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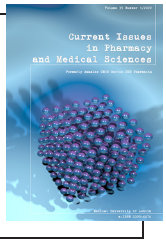

# Effect of heat treatment on the secondary metabolites composition of *Curcuma longa* L. rhizome

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**ABSTRACT**

Turmeric (*Curcuma longa* L.) is a widely known plant that is commonly used as a spice. It is also a valuable raw material that is increasingly used in the pharmaceutical industry and, notably, in dietary supplement recipes. For a long time, the healing properties of turmeric have been used in folk medicine in many regions of the world, mainly to treat various types of diseases. When developing recipes and preparing preparations with medicinal properties, the turmeric rhizome is subjected to various types of thermal treatment. These processes cause qualitative and quantitative changes in the composition of the secondary metabolites present in the turmeric rhizome. Due to its great popularity and widespread use as a raw material with health-promoting properties, turmeric undeniably deserves an in-depth analysis in order to optimize the treatment process and minimize its negative impact on active compounds. The presented review summarizes the current state of knowledge on the impact of thermal treatment of the turmeric rhizome on the composition of its biologically active compounds. The data provided in this review indicate that the content of active compounds in turmeric rhizomes is strictly correlated not only with the used type of processing, but it also strongly depends on the selection of key parameters. Therefore, it is difficult to clearly indicate the type of processing that would be the most beneficial for the composition of its active compounds.

## INTRODUCTION

Over the past decades, products containing plant ingredients have increased in popularity around the world. These include dietary supplements, nutraceuticals and functional foods. This is due to the increased interest of consumers in products of natural origin, their health-promoting properties and the belief that their use is safer than synthetic products [1-4]. One of the plants with great therapeutic potential is turmeric (*Curcuma longa* L.), the beneficial effects of which on the human body have been confirmed in many studies [5,6]. It has been demonstrated that the substances present in this plant have neuroprotective, antioxidant, anticancer, cardioprotective, antinephrotoxic, hepatoprotective, antiviral, antifungal, anti-inflammatory, antiarthritic and radioprotective effects [7-17]. This plant may also be helpful in the treatment of depressive disorders, Alzheimer's disease and sexually transmitted infections [18-20]. Therefore, there are many dietary supplements and pharmaceutical preparations available on the market containing this plant [21-22].

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Turmeric is a plant belonging to the genus *Curcuma* and the family Zingiberaceae [23,24]. It is cultivated in various parts of the world, but its natural habitat is Malaysia, India, Indonesia, China, Thailand and northern Australia [23,24]. The place of origin, climate and soil type directly affect the nutritional value and content of active substances in the turmeric rhizome [25-27]. The variable content of these substances has a significant impact on the effect of these compounds on the human body [27-29].

Turmeric has been used for years as a spice, dye and preservative, primarily in Asian cuisine [24,30]. *Curcuma longa* is also employed as a dye in the confectionery, pharmaceutical and textile industries (dyeing cotton and silk) [31,32]. *Curcuma longa* L. has been exploited for centuries and plays a significant role in traditional Ayurvedic, Pakistani, Chinese and Islamic medicine due to a wide spectrum of various ingredients with multi-directional health-promoting potential [33-36]. In ethnomedicine, turmeric has been applied in various forms, mainly as decoctions, juices, tonics, pastes and powder [37-39]. This plant is believed to have beneficial effects on many systems, including the cardiovascular, respiratory, digestive and musculoskeletal systems [40,41].

Additionally, turmeric preparations are recommended for use on wounds and skin lesions, in the treatment of colds, diabetes and obesity [33,37-41]. Turmeric is also widely used as an anti-inflammatory and antiseptic plant [38,40,42].

The most valued raw material obtained from this plant is the rhizome [43]. This is due to the abundance of active substances with a wide range of applications [6]. Particularly valuable are curcuminoid compounds such as curcumin (CUR), bisdemethoxycurcumin (BDMC) and dimethoxycurcumin (DMC), as well as compounds present in essential oils (mono and sesquiterpenoids) [44,45]. According to various studies, the content of individual curcuminoids in the crude turmeric extract is: CUR 59-71.5%, BDMC 9.1-18% and DMC 19.4-27% [46-49].

*In vitro* and *in vivo* studies on the health-promoting properties of curcuminoids have shown their antiproliferative, anticancer, antioxidant, antimicrobial and neuroprotective effects. These compounds also have a positive effect on memory, which may be applied in the treatment of Alzheimer's disease [13,50-56].

The main active substance contained in *Curcuma longa* L. is curcumin (1,7-bis(4-hydroxy-3methoxyphenyl)-1,6-hepadiene-3,5-dione). This substance was first described in scientific literature in 1910 [44]. It is a yellow-orange dye that gives the characteristic colour to the rhizome of this plant. Curcumin is classified as a curcuminoid and is a polyphenolic compound with a lipophilic nature [57]. Literature data indicate that structural changes in the curcumin molecule may have a beneficial effect on its physicochemical properties and increase its biological activity [58]. Numerous authors point to the wide spectrum of health-promoting properties of curcumin, which is one of the main phytochemicals present in turmeric rhizomes. Thanks to this, it can be used prophylactically as a substance supporting the maintenance of body homeostasis, as well as a pharmacologically active substance [40].

