 30 min of intensive CV-MW drying, microwave generator was turned off, and the further part of the process proceeded only by convection. Obviously, this led to a marked decrease in the drying rate and thus increase in the drying time (Fig. 2, 3).

In last two schemes of drying, convective and microwave processes were additionally enhanced with infrared radiation. It can be seen in Fig. 2 and Fig. 3 that application of IR radiation positively influenced the kinetics of both convective and microwave drying. Due to significant growth of the drying rate (DR_a), time of drying was shortened in these schedules by almost 73% (for MW+IR_{per}) and 75% (for CV-MW+IR_{per}). Very positive influence of IR radiation may be attributed to the highly efficient mechanism of heat transfer. It is generally assumed that, at the beginning of the drying, the surface of material is coated with a film of water. At this CDRP period, internal moisture transfer (diffusion) is very efficient and the rate of the process is fully controlled by the evaporation of moisture from the surface of the material. Thus, the drying process may be considered as evaporation from the free surface of water. For this reason, application of an efficient source of energy such as thermal radiation (e.g. IR) to intensify evaporation of moisture present on the surface of the material is reasonable. Obtained results confirmed that this additional energy in the form of thermal radiation intensified the heat and mass transfer, and led to improvement in the drying kinetics. On the other hand, excessive heating of the surface of the sample may lead to deterioration in the quality of the product (in particular colour). Therefore, IR was applied periodically and controlled by the temperature of sample surface. Specifically, when the measuring system (pyrometer) recorded a temperature higher than 75 °C, IR heater was turned off for 10 min ("relaxation" phase). Application of continuous IR enhance-

ment was not possible due to technical and safety restrictions.

Results obtained in this study are in good agreement with our previous studies, where the application of microwave and/or infrared radiation also positively influenced the kinetics of convective drying of beetroot [27] and red pepper [29]. Moreover, the complementary action of hot air drying with microwave and infrared radiation was correspondingly stated. Nevertheless, in the case of fruits and vegetables, the kinetics of the drying operation is not the only point of interest. The efficiency of each process should be also assessed in terms of product quality and energy consumption. Thus, in the second stage of research, qualitative assessment of the obtained products and analysis of the specific energy consumption were done.

Tab. 2. Radial shrinkage coefficient for samples dried at different conditions.

Schedule	Code	Radial shrinkage coefficient *RS* [%]
1	CV	33.7 ± 1.7
2	MW	27.7 ± 1.4
3	CV-MW	27.2 ± 1.5
4	CV+MW_{30}	29.7 ± 1.4
5	MW+IR_{per}	30.1 ± 1.5
6	CV-MW+IR_{per}	28.2 ± 1.4

CV – convective drying, MW – microwave drying, CV-MW – convective-microwave drying, CV+MW30 – convective drying enhanced with microwave radiation during first 30 min, MW+IR_{per} – microwave drying enhanced with infrared radiation, CV-MW+IR_{per} – convective-microwave drying enhanced with infrared radiation.

Quality of products

In Fig. 5, data on the appearance of the samples dried with all schedules are presented. Tab. 2 presents radial shrinkage coefficient (*RS*) measured after each drying process.

It can be easily noticed that, during solely CV drying, significant deformations of sample occurred (Fig. 5A). Sample shrank significantly (Tab. 2), lost its original shape (Fig. 5A) and its surface became rough and hard. Moreover, aroma was weakly noticeable, even after rubbing with a finger. All these negative effects of drying

