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# Impact of cooking and drying operations on colour, curcuminoids and aroma of *Curcuma longa* L.

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**Abstract**
Effects of cooking and drying on colour, curcuminoids, essential oil and aroma compounds of *Curcuma longa* L. were assessed. Sliced fresh turmeric rhizomes were air-dried at 60 °C directly or after cooking at 95 °C for 3 or 60 min. Microscopic observations showed that curcuminoids and essential oil are located in different dedicated cells. Curcuminoids and essential oil of dried turmeric were both around 10 % db. After processing, curcuminoids were dispersed throughout the matrix. Drastic cooking and drying operations decreased chromatic values more than smooth cooking. Cooking had no impact on curcuminoid and essential oil contents and slightly modified aromatic profile of essential oils. Drying decreased the curcuminoid (< 38 %) and essential oil (< 13 %) contents. Turmeric starchy matrix preserves the curcuminoids and essential oil during the process. We recommend a preliminary smooth cooking step to reduce drying time, save energy consumption and preserve turmeric quality.

**Keywords :** Turmeric; Blanching; Curcuminoids; Essential oil; Microscopy

## 1. Introduction

Turmeric (*Curcuma longa* L.) belongs to the Zingiberaceae family and is widely distributed throughout tropical and subtropical regions of the world (Kutti Gounder & Lingamallu, 2012). Curing turmeric is a significant postharvest processing operation that involves cooking fresh turmeric in boiling water. The goals of curing are to reduce microbial load, inactivate enzymes, avoid unpleasant odours, gelatinize the starch, and change the cell walls of the turmeric facilitating its permeability and reducing resistance to mass transfer which leads to an increase in the drying rate (Jayashree et al., 2018). The main aim of drying is to reduce the moisture present in turmeric, from 2.3 – 4.0 (kg $kg^{-1}$ db) at the time of harvest to a safe value of 0.11 (kg $kg^{-1}$ db) (International Organization for Standardization, 2015).
Air drying is an alternative to sun drying, not only to increase drying rate and reduce drying time but also to better preserve the quality of the product (Prathapan et al., 2009). The optimum drying conditions for best product quality were found to be air temperature of 55 – 60 °C and air velocity of 2 m $s^{-1}$ (Singh et al., 2010). High air temperature (> 60 °C) caused degradation of volatile compounds and curcuminoids.
Traditionally, the rhizomes are dried directly or cooked and then dried. We question the value of using these operations in a combined way, as cooking transfers water inside the product and drying will have to remove the water from the cooked rhizome. In the traditional process, whole rhizomes are cooked for a long time at high temperatures. Moreover, numerous studies have demonstrated the impact of processes on the quality of turmeric powder. However, they did not focus on the impact of each unit operation (cooking and drying) on turmeric's quality.

In our study, we applied, as an alternative, short cooking time to sliced rhizomes and microscopic observation and biochemical contents evolution during the process were studied. Our objective was to assess the impact of cooking and drying in controlled conditions on the quality of *Curcuma longa* L. The quality characteristics considered in this study were colour, curcuminoids and aromatic profiles. The impact of cooking on drying kinetics was studied. Mass balances of dry matter, water and curcuminoids were assessed. Microscopic analysis was realized to localize essential oil, starch and curcuminoids and to assess process effects.

## 2. Materials and methods

### 2.1. Materials

Solvents (ethanol and dichloromethane), sodium sulfate, homologous series of C8 – C20 n-alkanes standards, and HPLC standards (curcumin, demethoxycurcumin and bisdemethoxycurcumin) were obtained from Sigma-Aldrich (Saint Quentin Fallavier, France). The polytetrafluoroethylene (PTFE) membranes were obtained from Sartorius (Palaiseau, France). The water used in all the experiments was purified water (milli-Q reference water purification). Turmeric, *Curcuma longa* L., used in this study was a product of Thailand which was purchased (4 kg) from an Asian grocery store (Wei Sin) in Montpellier, France, on the 20$^{th}$ of February 2020. Fresh turmeric rhizomes were stored at 4 °C until being processed. Before processing, the fresh turmeric rhizomes were cleaned and washed thoroughly under running water to remove adhering soil and mud, spray residues, roots and other foreign materials. Then, the excess water was drained and the cleaned turmeric rhizomes were sliced manually to a thickness of 5 mm. The sliced turmeric is called “fresh” turmeric.

### 2.2. Processing experiments

#### 2.2.1. Cooking

Two-unit operations were applied to obtain different samples (**Figure 1**). The sliced fresh turmeric (F) was divided into two lots of 420 g for cooking experiments and one lot of 360 g for direct drying assessment. Cooking treatment consisted of soaking sliced turmeric in a nylon net in hot water at a ratio of 1:10 w/w material to water at two different conditions: FC1: 95 °C/3 min and FC2: 95 °C/60 min. The starch could be completely gelatinized in these cooking conditions. After cooking, the cooked turmeric was immediately soaked in an ice water bath for 1 min to stop the cooking process, before being drained. About 60 g of each sample was collected for further analysis.

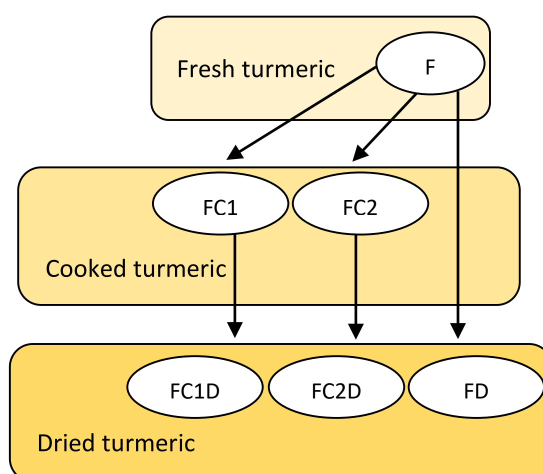


**Figure 1.** Processes applied to turmeric. F: fresh turmeric; C: cooking (C1: 95 °C/3 min; C2: 95 °C/60 min); D: drying (60 °C, 40 % RH).