The beneficial properties of turmeric rhizome also result from the presence of other chemical compounds. In addition to basic nutrients such as fats, carbohydrates and proteins, this plant also contains essential oil, various minerals (Ca, Na, K, Fe) and vitamins (B1, B2, B3, C). Moreover, the rhizome contains secondary metabolites such as steroids, terpenes and various compounds classified as polyphenols [5,6,59,60].

Heat treatment of turmeric rhizomes is an important element in preparing this raw material for use in the recipes of various types of pharmaceutical preparations and dietary supplements. Currently, high temperature or application of microwaves are the most common methods of processing the raw turmeric rhizome. Procedures using elevated temperatures include, primarily, drying, blanching, heating, boiling and frying. All the above-mentioned processes have a significant impact on content and bioavailability of biologically active compounds present in the plant material. Therefore, when choosing a method of heat treatment of plant raw materials, it is important to choose an approach that will cause the least degradation of phytochemicals present in the plant. Moreover, it is also important to maintain the biological activity of the raw material used in the formulation of preparations with the desired properties and therapeutic activity [61].

It should be noted that this processing may also have a positive effect on the bioavailability of active compounds, increasing their release from the plant material and absorption in the digestive system [62]. Therefore, the selection of the appropriate type of heat treatment, along with additional parameters, is significant for the process of creating preparations with the desired pharmacological effect.

Curcumin is a curcuminoid that is very sensitive to heat, compared to other compounds from this group, such as demethoxycurcumin or bisdemethoxycurcumin [63,64]. Another factor causing a decrease in the content of curcuminoids is the effect of visible and ultraviolet light on turmeric [65]. Additionally, an oxygen-rich environment intensifies the action of polyphenol oxidase, an enzyme that contributes to the degradation of curcuminoids [66]. The influence of these factors on the content of curcuminoids was confirmed by studies in which freeze-dried samples (low temperature, lack of light, vacuum) were characterized by the highest content of curcuminoids. A slightly lower content was observed for the raw material dried in an oven, and the lowest amount of these compounds was recorded for samples dried in the sun (influence of heat, light, oxygen) [63,64].

The review aims to present the current state of knowledge on the relationship between thermal treatment and the content of biologically active compounds in *Curcuma longa* L. rhizome. The work focused mainly on assessing the content of curcuminoids (curcumin, demethoxycurcumin, bisdemethoxycurcumin), which are the main phytochemicals present in this plant. Widely used processing methods, including data on the pre-treatment of fresh turmeric rhizomes, and their influence on the content of the studied compounds were described and discussed and the main conclusions are presented in Table 1.

## MATERIALS AND METHODS

Available online databases (Scopus, Pubmed, Google Scholar, Science Direct, Web of Science) were comprehensively searched to find scientific articles on the topics discussed in this review. The keywords used in the search were: "turmeric", "*Curcuma longa*", "ingredients", "composition", "thermal treatment", "cook", "drying", "microwave", "boil", "roast", "fry", "blanch", "steam", "lyophilization", "freeze drying". The review included manuscripts published in the years 2009-2023. The literature search was limited to English language articles. The review included articles that compared the effect of thermal treatment on the composition of the biologically active compounds in *Curcuma longa* L. rhizome. The major limitation of the study is that not all cited research contained data on the content of secondary metabolites in the raw (unprocessed) material. However, due to the limited availability of literature, this type of research was also considered. Therefore, the review included all articles describing the composition of thermally processed rhizome of *Curcuma longa* L. in comparison to the unprocessed raw material, if these data were available.

## Influence of various thermal processing techniques on the composition of the *Curcuma longa* rhizome

*Blanching process*

One of the most frequently used thermal treatments to which turmeric rhizome is subjected is the blanching process. Gan *et al*. revealed that blanching of turmeric for 15 min prior to the drying process (50°C and at a relative moisture content of 20%) significantly increased curcumin content. In contrast, drying under the same conditions without prior blanching of turmeric or drying with the blanching lasting for 5 or 30 min did not significantly affect the curcumin content, which was 75.2-78.1% of the concentration obtained through optimal treatment [67]. It has been observed that blanching contributes to a lower degradation of active and colouring compounds – mainly the curcumin present in turmeric – compared to drying or cooking [68]. The results clearly confirm that blanching favoured curcumin retention in the dried product and should be considered to develop an optimal process.

*Drying in an oven*

Research has provided evidence that drying turmeric at 60°C and a relative humidity [67] of 20% provides the highest curcumin retention. This study also showed that as the drying temperature increases at 20% relative humidity, curcumin retention is higher than under the same temperature conditions and 40% relative humidity. Its content in turmeric samples dried at temperatures of 40-60°C at a relative humidity of 20% ranged from 73.7 to 82.2% normalized concentration, while at a relative humidity of 40% it was 58.9-65.8% normalized concentration [67].

