Feasibility of microwave drying for analysis and processing of medicinal plants

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Research Article

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Abstract

Drying herbal products is essential for sample preparation and ensuring product quality. This study explored the efficacy of microwave-based drying (MW) as an alternative method for moisture content (MC) determination and quality preservation of herbal plants viz, *Centella asiatica*, *Eryngium foetidum*, *Enhydra fluctuans* and *Marsilea minuta*. Compared to the standard drying method (oven drying at 105°C), the microwave-based loss-on drying method demonstrated significantly more efficiency in reducing drying time and spatial distribution. The study confirms that MW has similar macro-properties and antioxidant activity to freeze-drying. Among the four herbs studied, MW had 10-20% more extractability and had high similarity (Pearson correlation coefficient <0.8 and low Euclidean distance) among soluble components. LC-MS analysis of *Centella asiatica* revealed that MW shared 46% common compounds while convective drying only had 27% common compounds to freeze drying. Overall, MW proved to be a faster drying process and reliable MC determination method with better retention of bioactive compounds. These findings contribute to rapid and qualitative sample preparation for analyzing both physicochemical properties and secondary metabolites of medicinal plants and herbal products. This, in turn, can positively impact the development of herbal products with improved drying techniques, meeting the growing demand for high-quality culinary and medicinal products.

1. Introduction

Herbs are part of traditional cuisine and pose essential health benefits. The increasing awareness about healthy food or herbal remedies creates great demand for such products. In 2017, the global herbal supplements market was worth USD 5.26 billion, and as per current estimate, it will continue to grow at a CAGR of 6.2% till 2025 [1]. Notably, *Centella asiatica*, *Eryngium foetidum*, *Enhydra fluctuans* and *Marsilea minuta* are four tropical herbs known for their culinary and medicinal use in many ethnic societies worldwide. *Centella asiatica* has gained recognition for its effectiveness in wound healing and various skin conditions (leprosy, lupus, eczema, psoriasis). Additionally, it has been used for treating diarrhoea, fever, amenorrhea and diseases of the female genitourinary tract [2]. Similarly, *Enhydra fluctuans* Lour is known for treating inflammation, skin diseases and smallpox [3]. *Eryngium foetidum*, besides being a flavouring agent, is effective against inflammation and bacterial and viral infection [4]. On the other hand, ethnomedicinal surveys have reported that *Marsilea minuta* has found use as a natural medicine for dermatological, digestive, respiratory and psychological diseases [5].

Considering the assessment of herbal quality and production of herbal products, moisture content emerges as the most critical quality parameter for fresh and dried herbs, since it decides the shelf life and other processing ability of the product. Many national and international bodies like FSSAI, FAO, OECD, AOAC, ISO, AOCS, and the Ministry of Ayush have prescribed the standard LOD methods of MC determination. Typically, 5–10 g of sample is kept for drying in a hot air oven at 105ºC for a prescribed hour and by the difference of weight, moisture content of the sample is determined. Nevertheless, drying time at 105ºC is in the range of hours and shows an intra-sample variation. Also, for commercial purposes, most herbs (roots, leaves, flowers, etc.) or herbal products are marketed in dehydrated form as a single powder or as a polyherbal mix for culinary or medicinal use. Often the dried plant parts are used as a feed material for different types of extraction for product formulation. Hence drying is one of the most common yet critical techniques used to extend the shelf life of herbal and other plant products that should pose the desired sensory and functional properties [6]. However, the traditional drying techniques, such as shade or sun drying, are inconsistent, prone to microbial contamination and oxidative damage due to longer drying time and only suitable for domestic or small-scale purposes. Several other drying methods include modified solar drying, hot air drying, heat pump drying, infrared drying, vacuum drying, freeze-drying, and so forth. The most common and favoured drying