#### 2.2.2. Drying and drying kinetics

A hot air dryer, developed in our laboratory, was used for drying the sliced turmerics. In the vertical drying chamber, 360 g of sliced turmerics were spread on-grid rack (0.25 m long × 0.25 m wide × 0.06 m high). Hot air (60 ± 1 °C, RH 40 ± 2 %) was circulated

downwards through the layer of sliced turmerics by a high capacity fan. The drying times are different for each treatment *i.e.* 7 h 14 min, 4 h 29 min and 3 h 38 min for fresh turmeric (F), FC1 (cooking at 95 °C/3 min) and FC2 (cooking at 95 °C/60 min), respectively. Airspeed was measured thanks to an anemometer (ALMEMO® 2690-8A, Ahlborn Mess, Germany). The air velocity was just high enough (2.1 ± 0.1 m $s^{-1}$) to have no significant effect on temperature when passing through the layer of sliced turmerics. Monitoring by weighing was carried out continuously during the drying process, every 10 min for the first hour and then every 15 min. The water content, which was measured on a dry basis (noted $X$) as a function of time, was estimated in line, using the mass reading of the sieve. Water content kinetics $X^{(t)}$ were fitted with a cubic smoothing spline (Matlab® Version 5.2, The Mathworks Inc., USA). The drying rate ($dX/dt$) was calculated as the direct analytical derivative of the cubic smoothing spline function on $X^{(t)}$.

### 2.3. Microscopic analysis

Thick cross-sections (100 – 135 µm) were obtained from fresh (F), cooked (FC), cooked and dried (FCD) and dried (FD) turmeric rhizomes using a microtome with a vibrating blade (Thermo Scientific, Microm HM650V, Walldorf, Germany) and then dipped in 10 mM phosphate buffer saline (7 mM $Na_2HPO_4$, 3 mM $NaH_2PO_4$, 120 mM NaCl, 2.7 mM KCl). Starch and terpenes were respectively stained dipping cross-sections in Lugol solution (2 g KI and 1 g $I_2$ dissolved in 100 ml distilled water) for 5 min or NADI solution (0.001% 1-naphthol, 0.001 % *N,N*-dimethyl-*p*-phenylenediamine dihydrochloride and 0.4 % ethanol in 100 mM sodium cacodylate-HCl buffer (pH 7.2) for 45 min (David & Carde, 1964). Rhizomes tissues were observed with a wide-field microscope Eclipse Ni-E (Nikon Instruments Inc., NY, USA). The pictures were obtained with 4x 0.2 NA, 10x 0.45 NA or 20x 0.75 NA Plan-APO objectives under transmitted light. The autofluorescence of curcuminoids was visualized with a multiphoton microscope (Zeiss 880, Jena, Germany, infra-red laser Chameleon Ultra II, Coherent, CA, USA) and an objective 20X Plan APO 1.0 NA. The spectral detector of this microscope was used at 720 nm (UV-like excitation) to obtain emission spectra of pure curcuminoids (curcumin, demethoxycurcumin and bisdemethoxycurcumin) between 400 and 690 nm, and to visualize the fluorescence of these molecules in the rhizome tissues (Talamond et al., 2015).

### 2.4. Sample preparation for colour, curcuminoids and essential oil measurements

The samples resulting from the different processing operations (approximately 50 g of each treatment) were frozen by using liquid nitrogen and then ground for 10 s at 10 000 rpm in a mill (Retsch Grindomix GM200, Retsch Gmbh, Germany) for immediate analyses of dry matter and colour. The samples for further essential oil and curcuminoids analyses were put in glass bottles and frozen at – 80 °C. The samples dedicated to curcuminoids analysis were made on the sliced rhizome.

### 2.5. Analytical methods

#### 2.5.1. Dry matter and water contents

The dry matter content (means ‘‘dry matter free of essential oil”) was obtained by drying 1 g of ground turmeric in an aluminium cup in the oven (Gefran 800, Italy) at 105 °C for 30 h (*i.e.* until constant weight). The mean relative deviation of repeatability was ± 4.4 % ($n$ = 4). Water content expressed on a dry basis was deduced from essential oil and dry matter contents.

#### 2.5.2. Colour measurements

Colour values *i.e.* lightness (L*), redness (a*) and yellowness (b*) of ground turmeric samples were determined using a chromameter (Minolta CR-400, Minolta, Osaka, Japan). The illuminant was D65, and an incidence angle of 0° was used. Each data point was the mean of three replications measured on the surface of the samples at randomly selected positions. Chroma value (C*) was calculated following this equation: $C^* = \sqrt{a*^2 + b*^2}$. The mean relative deviation of repeatability was 3.5 %, 4.2 %, 5.8 % and 5.4 %, respectively for L*, a*, b* and C* ($n$ = 6).

#### 2.5.3. Curcuminoid contents

Approximately 0.3 g of sliced turmeric was mixed with 30 mL of 60 °C ethanol (99.8 %) and homogenized for 2 min at 30 000 rpm (IKA T10 basic Ultra-Turrax, Prolabo, France). The samples were heated for 30 min at 60 °C (Sogi et al., 2010). After cooling, the extracts were diluted 1/10 with ethanol and filtered on 0.45 µm PTFE Minisart SRP4 membrane (Sartorius, Palaiseau, France). Curcuminoids were analysed by high-performance liquid chromatography (Agilent System 1200 series, Massy, France). The column was a polymeric ACES $C_{18}$ (250 × 4.6 mm, 5 µm particle size, Inc Wilmington NC) and the injection volume was 5 µL. The quantification of curcuminoids was carried out according to the method of Sepahpour et al. (2018) with small modifications. The elution was done isocratically with a mixture of acetonitrile and 0.1 % acetic acid (40:60) at a flow rate of 1.0 mL/min and the temperature of the column was set at 25 °C. Chromatograms were recorded over 30 min period with a UV-visible photodiode array detector (Agilent Technologies 1200 series) at the wavelength of maximum absorption of the curcuminoids in the mobile phase (*i.e.* 425 nm). The curcuminoids were identified by their retention time and spectrum. External calibration was realized weekly with standard solutions of the pure chemicals in ethanol in the range of 1 to 50 mg/L. The curcuminoid contents were expressed in g/100g of initial dry weight basis (g/100g db). The mean relative deviation of repeatability was 12.5 %, 11.2 %, 16.8 % and 13.5 %, respectively for curcumin, demethoxycurcumin, bisdemethoxycurcumin and total curcuminoids ($n$ = 4).