After drying turmeric mother rhizomes and finger rhizomes in different combinations of air flow velocity (1, 2 or 3 m/s) and temperature (45, 50, 55, 60, or 65°C), researchers noted that both parameters affect the oleoresin content of the dried rhizome. In most cases, the oleoresin content increased with increasing temperature and gradually decreased after reaching the maximum value at 55°C. In the case of the air flow velocity changes, no clear relationships between the flow velocity and the content of the determined substances were observed. For both finger rhizomes and mother rhizomes, 55°C and the air flow velocity of 1 m/s were found as the optimal process parameters to preserve the highest amount of oleoresin in turmeric rhizomes. After such treatment, the oleoresin content in finger rhizomes was 13.1%, and in mother rhizomes – 12.8%. On the other hand, the lowest oleoresin content was determined in finger rhizomes samples (8.5%) dried at 65°C and air flow 3 m/s, and in mother rhizomes (9.6%) at 45°C and 3 m/s [69].

As a result of hot air drying of turmeric rhizomes, a decrease in the content of various active chemicals was observed compared to the fresh raw material. After drying in the oven, the total phenolic content (TPC) decreased from 58 to 30.5 mg GAE/g DB (mg gallic acid equivalents per g dry basis) and the amount of total flavonoid (TF) from 173.82 to 151.15 μg/g DB (μg per g dry basis). Of note, the amounts of curcumin (CUR), demethoxycurcumin (DMC) and bisdemethoxycurcumin BDMC) were particularly reduced, which translated into a decrease in the content of curcuminoids more than twice compared to the unprocessed sample, for which the value of this parameter was 3795 μg/g DB. In contrast, after heat treatment, the amount of total phenolic acid (TPA) increased from 41.47 to 100.44 μg/g DB [63].

Ar-Turmerone, a compound found in turmeric essential oil, has an inhibitory effect on enzymes such as α-glucosidase and α-amylase, so it can be considered a glucosidase inhibitor and used in the treatment of type II diabetes to control postprandial hyperglycemia. The percentage of Ar-Turmerone in the essential oil was found to increase as a result of drying. Of the total composition, the content of this compound in dried turmeric oil was 58% and only 45% in essential oil derived from the fresh turmeric rhizome [70].

In oven drying, temperature, relative humidity, air flow velocity, rhizome fragmentation and even oven design are parameters affecting the content of active compounds. As revealed above, the optimal conditions depend on the selection of the active compound priority, because each will react differently to the drying conditions used.

*Heating performed in hot water*

In one research project, processed rhizomes were immersed in water for 30 min (50-100°C), then the samples were divided into 3 parts: 1st – ground; 2nd – kept at 25-27°C for 1 h and ground; 3rd – dried for 4-5 h at 50°C and ground. Regardless of the heating temperature of turmeric, the extracts obtained from samples without additional drying process after heating were characterized by the highest total phenolic content (TPC). However, in the samples additionally dried in the oven, the lowest TPC values were recorded, but an intermediate value of the total phenolic content was noted for extracts from samples set aside after heating for 1h. The same relationship was noticed for control turmeric extracts obtained from samples not heated in warm water [66].

In another study, turmeric was heated in warm water at 60-100°C for 10-60 min. Then, part of the samples was dried in an oven at 50°C. Turmeric extracts subjected to heating in warm water only, were characterized by a higher TPC than samples additionally dried. Irrespective of the heating temperature of turmeric, within the duration of wet heating, the TPC in the extract increased [66].

Wet heating also did not significantly affect the curcuminoid content in turmeric. Interestingly, a similar amount of these compounds was present in the control sample (marked as fresh) [66]. In general, heating with hot water, regardless of the temperature, had a positive effect on the concentration values. However, additional dry heat treatment had a negative impact on the active compounds.

*Boiling process*

The effect of different boiling times (1, 2, 5 and 10 min) of turmeric on the TPC was also investigated. Researchers noted that extension of the time of treatment increased the TPC in the turmeric samples. Thus, the highest TPC was determined in samples boiled for 10 min – 527.00 mg/L. In the case of fresh turmeric, the TPC was – 410.00 mg/L. Only the samples boiled for 1 min had a lower value of this parameter (402.67 mg/L) than unprocessed turmeric.

An analysis of the effect of turmeric rhizome boiling time on the content of individual curcuminoids showed that the longest processing time, i.e. 10 minutes, provided the highest amount of CUR – 204.00 mg/g, DMC – 56.87 mg/g and BDMC – 82.03 mg/g, compared to samples from turmeric boiled for a shorter time. Interestingly, the content of curcuminoids in the samples from fresh turmeric was lower and amounted to: CUR – 113.92 mg/g, DMC – 40.27 mg/g and BDMC – 42.90 mg/g [71]. In most of the processed samples, the content of curcuminoids was higher in comparison to the fresh turmeric, which may provide strong evidence of the positive effect of boiling on the content of these active compounds in *Curcuma longa* L. rhizome.