method for a small-scale industry or lab scale is low-temperature convective drying [7]. At the same time, convective drying takes longer and threatens the bioactive compounds of plant products due to high temperature and atmospheric oxygen. Therefore, to overcome these limitations microwave drying method can be used as an alternative fast and reliable method for moisture content determination and quality assessment. Reports suggests that microwave-based loss on drying method provides low uncertainty in MC determination with affordable cost and time [8–11]. This method utilizes electromagnetic waves to heat and evaporate moisture from the plant products, potentially creating a porous structure in solid matrices [12, 13]. Therefore, this study can provide valuable insight into the potential use of microwave oven drying as an efficient and time-saving alternative drying method for herbal products. The evaluation of microwave oven-based drying for effective moisture content determination is valuable as it provides the efficiency of this method for removing moisture from the herbs. At the same time, the three drying techniques, viz, convective, microwave and freeze drying were evaluated. Though these drying techniques are quite different in terms of their drying mechanism and performance but convective and freeze-drying are two well-known industrial and lab-scale drying processes for herbal products. It is generally accepted that freeze drying can restore the most bioactive due to its ultra-low temperature operation. However, it is a sophisticated and costly drying process. Alternatively, low-temperature convective drying is a convenient, cheaper but somewhat quality-compromising choice for both lab and industrial scale drying. These findings lead to the sustainability, resource utilization and development of improved drying methods where microwave drying could be equally or more effective in preserving the bioactive compounds and can have significant implications for the herbal industry and culinary applications.

2. Materials and Methods

2.1. Plant sample preparation

Centella asiatica (CA), *Eryngium foetidum* (EGF), *Enhydra fluctuans* (ENF) and *Marsilea minuta* (MN) were grown extensively between April to December. The plants were harvested at matured state between 2–3 months. The specimen was recognized by the Botanical Survey of India, Shillong.

2.2. Methods of drying

2.2.1. Hot air drying at low temperature

40 g of samples were dried at 50ºC on a perforated tray with an average flow rate of 0.1–3.6 m/s and weighed every hour till its equilibrium moisture content was reached.

2.2.2. Microwave drying

A domestic microwave oven (IFB, 20BC4, India) with a maximum output of 800W at 2450 MHz was used. The dimension of the microwave cavity was 262 mm × 452 mm × 390 mm. The oven was equipped with a rotating glass plate at its base. 40 g of samples were placed in a borosil glass bowl with a dimension of 150 × 75 mm and dried at 720W till the sample reached its equilibrium moisture content.

2.2.3. Freeze drying

The plant materials of 40 g were placed in a freeze-dryer (NovaDryer-HF100, Senova) at -40°C in a vacuum of 10 Pa and dried for 48 h. The weight change of the samples was recorded once after 12 h and dried till the sample reached its equilibrium moisture content.

2.3. Comparison of microwave oven and convective oven drying for determination of moisture content in herbs

2.3.1. Moisture content comparison

The leaf samples (40 g) were dried in a hot air oven at 105 ± 2ºC and microwave oven (720W) until constant weight. Moisture content was calculated using the weight difference method. The moisture content values estimated by the LOD methods were then correlated.

2.3.2. Effective moisture diffusivity estimation

The effective moisture diffusivity was estimated from the slope of the semilogarithmic plot of M_R from experimental data versus time. The slope of the straight line was considered as the quantity of the effective diffusivity.

2.3.3. Estimation of intra-sample variation

Equal weight of ten sets of samples of an herb CA was taken in different batches for drying. The samples were dried in hot-air oven at 105ºC and a microwave oven at 720W until constant weight was reached. The variation in moisture content was estimated in the Box whisker plot.

2.3.4. Spatial distribution of temperature and airflow rate estimation

The temperature of different locations was measured with an IR thermometer in the cabinet of oven dryers and microwave oven. The air flow rate of the oven dryer was measured in the same locations with the anemometer.

2.4. Drying characteristics of four herbs in three different types of dryers and properties of their powder

The effect of hot air drying at low temperature (50ºC), microwave oven at 720W and freeze-drying (-40 ºC) on four varieties of herbs were estimated in terms of drying rate and water activity, particle size, bulk density and tapped density.

2.4.1. Analytical Methods

2.4.1.1. Water activity

Water activity indicates the amount of water available for chemical and biochemical reactions. The water activity of dried leaves was determined by a humimeter RH2 water activity meter and analyzed at a temperature of 21 ± 2°C.

2.4.1.2. Particle size, bulk and tapped density

The particle size of ground samples was estimated using the sieve analysis method. A set of standard sieves was used to separate different size fractions of the leaf powder. The bulk density, tapped density and apparent porosity were determined according to the respective USP procedure [14].