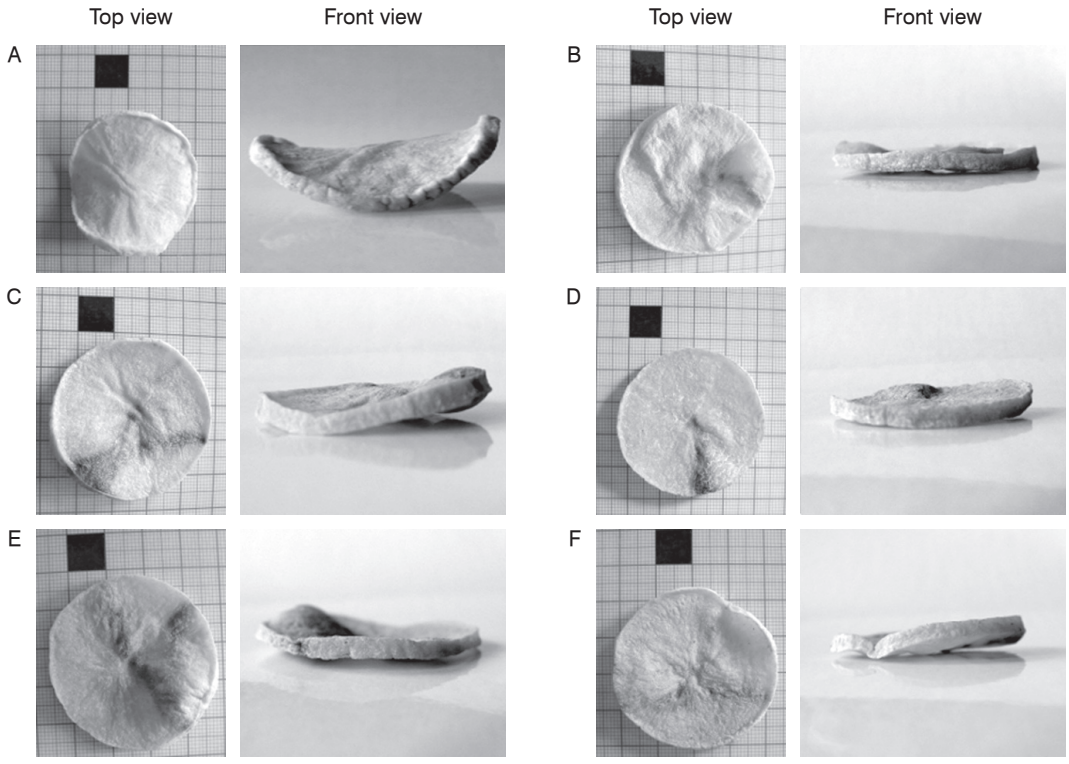

Fig. 5. Appearance of the samples dried at different conditions.

A – solely convective drying (CV), B – solely microwave drying (MW), C – convective-microwave drying (CV-MW), D – convective drying enhanced with microwaves for the first 30 min (CV+MW_{30}), E – microwave drying enhanced with infrared radiation (MW+IR_{per}), F – convective-microwave drying enhanced with infrared radiation (CV-MW+IR_{per}).

resulted from the long drying time at a relatively high temperature. As it was stated in respective literature, the long convective drying usually leads to many physical changes (cell shrinkage and collapse) and biochemical conversions (enzymatic and non-enzymatic browning, degradation of carotenoids, vitamins, and other nutrients, oxidation of lipids, etc.) [30].

MW drying caused significantly smaller changes in the appearance of samples (Fig. 5B). Although the surface of material hardened and became rough (similar to CV), deformations (compare front view in Fig. 5A and 5B) and shrinkage (Tab. 2) were visibly smaller. The colour of the obtained products was similar to the original one, and aroma was easily sensed.

In the third program of drying (CV-MW), where convection was enhanced with microwaves during the whole process, shrinkage and deformations were also smaller compared to CV process (compare front view in Fig. 5A and 5C, Tab. 2). Unfortunately, non-uniform distribution of the microwave intensity caused local overheating of material (so-called hot spots), which leads to change in the colour of samples. Distinctive black streak located along the bottom part of the sample (Fig. 5C) revealed that the part of the sample was exposed to excessive MW irradiation. Since such phenomenon was not observed in the MW program (Fig. 5B), it may be assumed that simultaneous application of microwaves and hot air might have induced local overheating.

This unfavourable phenomenon may be limited by intensive mixing of the dried material (e.g. in a drum or on a rotatable tray) or by reduction of MW irradiation time. Thus in schedule 4 ($CV+MW_{30}$), microwave irradiation was limited to 30 min in the beginning of CV process. Reduction in the time of MW irradiation brought desirable results and the colour degradation due to the overheating phenomenon was visibly smaller (Fig. 5D). Similar observation was made in last two schedules of drying ($MW+IR_{per}$, $CV\text{-}MW+IR_{per}$). Although the change in shape and colour of material took place then, its range was small and acceptable in terms of quality (Fig. 5E, 5F, Tab. 2).

Because sensorial analysis is very subjective and depends on many specific parameters, additional quality judgment was made on the basis of colorimetric measurements. The colour of the products is a very important parameter and constitutes one of the key (or even decisive) factors, which are taken into account during judgment of the product quality. Colour, next to smell/odour, is one of the first stimuli that arrive at the human brain even from far distance. On this first observation, a customer already tends to accept or reject the presented product. Moreover, due to the lack of special devices or time, colour, smell and tactile feelings are usually the only tools to judge the quality of most of the food products such as fruits, vegetables or bakery products.