*Steaming process*

A study performed by Ferzana *et al*. compared the effect of steaming methods on curcumin, essential oils and oleoresin content in turmeric. The control sample consisted of a rhizome in which the amount of curcumin was almost 6%, and the amount of essential oils and oleoresin was 10% each. The curcumin content in rhizomes processed under specific conditions was as follows: 4.67% (open steaming), 6.61% (parboiling drum) and 7.73% (improved vessel – developed drum). The amount of essential oils after turmeric processing using these methods were 9.8%, 10% and 10%, respectively, and oleoresin 4.67%, 4.9% and 12.7%, respectively. These results show that the device constructed by the researchers (consisting of a steam generation unit and blanching vessel) was the best of the investigated methods of turmeric thermal treatment, as it provides the highest retention of all the studied components [68].

The developed heating vessel was further employed to determine the optimal processing conditions limiting the loss of curcumin, essential oils and oleoresin in the rhizome. The variable parameters were processing time, vapour pressure and temperature. Ferzana *et al*. observed that the highest amount of curcumin and essential oils were determined for the following process parameters: 15 min, vapour pressure of 1.50 kg/cm$^2$ and temperature of 92.5°C. After the turmeric rhizome processing under such conditions, the amount of curcumin was 4.937% and the amount of essential oils was 2.31%. On the other hand, in the case of oleoresin, the following conditions turned out to be the least favourable: 5 min, 1.00 kg/cm2, 90°C and 95°C. Such treatment reduced the oleoresin content to 10.6%. Based on the obtained results, it can be concluded that with the extension of the treatment time and the increase in pressure, the amount of the studied ingredients decreased It was found that there was an optimal combination of the studied parameters of the described process. These were: 5 min, 0.50 kg/cm$^2$ and 92.5°C. Thermal treatment performed under such conditions resulted in the highest retention of all determined components of turmeric rhizome, the content of which was as follows: curcumi – 8.809%, oleoresin – 12.3% and essential oil – 3.00% [68]. This study clearly revealed that not only temperature itself, but also other parameters (pressure and time) are crucial for producing the highest retention of active components of the turmeric rhizome.

*Microwave heating*

The effect of microwave heating time (1, 2 and 5 minutes) of *Curcuma longa* rhizomes on the TPC and the content of individual curcuminoids: curcumin, demethoxycurcumin and bisdemethoxycurcumin was evaluated by Zagórska *et al*. Determined TPC for fresh turmeric was 410.00 mg/L. Short-term exposure to microwave radiation contributed to a gradual increase in TPC compared to unprocessed turmeric – 491.00 (1 min) and 553.00 mg/L (2 min), respectively. In contrast, longer heating (lasting 5 minutes) caused significant reduction of the TPC parameter to 327.00 mg/L, i.e. below the value of the fresh raw material. Moreover, the content of individual curcuminoids (CUR, DMC and BDMC) in the samples decreased with the prolongation of microwave heating. Therefore, the samples subjected to the shortest treatment (1 min) were characterized by the highest content of curcuminoids (CUR – 200.67; DMC – 41.37 and BDMC – 49.13 mg/g).

The researchers found that only such short-term microwave heating allowed to obtain values higher than those determined for the sample from fresh turmeric (CUR – 113.92; DMC – 40.27 and BDMC – 42.90 mg/g), in other cases (2 and 5 min) the content of all curcuminoids was lower than in the unprocessed sample [71]. This study showed that microwave heating may have beneficial effect for the composition of the *Curcuma longa* rhizome, but only when the process is conducted for a very short time. Extending the microwave heating time will result in a significant decrease in the curcuminoid content.

*Microwave-vacuum drying*

Hirun *et al*. investigated the effect of different combinations of microwave-vacuum drying conditions (10, 20 or 30 min; microwave power of 2400, 3200 or 4000 W) on total phenolic content (TPC) and content of curcuminoids. In the investigated fresh turmeric, the total phenolic content was 59.6 mg GAE/g DB (Gallic acid equivalents in mg/g dry basis), and curcuminoid content 9.4 g/100 g DB (g/100 g dry basis). Taking into account the total phenolic content, only a sample of turmeric dried for 30 min at 2400 W contained higher content (113.10 mg GAE/g DB) than a sample of fresh turmeric. In other cases, TFC decreased under the influence of treatment, and the lowest amount was determined for samples treated for 20 min and 4000 W power (24.62 mg GAE/g DB). With regard to curcuminoids content after treatment, an increase or decrease was observed, depending on the drying conditions. The highest determined content of curcuminoids after treatment was 19.04 g/100 g DB (30 min, 4000 W), and the lowest 4.19 g/100 g DB (20 min, 3200 W). Out of 9 combinations of variable parameters (time, power) of the process, no conclusive results were obtained [72]. No specific one combination that would provide the highest values of the determined turmeric components was found, however, it should be noted that low microwave power seems to be beneficial in order to obtain a high level of TPC.

*Sun drying*

Effect of heat treatment on curcuminoid, colour value and total polyphenols of fresh turmeric rhizome was evaluating considering exposure to sun radiation [66]. Turmeric was heated in water at 100°C for 1 hour, then divided into 3 groups: 1st – ground; 2nd – left open for 1 hour at ambient temperature (25-27°C) and ground; 3rd – dried for 15 days in the sun and ground. Samples from 1st part were characterized by the maximum TPC, and the lowest were sun-dried and control samples (marked as fresh) [66].