#### 2.5.4. Essential oil content

The essential oil content was determined using a method adapted from the international official standard method ISO 6571:2008 (International Organization for Standardization, 2008). The modification in the applied method was the elimination of xylene. Approximately 20 g of ground turmeric samples were weighed and transferred to 1 L of a round bottom flask, then 250 mL of distilled water was added and about 10 pieces of pumice stones were added to homogenize boiling. It was heated at medium heat for 4 h and the condensed vapour was separated. The essential oil present at the uppermost layers was collected and put in a vial containing sodium sulfate and then stored at – 20 °C for later essential oil compounds analysis by gas chromatography-mass spectrometry (GC-MS). The essential oil content was expressed in mL/100g of initial dry weight basis (mL/100g db). The mean relative deviation of repeatability was ± 4.7 % ($n$ = 4).

#### 2.5.5. Identification of essential oil compounds

***Separation on a polar column***

An Agilent 6890 series GC (Agilent Technologies, Palo Alto, CA, USA) equipped with a DB-WAX UI column (60 m × 250 µm, 0.25 µm phase film thickness, Agilent J&W GC column) coupled to an Agilent 5973 mass spectrometer detector (Agilent Technologies) was used. Hydrogen was used as carrier gas at 1.5 mL/min at a constant flow. Column temperature program was 100 °C to 200 °C at the rate of 2 °C/min, then to 250 °C at the rate of 10 °C/min. The sample injection volume was 1.0 µL with a split ratio of 100:1. The samples (essential oils) were diluted 1/10 with dichloromethane before injecting. The retention indices were calculated using a homologous series of n-alkanes C8 – C20.

***Separation on a non-polar column***

On the same GC-MS with the same column program temperature, a DB-5MS column (60 m × 250 µm, 0.25 µm phase film thickness, Agilent J&W GC column) was used. The retention indices were calculated using a homologous series of n-alkanes C8 – C20.

***Identification***

The aroma compounds separated on both polar and apolar columns were identified by comparing their mass spectrum to those available in commercial libraries (NIST 14 and PubChem). The mean relative deviation of repeatability was ±13.2 % ($n$ = 8).

#### 2.5.6. Statistical analysis

Differences in the mean values of colour (L*, a*, b* and C* values), curcuminoid contents, essential oil content and its composition were tested by analysis of variance (ANOVA); the significance of differences between samples was determined using Duncan's test. The level of significance was $P \leq 0.05$.

## 3. Results and discussion

### 3.1. Characterization of fresh turmeric

#### 3.1.1. Localization of essential oil, starch and curcuminoids

The distribution of essential oil, starch and curcuminoids was represented in **Figure 2** and **Figure 3**. The essential oils (**Figure 2.I**) were particularly abundant in the cortex. They were more concentrated under the epidermis and in the endoderm than in other parts. Starch was present in amyloplasts throughout the whole rhizome and was most abundant in the cortex (**Figure 2.IV**).

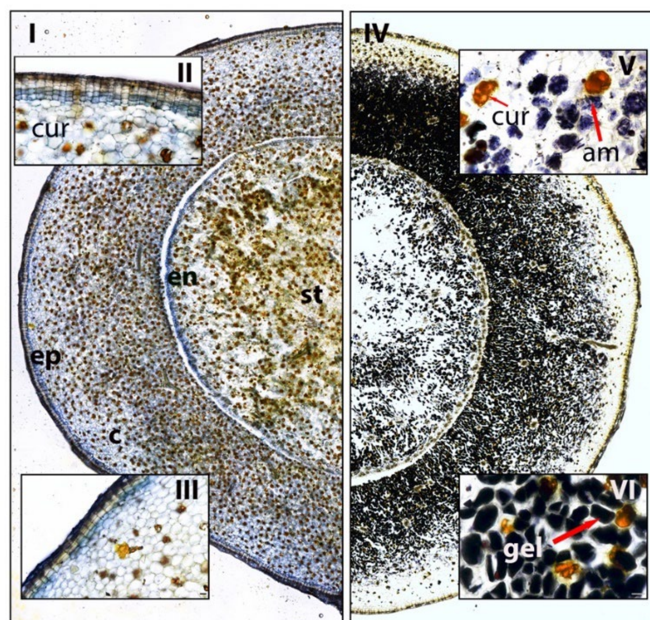


**Figure 2.** Visualization of essential oil, starch and curcuminoids distribution in turmeric rhizome by wide-field microscopy. (**I**) essential oil distribution (blue Nadi colouration) in a cross-section of turmeric rhizome, (**II**) essential oil distribution in the epidermis of fresh (F) turmeric, curcuminoid distribution (natural orange colour) in the epidermis of fresh (F) turmeric, (**III**) essential oil distribution in the epidermis of cooked (FC1) turmeric, curcuminoid distribution in epidermis cooked (FC1) turmeric, (IV) starch distribution (black Lugol colouration) in a cross-section of turmeric rhizome, (V) starch distribution in the cortex of fresh (F) turmeric, curcuminoid distribution in the cortex of fresh (F) turmeric and (VI) starch distribution in the cortex of cooked (FC1) turmeric. am, amyloplast; c, cortex; cur, curcuminoids cell; en, endodermis; ep, epidermis; gel, gelatinized starch; st, stele; bar = 500 µm (**I** and IV) or 50 µm (**II**, **III**, V and VI).

The curcuminoids were distributed throughout the whole rhizome; two cells containing curcuminoids were never adjacent (**Figure 3.I**). Curcuminoids occupied the entire cell volume in fresh turmeric (**Figure 3.I**). They were recognizable by their orange colour, but as they had the property of fluorescing in UV, they could be identified more specifically. Curcuminoids had the property of being fluorescent under UV light; they emitted in yellow (**Figure 3**). The observed fluorescence was obtained between 500 and 650 nm. The maximum fluorescence emission of the three curcuminoids (curcumin, demethoxycurcumin and bisdemethoxycurcumin) was observed between 500 and 600 nm (**Figure 3.III**).