2.5. Effect of three different drying on extractability of alcohol soluble components and antioxidant activity of the resultant extract

The effect of hot air drying at low temperature (50ºC), microwave oven at 720W and freeze-drying (-40ºC) for extraction of antioxidant rich polyphenols were estimated with different analytical methods as described below.

2.5.1. Analytical Methods

2.5.1.1. Total soluble solids (TSS)

The soluble solids of 4 g of dried powder of CA, EGF, ENF and MN were macerated in 400 mL of methanol for 48 h. The loss on drying method was used for determining total soluble solids of the extracts. 5 mL of the samples were dried and the difference of weight was used to calculate mg of solids/g of dry weight of powder.

2.5.1.2. Total phenolic content (TPC)

The total phenolic content of the extracts were determined using the Folin Ciocalteu's reagent, with a modification as described by Singleton and Rossi [15]. 0.2 mL of extracts were dissolved in 0.6 mL of distilled water, and 0.2 mL of 1 N Folin Ciocalteu's reagent was mixed to the reaction mixture and incubated for 5 minutes at 25ºC. 1 mL of 8% sodium carbonate (Na_2CO_3) was added to the reaction mixture and incubated further at 25ºC for 1 h. The absorbance was measured at 750 nm using UV-visible spectrophotometer (Shimazu UV-1900). The results of total phenolic contents were expressed as mg of gallic acid equivalent (GAE) equivalent/g of dry powder.

2.5.1.3. Total flavonoid content (TFC)

The total flavonoid content was estimated as described by Patel et al. [16]. 200 µL of extracts dissolved in 5% of 0.1 M sodium nitrate ($NaNO_3$) and incubated for 6 minutes at 30ºC. 10% of 0.1 M aluminium chloride ($AlCl_3$) was added to the reaction mixture and allowed to react for 5 minutes. 1 M of sodium hydroxide (NaOH) was added and absorbance was measured in UV-vis spectrophotometer (Shimazu UV-1900) at 410 nm after 40 minutes of incubation. The results of total flavonoid contents were expressed as mg of quercetin (QE) equivalent/g of dry powder.

2.5.1.4. Reducing power (IRP)

The iron reducing power was determined with potassium ferricyanide reduction assay as described by Oyaizu [17] with slight modification. 100 µL of extracts dissolved in 300 µL of phosphate buffer (0.2 M, pH 6.6) and 300 µL of 1% potassium ferricyanide (K [Fe(CN)]) incubated at 50ºC for 20 minutes. The reaction was stopped with the addition of 300 µL of 10% trichloroacetic acid (TCA). Absorbance was measured at 700 nm with the addition of 800 µL distilled water and 200 µL of 0.1% ferric chloride ($FeCl_3$). Results were expressed as mg ascorbic acid equivalent (AA) equivalent/g of dry powder.

2.5.1.5. Radical scavenging activity (ARSA)

The free radicals scavenging capacity was determined by 2,2'-azinobis-3-ethylbenzothiazoline-6-sulfonic acid (ABTS) assay with slight modification as described by Re et al. [18]. ABTS radical cation ($ABTS^{\bullet+}$) was produced with 7 mM ABTS solution and 2.45 mM potassium persulphate ($K_2S_2O_8$) and equilibrated at 30ºC for 16 h before use. The $ABTS^{\bullet+}$ solution was diluted with acetate buffer (4.5 pH) and incubated for 30 minutes for a stable absorbance of 0.70 ± 0.02 at 734 nm. 1.8 mL of the ABTS radical solution was mixed with 90 µL of extracts and incubated for 6 minutes. The absorbance was measured at 734 nm using UV-visible spectrophotometer (Shimazu UV-1900). The results were expressed as mg trolox (TE) equivalent/g of dry powder.

2.5.1.6. Lipid peroxidation inhibition (LPOX)

A modified thiobarbituric acid-reactive species assay was used to measure the lipid peroxidation inhibition potential of extract with a slightly modified method of Ohkawa et al. [19]. The egg-yolk homogenates were used as a test lipid

media. Egg homogenate (250 µL, 10% in distilled water, v/v) and 50 µL of extracts were mixed and made up to 500 µL by adding methanol. Subsequently, 25 µL of 0.07 M ferrous sulphate ($FeSO_4$) was mixed and incubated for 30 minutes to induce lipid peroxidation. 750 µL of 20% acetic acid (pH 3.5) and 750 µL of 0.8% (w/v) thiobarbituric acid (TBA) (prepared in 1.1% sodium dodecyl sulphate) and 25 µL of 20% TCA were added to the reaction mixture, vortexed, and then heated at 95ºC for 60 minutes. After cooling, 3 mL of 1-butanol was added to each tube and centrifuged (Remi, CPR-24 Plus) at 6000 × *g* for 10 minutes. The absorbance of the organic upper layer was measured against 3 mL butanol at 532 nm. The results were expressed as mg malondialdehyde (MDA) equivalent/g of dry powder.