Another study showed that after drying in the sun, the content of various components in the extract obtained from turmeric decreased compared to the extract obtained from fresh turmeric. Under the influence of the treatment, the TPC was reduced by about half, and the amount of total flavonoid (TF) decreased from 173.82 to 129.91 µg/g DB (µg per g DB). Notably, under these conditions, the curcumin (CUR), demethoxycurcumin (DCM) and bisdemethoxycurcumin (BDCM) amount decreased, which resulted in a reduction in the content of all curcuminoids from 3795 to 1165 µg/g DB. Interestingly, drying the raw material in the sun significantly increased the total phenolic acid (TFA) concentration in the extract. TFA was 41.47 µg/g DB in unprocessed sample, and 261.46 µg/g DB after treatment [63]. Research clearly shows that sun drying is accompanied by curcuminoids content lost. The total curcuminoid content in the dried samples was clearly lower than in the fresh samples. The results showed that drying in the sun is a less advantageous method of heat treatment than heating (also described in this article).

*Frying*

Frying the turmeric rhizome (1, 2, 5 and 10 minutes) was found to affect the total phenolic content (TFC) and the content of individual curcuminoids: curcumin (CUR), demethoxycurcumin (DMC) and bisdemethoxycurcumin (BDMC). TPC in the fresh turmeric sample was 410.00 mg/L. As a result of frying, the TPC value increased for treatment lasting 2 min and 10 min, while for 1 min and 5 min, it decreased compared to the unprocessed sample. The highest TPC was recorded for samples fried for 10 min and amounted to 592.00 mg/L. Curcuminoid content in the fresh sample was as follows: CUR – 113.92 mg/g; DMC – 40.27 mg/g and BDMC – 42.90 mg/g. In the case of curcumin, its content in each of the fried samples was higher than in fresh turmeric, and the highest amount was determined in samples fried for 1 min (246.00 mg/g). The highest concentration of other curcuminoids was evaluated after 10 minutes of treatment (even higher than in fresh turmeric samples) and it amounted to: DMC – 55.13 mg/g and BDMC – 67.77 mg/g. In both DMC and BDMC, frying for 1 or 5 min caused the drop of the content below the concentration observed for the fresh sample [71]. The results show that it is possible to obtain a higher concentration than in the fresh sample by selecting appropriate frying parameters. The TPC, DMC and BDMC values are higher for longer frying times, while short frying times favor the curcumin level.

*Freeze drying*

Chumroenphat *et al*. investigated extracts obtained from freeze dried turmeric. Their results demonstrate that the content of various components in the extract was reduced in comparison to the untreated turmeric extract. In the case of fresh turmeric extract, the TPC was 58 mg GAE/g DB (mg gallic acid equivalents per g dry basis), and the amount of TF was 173.82 µg/g DB, while the values of these parameters for freeze-dried turmeric extract were lower and amounted to 35.7 mg GAE/g DB and 158.79 µg/g DB (µg per g dry basis), respectively. This study also reported a decrease in curcuminoid content after turmeric treatment at low temperature. Specifically, the content of curcumin (CUR), demethoxycurcumin (DCM) and bisdemethoxycurcumin (BDCM) decreased, which translated into a decrease in the content of curcuminoids from 3795 µg/g DB (fresh turmeric) to 1742 µg/g DB (freeze dried turmeric). However, freeze drying increased total phenolic acid (TPA) content in the sample from 41.47 to 79.61 µg/g DB [63]. The results show that low-temperature treatment does not have a beneficial effect on the TPC, TF and curcuminoids levels. However, low-temperature methods allowed to obtain an extract with a high TPA content.

*Boiling followed by microwave/oven drying*

The effects of boiling as a pre-treatment followed by drying in an oven or microwave (450 W and 850 W) on the total curcuminoid content, essential oils and the content of individual curcuminoids; curcumin (CUR), desmethoxycurcumin (DMC), bisdesmethoxycurcumin (BDMC) was evaluated. The obtained results showed that the boiled samples were characterized by a lower content of essential oils (5.00-6.00% v/w) than the non-boiled samples, for which the values were 6.75-7.00% v/w. In contrast, the total curcuminoid content was at a similar level for the pre-treated (7.96-8.58% w/w) and unpre-treated samples (7.85-8.21% w/w). The content of individual curcuminoids was slightly higher for boiled samples: DMC – 1.84-2.52% w/w; CUR – 2.69-3.77% w/w; BDMC – 4.57-5.76% w/w, while in non-boiled samples it amounted to: 1.85-2.14% w/w; 2.84-3.68% w/w and 4.68-4.99% w/w. In contrast, when comparing drying methods, both microwave and hot air drying did not show any significant differences in the content of essential oil (5.00-7.00% v/w) and the total content of curcuminoids (7.85-8.58% w/w). Comparing the content of individual curcuminoids, it can be seen that a slightly smaller amount of each of the tested compounds was recorded for oven-dried samples than in the microwave dried.