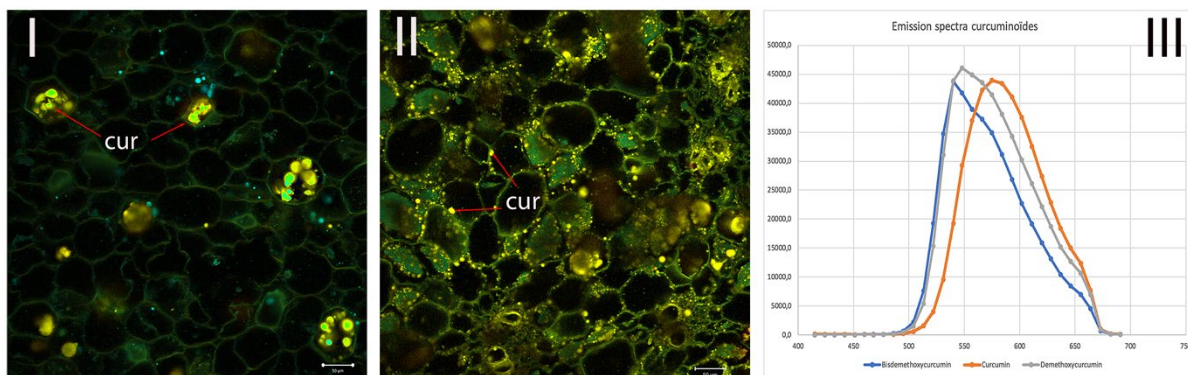

**Figure 3.** Visualization of curcuminoids distribution by multiphotonic microscopy. (**I**) curcuminoids distribution in the cortex of fresh turmeric, (**II**) curcuminoids distribution in the cortex of cooked and dried (FC2D) turmeric and (**III**) Emission spectra of curcuminoids between 400 and 700 nm, excitation 720 nm, bar = 50 µm.

#### 3.1.2. Curcuminoid and essential oil contents

The major curcuminoid compound found in our fresh turmeric was curcumin (6.24 g/100g db) followed by bisdemethoxycurcumin (5.70 g/100g db) and demethoxycurcumin (2.92 g/100g db). Moreover, the total curcuminoid contents (the sum of the three curcuminoids) in the turmeric was 14.86 g/100g db (equal to 1.95 g/100g wb). This value was higher than the values found by Hirun et al. (2014) (9.39 g/100g db), Govindarajan & Stahl (1980) (2 – 9 g/100g db) and Garg et al. (1999) (0.61 – 1.45 g/100g wb). The essential oil content of our fresh turmeric was 10.72 mL/100g db (equal to 1.32 mL/100g wb). This value was higher than that reported by Govindarajan & Stahl (1980) who found the content of essential oil up to 6.3 % db. However, the value was in agreement with Garg et al. (1999) who stated that the essential oil contents of *Curcuma longa* rhizomes collected from the sub-Himalayan Tarai region of India were in the range of 0.16 – 1.94 mL/100g wb. The disparity of the content of active phytochemicals could be due to environmental factors of each growing location, plant development stage, planting period, harvesting season and turmeric varieties (Hirun et al., 2014; Monton et al., 2019b).

### 3.2. Impacts of the unit processing operations

#### 3.2.1. Impact of cooking on colour values, curcuminoid content, essential oil content and drying curve

By mass balances (data not shown), we measured low water gain (whether for short or long cooking time); the water gain was lower than 3.0 % (kg water per 100 kg initial product). Moreover, very little dry matter and curcuminoids were transferred from the turmeric to the cooking water (not significantly different from zero). Thus, the cooking process only slightly increased the water amount, which must be removed during drying. Cooking had a slight impact on colour values (**Figure 4**). Our results showed that both cooking conditions had no impact on L*; however, smooth cooking significantly decreased a* value (8.3 %), while drastic cooking significantly decreased a* (6.1 %), b* (9.3 %) and C* (8.6 %) values. Heat treatment of the rhizome before dehydration can inactivate oxidative enzymes and limit the browning of the products. The browning of the turmeric during drying could be due to the Maillard reaction. However, rhizomes subjected to immersion cooking should have limited Maillard reactions because some of the reducing sugars could have diffused into the cooking water. Overall, drastic cooking impacted b* and C* colour values more than smooth cooking.
Cooking had no impact on curcuminoid content (**Figure 4**). This may be because curcuminoid is an oil-soluble pigment, practically insoluble in water at acidic and neutral pH, soluble in alkali. Moreover, it is stable at high temperatures and in acids, but unstable in alkaline conditions and the presence of light (Lee et al., 2013). Curcumin, demethoxycurcumin, bisdemethoxycurcumin and total curcuminoid contents of fresh and cooked turmerics (F, FC1 and FC2) ranged from 6.00 – 6.24, 2.92 – 3.31, 5.35 – 5.71 and 14.71 – 15.02 g/100g db, respectively.