In Fig. 6A, the overall colour changes (dE_a) of samples dried by individual drying programs are shown. This parameter directly indicates the differences in the colour of fresh and dried samples. The higher value of dE_a, the more visible differences between the fresh and processed material.

It can be seen that the highest dE_a was observed for control process – solely CV drying. It

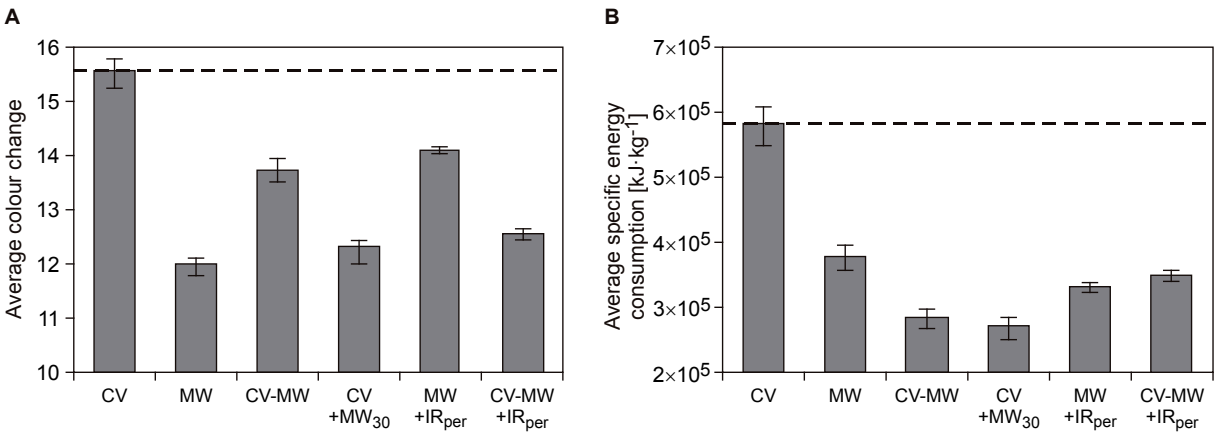

Fig. 6. Colour change parameter and specific energy consumption for particular processes.

A – average colour change, B – average specific energy consumption.
CV – convective drying, MW – microwave drying, CV-MW – convective-microwave drying, CV+MW30 – convective drying enhanced with microwave radiation during first 30 min, $MW+IR_{per}$ – microwave drying enhanced with infrared radiation, $CV\text{-}MW+IR_{per}$ – convective-microwave drying enhanced with infrared radiation.

apparently resulted from the long drying time at a relatively high temperature, and in the oxygen-rich atmosphere. Both high temperature and oxygen content in the drying medium always lead to undesirable bioconversion of enzymatic and non-enzymatic type [8, 31].

In the case of microwave processes, the colour of the samples was affected to a definitely smaller degree. The smallest values of dE_a were observed for the solely MW drying program, whereas the biggest for microwave-infrared one ($MW+IR_{per}$). Positive results during MW drying might have resulted from the short drying duration at a relatively low temperature of the ambient air (T_a = 20 °C). In the case of convective-microwave (CV-MW) and microwave-infrared ($MW+IR_{per}$) schedules, samples were heated intensively both from the outside (by hot air or IR) and from the inside (by microwaves). Thus, the temperature of the material grew rapidly, which might have led to visible discolouration. Moreover, due to inhomogeneity of the microwave field, "hot spots" occurred and influenced the overall colour change parameter. Nevertheless, change in colour was still smaller in comparison to CV program.

In the $CV+MW_{30}$ drying schedule, the microwave enhancement was shortened to the first 30 min of the process. This modification had a positively effect on the colour of the products. Overall colour change parameter (dE_a) decreased almost by a half and reached a level close to that observed for solely MW drying. Similar results were obtained for $CV\text{-}MW+IR_{per}$ program, where dE_a was visibly smaller in comparison to control process (CV) and attained a level observed for MW and $CV+MW_{30}$ programs.

Specific energy consumption

Fig. 6B presents specific energy consumption (EC_a) recorded during certain drying operations. High values of this parameter followed from the small load of the dryer during particular processes (ratio of the samples to the dryer chamber volume). Energy efficiency could be improved by increasing the volume of a single batch. Nevertheless, on the basis of the obtained results, the influence of MW or IR enhancement on the specific energy consumption of convective process could be clearly identified.

As expected, solely CV drying was the most energy-intensive operation. This mainly resulted from the long duration of the process, and the low efficiency of drying in its second period, when the rate of the process is limited by the diffusion of moisture from the interior to the surface of the material. The energy delivered from hot air is not entirely utilized for drying and its vast majority is wasted with the offtake stream.