Raw material dried with the use of hot air exhibited levels of individual curcuminoids such as: DMC 1.84-1.92% w/w; CUR 2.69-2.96% w/w; BDMC 4.57-4.81%w/w, and after drying with microwave radiation, respectively, the related figures are: DMC 1.85-2.52% w/w; CUR 2.84-3.77% w/w; BDMC 4.68-5.76% w/w. During these analyses, the researchers did not observe a significant effect with regard to different microwave powers (450 and 850 W) on the quality of turmeric samples [73]. Boiling, however, negatively affected the level of essential oils, but did not affect significantly the total content of curcuminoids. The hot air

***Table 1.*** Effect of thermal processing on the secondary metabolites content in *Curcuma longa* L. rhizome

| Lp | Type of Processing | Conditions | Tested Compounds | Conclusions | References |
|---|---|---|---|---|---|
| 1 | Blanching | – water bath 70°C<br>– for 5-30 min<br>– dried at 50°C<br>– relative humidity 20% | Curcumin | – the highest curcumin content in turmeric samples blanched for 15 min | [67] |
| 2 | Drying in an oven | – dried at 40-70°C<br>– relative humidity 20%-40% | Curcumin | – the curcumin content was affected by temperature and relative humidity<br>– the highest curcumin content was found in turmeric samples dried at 60°C and at a relative humidity of 20% | [67] |
| 3 | | – boiled at 100°C for 45 min,<br>– dried for 30 min; air flow rate 1-3 m/s; 45-65°C | Oleoresin | – the oleoresin content was affected by the drying temperature and the air flow<br>– the highest oleoresin content was found in rhizomes dried at 55°C and an air flow of 1 m/s | [69] |
| 4 | | – dried in an electric oven at 50°C | Total flavonoids, curcumin, demethoxycurcumin, bisdemethoxycurcumin, curcuminoids, phenolic acid | – ↓ amount of flavonoids, curcumin, demethoxycurcumin, bisdemethoxycurcumin, sum of these curcuminoids<br>– ↑ phenolic acid content | [63] |
| 5 | | – dried in a hot air oven at 50°C for 36 h | Ar-Turmerone | – ↑ the ar-Turmerone content in turmeric essential oil | [70] |
| 6 | Heating in hot water | – immersed in water for 30 min; 50-100°C<br>Then the samples were divided into 3 parts:<br>– 1$^{st}$: ground<br>– 2$^{nd}$: kept at room temperature and ground<br>– 3$^{rd}$: dried and ground | Total phenolic content | – no effect of heating temperature on the total phenolic content<br>– the highest total phenolic content was found for undried rhizome, and the lowest for samples heated at 50°C | [66] |
| 7 | | – immersed in water for 10-60 min; 60-100°C<br>Then divided into 2 parts:<br>– 1$^{st}$ kept at room temperature and ground<br>– 2$^{nd}$ dried and ground | Total phenolic content | – samples dried at ambient temperature had a higher total phenol content than samples dried at 50°C<br>– total phenolic content increased with increasing processing time at each of the tested temperatures | [66] |
| 8 | | – immersed in water for 30 min; 50-100°C | Total curcuminoids content | – the total content of curcuminoids was at a similar level in all of the processed samples<br>– a similar amount of curcuminoids was present in the fresh sample | [66] |
| 9 | Boiling | – boiled in deionized water; for 1-10 min | Total phenolic content, curcumin, demethoxycurcumin, bisdemethoxycurcumin | – total phenolic content: ↓ 1 min, ↑ 2, 5, 10 min<br>– the content of curcumins: ↓ 2 min, ↑ 1, 5, 10 min<br>– the content of demethoxycurcumins: ↓ 1, 2 min, ↑ 5, 10 min<br>– the content of bisdemethoxycurcumin increased after each test time | [71] |
| 10 | Steaming | – cooked using 3 methods:<br>– open steaming for 25 min<br>– parboiling steaming for 15 min<br>– improved vessel – developed drum for 10 min<br>– then dried | Curcumin, oleoresin, essential oil | – the lowest content of turmeric components was found in rhizomes processed by open steaming<br>– the highest content was found for use of the improved vessel | [68] |
| 11 | | – cooked in improved vessel – developed drum<br>– boiling time 5-15 min<br>– steam pressure 0.5-1.5 kg/cm$^2$<br>– temperature 90-95°C | Curcumin, oleoresin, essential oil | – the lowest content of curcumin and essential oil was found in rhizomes processed under the following conditions: 15 min, 1.50 kg/cm$^2$, 92.5°C<br>– the lowest content of oleoresin was found in rhizomes processed under the following conditions: 5 min, 1.00 kg/cm$^2$, 90°C and 95°C | [68] |
| 12 | Microwave heating | – treated in a microwave oven<br>– 800 W<br>– for 1-5 min | Total phenolic content, curcumin, demethoxycurcumin, bisdemethoxycurcumin | – the total phenolic content ↑ for 1, 2 min, ↓ 5min<br>– the curcumin, demethoxycurcumins and bisdemethoxycurcumin content ↑ for 1 min, while ↓ after treatment for 2 and 5 min | [71] |
| 13 | Microwave-vacuum drying | – dried in an industrial microwave-vacuum dryer<br>– for 10-30 min<br>– 2400-4000 W | Total phenolic content, curcuminoids | – the total phenolic content ↑ only in the sample dried for 30 min at 2400 W<br>– the content of curcuminoids ↑ when treated for 10 min/2400 W, 30 min/2400 W and 30 min/4000 W, while in the other processed samples, values were lower than in the fresh turmeric extract | [72] |
| 14 | Drying in the sun | – boiled at 100°C for 1 h<br>– drained<br>Then the samples were divided into 3 parts:<br>– 1$^{st}$ ground<br>– 2$^{nd}$ kept at room temperature and ground<br>– 3$^{rd}$ dried in the sun and ground | Total phenolic content | – the highest total phenolic content was found in the directly ground sample, and the lowest in the sun-dried sample | [66] |
| 15 | | – boiled at 100°C for 1 h<br>– drained<br>– dried in the sun | Total curcuminoids content | – sun-dried turmeric extract had a lower total curcuminoids content than fresh turmeric extract | [66] |
| 16 | | – exposed to the sun for 3-5 days<br>– 35-45°C | Total phenolic content, total flavonoids, curcumin, demethoxycurcumin, bisdemethoxycurcumin, curcuminoids, phenolic acid | – ↓ the total phenolic, total flavonoids, curcumins, demethoxycurcumin, bisdemethoxycurcumin and total curcuminoids content<br>– ↑ the phenolic acid content | [63] |
| 17 | Frying | – fried (without oil)<br>– 1-10 min | Total phenolic content, curcumin, demethoxycurcumin, bisdemethoxycurcumin | – total phenolic content: ↓ 1, 5 min, ↑ 2, 10 min<br>– the curcumin content ↑ for all frying times<br>– the content of demethoxycurcumins and bisdemethoxycurcumin: ↓ 1,5 min, ↑ 2, 10 min | [71] |
| 18 | Freeze drying | – frozen at -50°C for 12 h<br>– then cooled to -100°C; vacuum 20 Pa under absolute pressure | Total phenolic content, total flavonoids, curcumin, demethoxycurcumin, bisdemethoxycurcumin, curcuminoids, phenolic acid | – ↓ total phenolic, total flavonoids, curcumin, demethoxycurcumin, bisdemethoxycurcumin and curcuminoids content<br>– ↑ phenolic acid content | [63] |