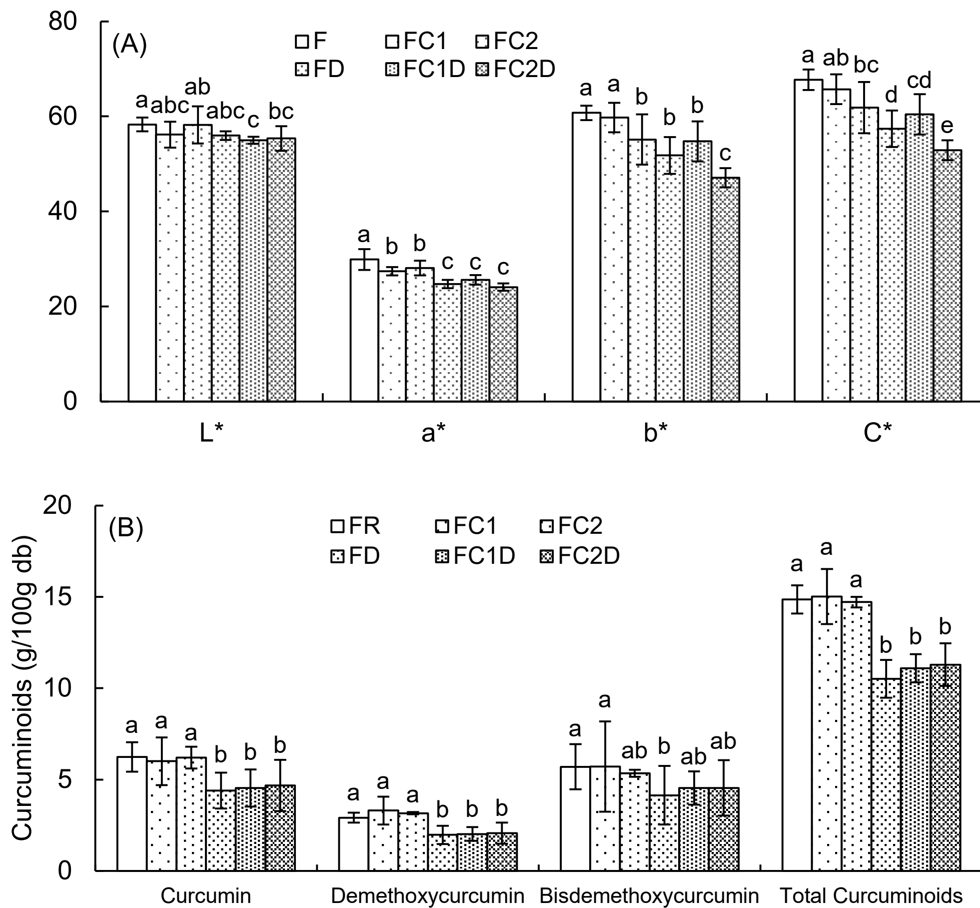


**Figure 4.** Impact of processes on (A) colour values (L*, a*, b* and C*) and (B) curcuminoid content (g/100g initial dry weight basis). FR: frozen rhizome; F: fresh turmeric; C: cooking (C1: 95 °C/3 min; C2: 95 °C/60 min); D: drying (60 °C, 40 % RH). The error bars represent the standard error (*n* = 6). Within the same parameters, the values followed by the same superscript letters are not significantly different ($P \leq 0.05$).

Cooking had no impact on essential oil content (**Figure 5**) as evidenced by the absence of a significant difference ($P \leq 0.05$) in the results obtained for essential oil in samples F, FC1 and FC2. The essential oil contents of fresh and cooked turmerics (F, FC1 and FC2) ranged from 10.70 – 11.06 mL/100g db). The results of microscopic analysis (**Figure 2.II** and **III**) also confirmed that the essential oils were not affected by cooking.

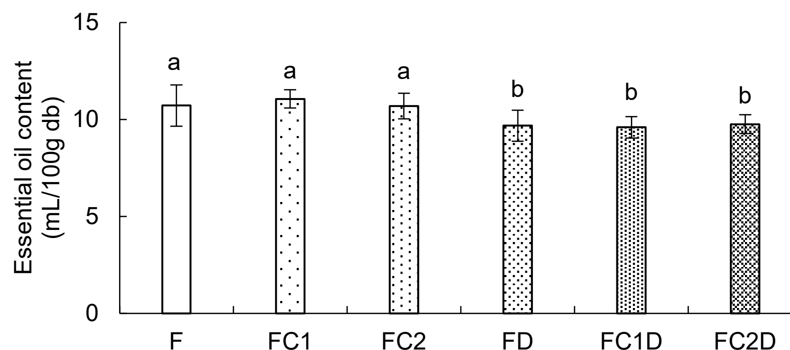


**Figure 5.** Impact of processes on essential oil content (mL/100g initial dry weight basis). F: fresh turmeric, C: cooking (C1: 95 °C/3 min; C2: 95 °C/60 min); D: drying (60 °C, 40 % RH). The error bars represent the standard error (*n* = 4). Within the same parameters, the values followed by the same superscript letters are not significantly different ($P \leq 0.05$).

The impact of cooking on the drying curves was shown in **Figure 6**. Cooking saved 38.1 % and 49.8 % of drying time for FC1 (cooking at 95 °C/3 min) and FC2 (cooking at 95 °C/60 min), respectively. About 59 min, 48 min and 45 min were required to obtain a 50 % reduction in the initial water content of fresh turmeric (F) and cooked turmerics *i.e.* FC1 and FC2, respectively. Drying kinetics presented a classical behaviour: an intense water loss during the initial stage and slowly at a later stage. This can be attributed to the fact that the moisture from the surface is easily evaporated while it takes time for the moisture to be removed from the interior. The comparison of the drying curves showed a much higher initial drying rate (5.05 ± 0.25 $kg.kg^{-1}.h^{-1}$ for FC2 and 5.01 ± 0.23 $kg.kg^{-1}.h^{-1}$ for FC1) in cooked turmerics than in fresh ones (F: 4.83 ± 0.33 $kg.kg^{-1}.h^{-1}$).

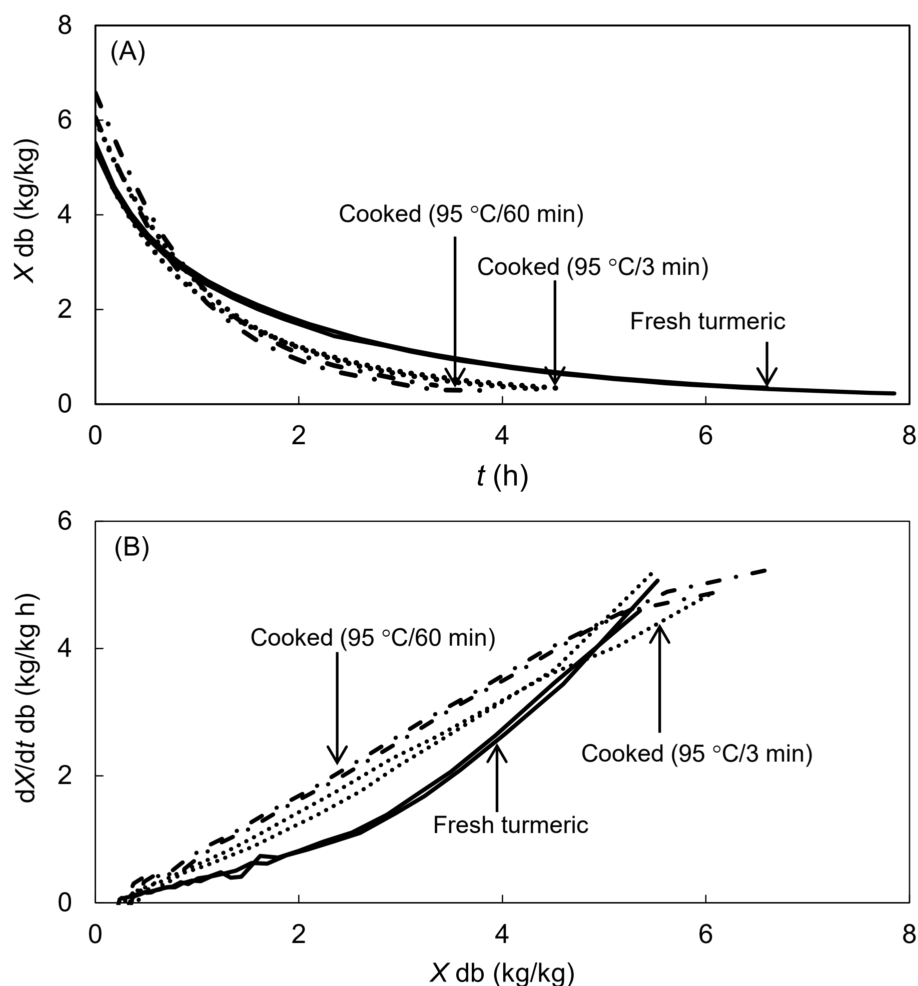


**Figure 6.** Drying curves of fresh and cooked turmerics. (A) water content ($X$) on a dry basis as a function of time ($t$) and (B) drying rate ($dX/dt$) as a function of $X$. Drying curves recorded by an air dryer (60 °C, RH 40 %, air velocity at 2.1 ± 0.1 $m\ s^{-1}$). The different dash types on curves correspond to different trials.