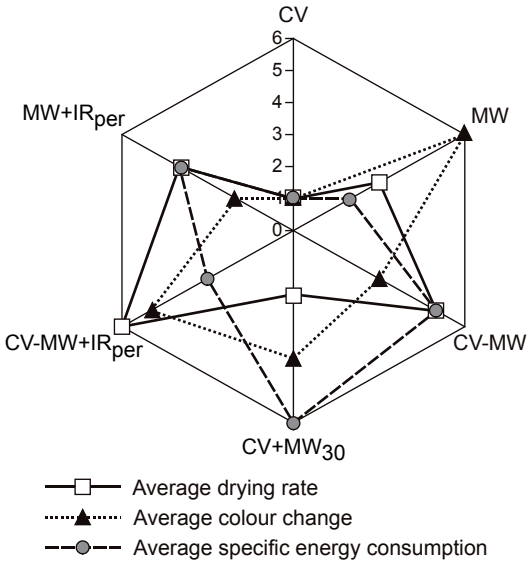

Fig. 7. Comparison of the drying schemes.

CV – convective drying, MW – microwave drying, CV-MW – convective-microwave drying, CV+MW30 – convective drying enhanced with microwave radiation during first 30 min, $MW+IR_{per}$ – microwave drying enhanced with infrared radiation, $CV\text{-}MW+IR_{per}$ – convective-microwave drying enhanced with infrared radiation.

On the other hand, it is obvious that application of the additional source of energy in the form of MW or IR radiation requires more power to supply to the system. However, the advantages in the kinetics of the processes (shortening of the drying time) resulted in the smaller overall specific energy consumption in the microwave and hybrid processes (Fig. 6B).

The smallest values of EC_a were observed for CV-MW and $CV+MW_{30}$ schedules, whereas, for MW, $CV\text{-}MW+IR_{per}$ and $MW+IR_{per}$ programs of drying, this parameter was slightly higher. Nevertheless, all of the hybrid schedules were characterized by lower EC_a compared to control solely CV process, which constitutes indisputable advantage from the economic point of view. If the average time of drying is reconsidered, it can be stated that average specific energy consumption depends mainly on the duration of the process. The longer operational time of process, the higher consumption of electricity.

In Fig. 7, a radar chart illustrating the overall assessment of schedules is presented. This graph was constructed on the basis of the evaluation of each drying schedule in terms of the drying rate (DR_a), colour change (dE_a) and specific energy

consumption (EC_a). Schedules were rated from 1 to 6 points in each category, where 1 is the worst and 6 is the best result. Thus, the farther from the centre of the graph, the better the rating in a given category.

Solely CV drying was the worst schedule of drying and, apart from the considered category, it always received the smallest note. This proved the low effectiveness of this method and motivates for further studying of new and modern drying technologies. Also interesting is that, in each of the considered categories, a different program of drying was assigned as the best one. However, it has to be stated that an efficient drying schedule needs not to be the best one in all categories. The efficient scheme of drying should be rather well balanced in terms of process kinetics, specific energy consumption and quality of the obtained products. Thus, the convective-microwave-infrared (CV-MW+IR_{per}) schedule of drying was chosen as the best from all of those evaluated. This scheme of drying was characterized by a high average drying rate, low specific energy consumption and moderate influence on the product quality.

CONCLUSION

The study proved that the purely convective drying is ineffective due to its long duration and high energy consumption. Moreover, significant quality deterioration occurred, being indicated by high discoloration of the dried material. The combination of several drying techniques in hybrid schedules positively influenced the process kinetics. Higher values of average drying rates in hybrid programs resulted in shorter drying times. Moreover, despite the application of additional "energy consumers" in the form of microwave generator and IR heater, overall specific energy consumption was smaller in these schedules compared to the control process (CV). The obtained results showed also that the period of microwave or IR enhancement should be properly identified to maximize kinetic advantages and minimize average specific energy consumption. The colorimetric data confirmed the dependency between the colour degradation, the time and temperature of drying. In the case of long-lasting processes, such as during solely convective drying, several types of biochemical reactions underwent in the material causing the noticeable colour change. Discolouration of products dried by hybrid schemes was visibly smaller and depended strictly on the process conditions. Nevertheless, the presented results lead to the final conclusion that combination of particular drying techniques in a hybrid process accelerates drying, minimizes the specific energy consumption (through shortening the time of drying) and, which is most important, allows to obtain good quality products.

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