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| 19 | Boiling as the pretreatment, followed by the oven or microwave drying | – boiled at 80°C for 30 min<br>– Then dried by one of three methods:<br>– 5 h in an oven at 60°C<br>– 5 min in a microwave; 450 W<br>– 5 min in a microwave; 850 W | Total curcuminoids content, curcumin, demethoxycurcumin, bisdemethoxycurcumin, essential oil | – boiling process effect: ↓ essential oil content; ↑ the contents of bisdesmethoxycurcumin, desmethoxycurcumin and curcumin; curcuminoids content remained unchanged<br>– drying method did not affect the essential oil and total curcuminoid content<br>– the content of bisdesmethoxycurcumin, desmethoxycurcumin and curcumin were lower for oven drying than the use of microwaves<br>– a significant effect of different microwave powers was not observed | [73] |
| 20 | Boiling as pre-treatment of sliced or uncut rhizomes<br>Drying in the sun or in the solar dryer | – research carried out both on sliced and unsliced rhizomes<br>– 3 different sample groups were prepared: non-pre-treated, boiled in water and steamed in an autoclave (103, 421.3 Pa)<br>– final samples were dried in the open sun or in a domestic solar dryer | Curcumin, essential oil | – slicing causes a decrease in curcumin and essential oil content<br>– the curcumin content was marginally affected by pre-treatment<br>– the highest content of essential oil was obtained for steamed samples and the lowest for samples boiled in hot water<br>– the drying method did not significantly affect the curcumin content in the samples<br>– drying in a solar dryer resulted in a higher content of essential oil than drying in open sun | [74] |

and microwave drying had similar impact on the previously mentioned compounds. In the case of individual curcuminoids, microwave drying seems to be favourable method.

*The influence of rhizome fragmentation*

In a study conducted by Gill *et al*., the effect of turmeric rhizome fragmentation (whole, 5 mm slices), pre-treatment method (water boiling, steam boiling, no treatment) and drying (open sun drying, domestic solar dryer) on the quality of turmeric powder was examined. The curcumin content, regardless of further processing of the raw material, in the sliced samples was about 2.8%, while in the samples derived from the uncut rhizome the value was slightly higher and amounted to about 3.1%. The highest concentration of curcumin was recorded for the powder obtained from uncut rhizome, not pre-treated and dried in a solar dryer (3.15%), and the lowest for the sample of turmeric sliced, not pre-treated and dried in open sun (2.7%). In addition, the essential oil content was higher in uncut turmeric powders (5.6-5.98%) than in samples from cut rhizomes (5.5-5.80%). The steaming of the uncut rhizomes and then drying them in a solar dryer provides the highest amount of essential oil (5.98%), while the least advantageous is cutting the rhizome, skipping the pre-treatment and drying in open sun (5.5%) [74]. This study showed that the degree of the raw material fragmentation had the greatest impact on the content of turmeric and essential oil.