Govindarajan & Stahl (1980) observed that when turmeric rhizomes are cooked, the starch granules gelatinize as a result of the heat treatment, which facilitates drying and increases the rate of dehydration; as a result, the total drying time is reduced. The results of the microscopic analysis confirmed that cooking for 3 min at 95 °C was enough to completely gelatinize the starch (**Figure 2.VI**). The amyloplasts were clearly visible in fresh (F) turmeric (**Figure 2.V**) while they were no longer visible in cooked (FC1) turmeric (**Figure 2.VI**). Moreover, cooking combined with drying caused the partial exit (dispersion) of the curcuminoids from their dedicated cells; curcuminoids were then found throughout the whole rhizome and seem to be partly adsorbed on the starch cells (**Figure 3.II**). The degradation of the cell walls allowing curcuminoid exited could also explain the easier water removal when turmeric was cooked prior to drying. Cooking at 95 °C/3 min is the optimum cooking condition for turmeric sliced

rhizome (5 mm thick) because it is a good compromise between drying time and the quality of turmeric in terms of b* and C* colour chromatic values and it is also less energy-consuming than cooking at 95 °C/60 min.

#### 3.2.2. Impact of drying on colour values, curcuminoid content and essential oil content

Drying did have a marked impact on colour and curcuminoid contents (**Figure 4**). There were significant differences between samples F/FD, FC1/FC1D and FC2/FC2D considered in pairs for all values (a*, b* and C*) except for L*. The greatest differences were observed between sample F and FD with reductions of 17.3 %, 14.8 % and 15.3 % for a*, b* and C* values, respectively. Similar results were described by Bambirra et al. (2002). In the absence of heat treatment, a product with lower intensity of a* and b* was obtained. These results indicated that cooking the turmeric prior to dehydration is essential to obtain a product with higher intensity of a* and b*.

There were significant differences ($P > 0.05$) between the F/FD, FC1/FC1D and FC2/FC2D samples considered in pairs for all curcuminoids and total curcuminoids with the exception of FC1/FC1D and FC2/FC2D for bisdemethoxycurcumin content. Direct drying significantly decreased curcumin, demethoxycurcumin and bisdemethoxycurcumin contents 29.5 %, 32.3 % and 27.4 %, respectively while drying with previous cooking significantly decreased curcumin and demethoxycurcumin contents 24.5 % and 34.6 – 38.8 %, respectively. These results were in agreement with Madhusankha et al. (2018) who indicated that there was an evident and clear relationship between the curcuminoid content and the colour values. When the curcuminoid content decreased, a*, b* and C* values also decreased. Curcumin, demethoxycurcumin, bisdemethoxycurcumin and total curcuminoid contents of our dried turmerics (FD, FC1D and FC2D) ranged from 4.40 – 4.68, 1.98 – 2.07, 4.14 – 4.54 and 10.51 – 11.29 g/100g db, respectively. These values were comparable to those found by Monton et al. (2016). These authors found that: the contents of curcumin, demethoxycurcumin, bisdemethoxycurcumin and total curcuminoids were 6.61 – 7.67, 2.76 – 3.33, 2.64 – 3.47 and 12.02 – 14.36 % w/w, respectively. However, our turmerics contained a higher amount of curcuminoids than those found by Monton et al. (2019a) who reported that their turmeric powders contained 2.3 – 3.6 % curcumin, 1.0 – 1.6 % demethoxycurcumin, 1.5 – 2.3 % bisdemethoxycurcumin and 4.8 – 7.3 % (w/w) total curcuminoids.

Drying did have an impact on essential oil content (**Figure 5**) as significant visible differences ($P > 0.05$) were observed between samples F/FD, FC1/FC1D and FC2/FC2D considered in pairs (relative loss of 8.8 – 13.2 %). The method of drying usually has a significant effect on the contents of the essential oil (Kutti Gounder & Lingamallu, 2012). The essential oil is present in the specific cells and ducts present in the meristematic region of the rhizome. These oleaginous cells are damaged during the cooking of the rhizome and the exposure of the essential oil to the atmosphere induces a loss by volatilization during drying (Díaz-Maroto et al., 2002). The essential oil content of our dried turmerics (FD, FC1D and FC2D) ranged from 9.60 – 9.76 mL/100g db. These values were higher than that found by Monton et al. (2016) (7.00 – 8.00 % v/w) and Monton et al. (2019b) (5.20 – 8.50 % v/w). The factors that might affect the content of curcuminoids and essential oil were seasonal variation, environmental condition, post-harvest handling, storage, manufacturing and microbial contamination (Monton et al., 2016).

### 3.3. Impacts of ‘‘full” processes

In this study, a “full” process referred either to a single drying or to a process including cooking before drying (**Figure 1**). The impacts of the “full” processes on colour and curcuminoid content (**Figure 4**), essential oil content (**Figure 5**) and aroma profile (**Table 1** and **Figure 7**) were described.