## CONCLUSIONS

Heat treatment may increase or decrease the content of components present in the rhizome of *Curcuma longa* L. Based on the literature data, we compared the effect of different types of treatment on the amount of active substances in turmeric, and selected the conditions that cause the greatest increase and the greatest decrease in the given components (as compared to their content in unprocessed turmeric).

In the case of the total polyphenol content (TPC), the treatment that produced the largest increase (almost 2 times) compared to the associated fresh turmeric sample was the processing of the plant material by subjecting it to microwave-vacuum drying (30 min, 2400 W), while the largest decrease in TPC (by almost 60%) was caused by the same treatment method, but with different process parameters (20 min, 4000 W) [72].

The largest increase in curcumin content (more than doubled) was ensured by frying the rhizome for 1 min, and the greatest loss (by 72%) by drying in the sun at 35-45°C for 3-5 days [63,71]. In the case of demethoxycurcumins and bisdemethoxycurcumins, the optimal method to provide the highest amounts (increases of more than 40% and almost 50%, respectively) was boiling at 100°C for 10 min, while the largest reduction of these compounds was recorded for 5 minutes of microwave treatment (by 70% and about 62%, respectively) [71]. In contrast, the largest increase in the amount of curcuminoids (2-fold) resulted in subjecting turmeric to microwave-vacuum drying (30 min, 4000 W), and the largest decrease in these active substances (more than 3-fold) – drying in the sun at 35-45°C for 3-5 days [63,72].

The highest oleoresin content was recorded for turmeric samples processed with the use of – ‘improved vessel – developed drum’ (10 min) – 12.7%, and the lowest for samples subjected to open steaming (25 min) – 4.67%, while in this study the amount of oleoresin in fresh turmeric samples was 10% [68].

Interestingly, the essential oil content was the same (10%) for samples of fresh turmeric, processed via parboiling drum (15 min) and ‘improved vessel – developed drum’ (10 min), while the largest reduction in the amount of essential oil (over 4 times) was caused by turmeric being treated in ‘improved vessel – developed drum’ at the process parameters: 15 min, 92.5°C and pressure 1.50 kg/cm2 [68]. It is worth noting that the content of essential oil was much higher for rhizomes processed as a whole, and not after grinding, which ensures limited losses of this component of turmeric [74].

To sum up, the information presented in this review indicates that not only the type of processing, but also its parameters, such as time, temperature, light and oxygen access, affect both the qualitative and quantitative composition of turmeric rhizome. Changes in the composition of biologically active compounds that occur during processing affect the health-promoting properties of turmeric rhizome. Therefore, having a knowledge on the impact of thermal treatment of *Curcuma longa* rhizome on the content of individual phytochemicals may prove useful when choosing the treatment that provides the highest amount of the compound with the properties tailored for a given application. This is especially required when creating recipes for various supplements, functional foods or pharmaceuticals with specific biological activity.

When choosing the type of processing, it should be taken into account whether the processing will concern fresh raw materials (rhizome), for example, those used to prepare extracts used in the recipes of pharmaceuticals and functional foods, or whether already pre-processed products (e.g. powders) will be treated. The general impact of thermal treatment on the qualitative and quantitative composition of turmeric rhizomes described in this review may therefore be a valuable source of information that can be used by producers to select the most optimal type of processing of this raw material for extract preparation. The published results allow us to assume that a fundamentally different treatment should be selected in the case of preparing a product intended directly for consumption compared to a product that is an intermediate product to produce active substance extract.

However, it is extremely difficult to clearly indicate which method of thermal treatment of the rhizomes of *Curcuma longa* L. has the most beneficial effect on the composition. This is primarily due to large differences in process parameters used by different authors, when it should be remembered that even nuances are important in this case. The differentiated and individual approach to the subject, manner and form of presentation of the results also make it difficult to easily and simply compare the available data.

It should be noted that several authors have determined the TPC parameter. This is only the equivalent of gallic acid. Much more valuable are chromatographic tests, which allow to determine the content of specific compounds. In addition, curcuminoid content is expressed differently in particular works - sometimes it is a percentage of composition, other times it is a concentration expressed in mg per g or kg of extract or fresh rhizome. Also, the concentrations of the individual active compounds are given by different authors in relation to the extract, and at other times to a specific mass of the raw material (raw or processed rhizome).

A significant problem that makes it difficult to clearly determine the optimal processing methodology is the biological nature of the samples and no defined control sample. The properties of the tested turmeric depend on the origin, weather conditions in each season, the period that has passed since the rhizome was harvested and the method of its storage prior to processing. Mechanical processing and the resulting specific surface area can have a huge impact on the extraction process, heat and moisture transport, loss of volatile substances and thermal degradation. Without unified processing method, it is purposeless to compare exact values, only general trends can be deduced and used to develop a method that will preserve the maximum amount of active compounds.

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