#### 3.3.1. Impact of the ‘‘full” processes on colour and curcuminoids content

The impact of the “full” processes on colour and curcuminoid content were illustrated in **Figure 4**. There were significant differences ($P > 0.05$) between samples F/FD, F/FC1D and F/FC2D considered in pairs for all colour values (L*, a*, b* and C*). When turmeric was cooked for short time (95 °C/3 min; FC1D) prior to the drying, the colour values decreased less than during drying alone. However, when drying was preceded by drastic cooking (95 °C/60 min;

FC2D), the colour values decreased more than during drying alone (FC1D>FD>FC2D). By comparing the three finished products (FD, FC1D and FC2D), the results showed that there were no significant differences ($P \leq 0.05$) between FD and FC1D for all colour values, while FC2D had more impact on b* and C* values as compared to FD and FC1D. The "full" processes did have a marked impact on curcuminoid content (**Figure 4**). There were significant differences ($P > 0.05$) between samples F/FD, F/FC1D and F/FC2D considered in pairs for all curcuminoid contents and total curcuminoids except that there were no significant differences ($P \leq 0.05$) between samples F/FC1D and F/FC2D considered in pairs for bisdemethoxycurcumin content. The greatest differences were observed between sample F and FD with reductions of 29.5 %, 32.3 %, 27.4 % and 29.3 % for curcumin, demethoxycurcumin, bisdemethoxycurcumin and total curcuminoids, respectively. These results were in agreement with Suresh et al., (2007) who stated that curcumin loss from heat processing of turmeric was in the range of 27 – 53 %, with maximum loss in pressure cooking (at high temperature) for 10 min. However, Bambirra et al. (2002) indicated that heat treatment (up to 100 °C) had no effect on curcuminoids in turmeric. Therefore, an appropriate treatment (not too high nor not too low) to dry the turmeric may play a vital role in preserving curcuminoids in the turmeric (Hirun et al., 2014). The ground turmeric obtained without heat treatment was the one of worst quality respect to curcuminoid pigments and good quality of ground turmeric can be obtained by cooking in plain water as cooking favours diffusion of pigments from cells to adjacent tissue, contributing to a better pigment homogenization (Bambirra et al., 2002). There were no significant differences ($P \leq 0.05$) between the three finished products (FD, FC1D and FC2D) for curcuminoid content as compared between them. These results were in accordance with Prathapan et al. (2009) who found no significant differences in curcuminoid contents between turmeric samples submitted to different cooking and drying conditions.

### 3.3.2. Impact of the "full" processes on essential oil content

The "full" processes did have a marked impact on essential oil content (**Figure 5**). There were significant differences ($P > 0.05$) between samples F/FD, F/FC1D and F/FC2D considered in pairs for essential oil content (relative loss of 9.0 – 10.0 %). This relative loss was lower than that of the traditional drying method which could result in the loss of volatile oil up to 25 % by evaporation and in the destruction of some light-sensitive oil constituents (Ararsa, 2018). Though, there were no significant differences ($P \leq 0.05$) between the three finished products (FD, FC1D and FC2D) for essential oil content as compared between them. These results were in agreement with those found by Jayashree & John Zachariah (2016) who reported that there were no significant differences for essential oil content once the duration of cooking in boiling water increased up to 60 min.

### 3.3.3. Impact of the "full" processes on aroma composition

Fresh sample (F) was used as a reference and 15 aroma compounds representing 95.0 % of the total essential oil were identified. Among these, 10 major compounds, all of which present at a rate greater than 7.0 %, represented 92.1 % (**Table 1**) of the total essential oil.

**Table 1** Major aroma compounds in *Curcuma longa* L. fresh turmeric (F) essential oil.

| Aroma compounds | DB-Wax UI column | | DB-5MS column | | Area (%) |
|---|---|---|---|---|---|
| | $RI^a$ | $RI^b$ | $RI^a$ | $RI^b$ | |
| Turmerone | 2198 | 2245 | 1682 | 1650 | 37.8 ± 3.4 |
| aR-Turmerone | 2274 | – | 1678 | 1637 | 16.8 ± 1.9 |
| β-Turmerone | 2261 | – | 1711 | 1680 | 16.1 ± 0.8 |
| α-Terpinolene | 1307 | 1283 | 1096 | 1079 | 8.1 ± 1.4 |
| β-Sesquiphellandrene | 1771 | 1772 | 1527 | 1515 | 4.0 ± 0.6 |
| α-Zingiberene | 1724 | 1724 | 1497 | 1488 | 3.7 ± 0.7 |
| α-Phellandrene | 1197 | 1167 | 1016 | 998 | 1.9 ± 0.3 |
| Caryophyllene | 1610 | 1595 | 1425 | 1419 | 1.6 ± 0.4 |
| α-Curcumene | 1773 | 1777 | 1482 | 1473 | 1.3 ± 0.3 |
| Eucalyptol | 1240 | 1213 | 1041 | 1022 | 0.7 ± 0.1 |
| *Total* | | | | | 92.1 ± 1.0 |

Mean values ($n$ = 8) ± 95 % confidence interval. $RI^a$ is retention indices relative to C8–C20 n-alkanes (Experimental value) and $RI^b$ is retention indices from NIST and PubChem (literatures).

The major compounds in fresh turmeric were sesquiterpenes *i.e.,* turmerone (37.9 %), aR-turmerone (16.8 %) and β-turmerone (16.1 %). These turmerones have similar chemical structures, physical properties and molecule weights, although they have different tastes (Kao et al., 2007) and they are believed to be an intermediate for the formation of zingiberene and sesquiphellandrene (Asghari et al., 2009). α-terpinolene (8.1 %), β-sesquiphellandrene (4.0 %), α-zingiberene (3.7 %), α-phellandrene (1.9 %), caryophyllene (1.6 %), α-curcumene (1.3 %) and eucalyptol (0.7 %) were also identified. Raina et al. (2005) reported that the major components of essential oils from turmeric were α-turmerone (44.1 %), β-turmerone (18.5 %) and aR-turmerone (5.4 %), while Naz et al. (2010) reported that the most abundant components of the oils were aR-turmerone (25.3 %), α-turmerone (18.3 %) and β-turmerone (12.5 %). The aroma composition of the fresh turmeric rhizome oils varies with species, origin, agricultural system, climate, or maturity.
The impact of the "full" processes on the aroma profile was shown in **Figure 7**. There were significant differences ($P > 0.05$) between samples F/FD, F/FC1D and F/FC2D considered in pairs for all molecules, except for turmerone and α-phellandrene. For aR-turmerone and β-turmerone, the greatest differences were observed between sample F and FD with relative loss of 21.6 % and 9.8 %, respectively. For α-curcumene, the greatest difference (30.8 %) was observed between sample F and FC1D. For α-terpinolene, β-sesquiphellandrene, α-zingiberene, caryophyllene and eucalyptol, the greatest differences were observed between sample F and FC2D with a reduction in the range of 19.7 – 46.3 %.

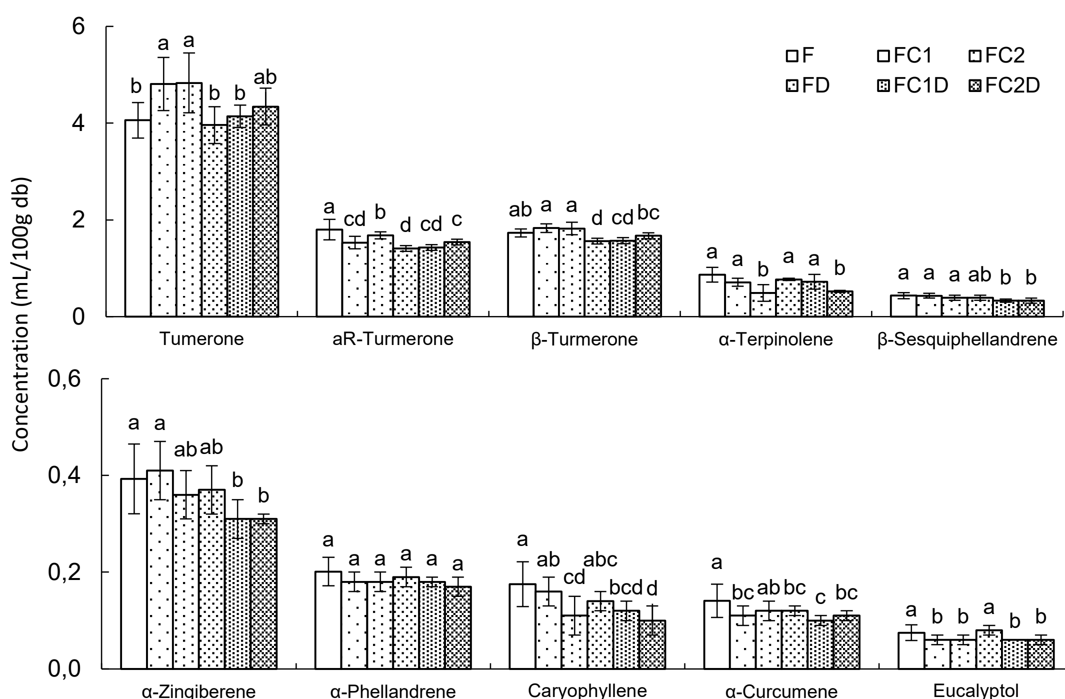


**Figure 7.** Composition of essential oil of fresh and processed turmerics. F: fresh turmeric; C: cooking (C1: 95 °C/3 min; C2: 95 °C/60 min); D: drying (60 °C, 40 % RH). The error bars represent the standard error ($n = 8$). Within the same parameters, the values followed by the same superscript letters are not significantly different ($P \leq 0.05$).

Cooking slightly impacted the concentration of aroma compounds (**Figure 7**). Smooth cooking significantly decreased 14.9 %, 21.7 % and 19.7 % of aR-turmerone, α-curcumene and eucalyptol, respectively. Drastic cooking significantly decreased aR-turmerone, α-terpinolene, caryophyllene and eucalyptol with a reduction of 6.5 %, 43.4 %, 37.2 % and 19.7 %, respectively. Conversely, cooking (smooth and drastic) significantly increased turmerone up to 19.0 %. The major aroma compounds in our fresh and cooked turmerics (F, FC1 and FC2) were turmerone (37.9 – 44.6 %), aR-turmerone (14.0 – 16.8 %) and β-turmerone (16.1 – 16.8 %) (data not shown).

Drying also had a slight impact on the concentration of aroma compounds (**Figure 7**) as there were significant differences ($P > 0.05$) between samples F/FD, FC1/FC1D and FC2/FC2D considered in pairs. Direct drying significantly decreased aR-turmerone, β-turmerone and α-curcumene with relative loss of 21.6 %, 9.8 % and 14.5 %, respectively. Drying with previous smooth cooking significantly decreased turmerone, β-turmerone, β-sesquiphellandrene and α-zingiberene with relative loss of 13.9 %, 14.2 %, 23.3 % and 24.4 %, respectively. Drying with previous drastic cooking significantly decreased aR-turmerone (8.3 %), β-turmerone (8.2 %) and β-sesquiphellandrene (15.4 %). The changes in the percentage of each aroma compound may be due to the complete release of these compounds during cooking and drying processes and another reason may be due to oxidation or rearrangement of less stable compounds to the more stable compounds (Kutti Gounder & Lingamallu, 2012). The major aroma compounds in our dried turmerics (FD, FC1D and FC2D) were turmerone (40.9 – 44.4 %), aR-turmerone (14.6 – 15.8 %) and β-turmerone (16.1 – 17.1 %) (data not shown). The major aroma compounds of dried turmeric from Thailand found by Monton et al. (2019a) were aR-turmerone (43 – 49 %), turmerone (13 – 16 %) and β-turmerone (17 – 18 %) and by Thongphasuk & Thongphasuk (2013) were aR-turmerone (32 %), α-turmerone (16 %), and β-turmerone (13 %).

## 4. Conclusion

Our original approach combining microscopy and biochemistry brought interesting results. Curcuminoid and essential oil were found in different dedicated cells. After processing, curcuminoids were dispersed throughout the matrix. This starchy matrix seems to protect essential oil and curcuminoid to a certain extent. Drastic cooking (95 °C/60 min) and drying operations impacted b* and C* colour values more than smooth cooking (95 °C/3 min). Cooking (either smooth or drastic) had no impact on curcuminoid and essential oil contents and only a slight impact on essential oil composition. Drying significantly decreased curcuminoid (between 24.5 – 38.8 %) and essential oil (between 8.8 – 13.2 %) contents. There is a real interest in combining cooking and drying unit operations. Indeed, cooking turmeric before drying saved 38.1 to 49.8 % of the drying time. Cooking at 95 °C/3 min is the optimum cooking condition for turmeric sliced rhizome (5 mm thick) because it is a good compromise between drying time and the quality of turmeric considering colour and aroma. It is also less energy-consuming than cooking at 95 °C/60 min. For further studies, we should focus on the impact of unit operations (cooking, drying and grinding) on the functional and sensory qualities of turmeric.

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## CONFLICTS OF INTEREST

There are no conflicts of interest to declare.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Novelty Impact Statement

Our study brings us to propose better practices for turmeric processing. A smooth cooking (95 °C/3 min) before drying is recommended to preserve the quality of the turmeric as the curcuminoids and essential oil are preserved during cooking. This protection could be linked to the starchy structure of the turmeric matrix.

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