2.5.1.7. Effect of drying on polyphenol oxidase activity (PPO)

Polyphenol oxidase activity was estimated as described by Tan et al. [20]. Crude extracts containing polyphenol oxidase enzyme were prepared by suspending 1 g of dried samples in 10 mL of 0.2 M potassium phosphate buffer, pH 7.0, containing 1% PVP-40 (w/v) and 1% Triton X-100 (v/v) at 4ºC for 1 h in a shaker incubator. The suspensions were centrifuged at 9000 × *g* for 1 h at 4ºC. The supernatant of samples was stored at -20ºC for the preparation of enzymatic assay. In a 2.9 mL reaction mixture with 1 mM catechin, 0.05 M potassium phosphate buffer (pH 6.5) was added. The reaction was started by adding 0.1 mL of supernatant containing PPO enzyme extracts. Reference cell was prepared containing only the reaction mixture without the enzyme extracts. The absorbance of the reaction mixture was measured for 10 minutes at 435 nm. PPO activity was expressed as ΔA435/min/g of dry powder.

2.6. Effect of drying on polyphenols of selected four herbs using HPLC

A signature chromatogram was developed for the extracts using an Agilent 1100 Series liquid chromatography (USA) equipped with a UV/DAD detector. Chromatographic separation was performed using a Poroshell 120 EC-C18 (4.6 mm × 100 mm, 2.7 µm) column. Eluent solvent had a constant flow rate of 1.0 mL/min. The mobile phase was distilled water with 0.1% glacial acetic acid (solvent A) and acetonitrile with 0.1% glacial acetic acid (solvent B). The gradient was as follows: 0–3.25 min, 8–10% B; 3.25–8 min, 10–12% B; 8–15, 12–25% B; 15–15.8 min, 25–30% B; 15.8–25 min, 30–90% B; 25–25.4 min, 90–100% B; and 25.4–30 min, 100% B. The injection volume was 20 µL, and the temperature was kept constant at 25°C. The detection wavelength was chosen considering the absorption maximums of UV spectra of the selected phenolic compounds, i.e., 280 nm [21]. This HPLC method was validated on known standard compounds and the compound in the extracts were identified based on peak retention time. The total run time for the analysis of compounds and type of extracts was 27 minutes. The reproducibility of HPLC analysis was examined by standard compounds.

2.7. Chemical profiling of one of the selected herbs for similarity analysis of drying process

The phenolic compounds of *Centella asiatica* dried in convection (50ºC), microwave (720W) and freeze (-40ºC) were identified by using an LC system coupled to a triple quadrupole mass spectrometer (Agilent 6410 Triple Quad MS-MS) equipped with an ESI source. The chromatographic separation of the phenolic compounds was carried out on Eclipse Plus column C18 (100 × 4.6 mm i.d., particle size 3.5 µm). The temperature of the column was set at 40ºC and the injection volume of the samples was 5 µL. The negative mode compounds were isolated in mobile phase consists of 0.1% acetic acid in 5 mM ammonium acetate (eluent A) and acetonitrile (eluent B) at a flow rate of 0.40 mL/min. The gradient conditions were as follows: 0–5 min, 2–2% B; 5–20 min, 2–40% B; 20–30 min, 40–90% B; 30–40 min, 90–2% B; 40–45 min, 2–2% B. The capillary voltage was of 135V; nebulizing gas (N_2) flow rate was 11 L/min, and the heat block and de-solvation line temperatures was of 300ºC, respectively. Mass spectra was recorded

between m/z 15–1650. The phenolic compounds of *Centella asiatica* were identified by comparing their mass spectrometry fragmentation patterns.

2.8. Statistical Analysis

All experimental data was expressed as mean ± standard error (SE) of triplicate runs. The Origin 9.0 program (2022) was used to analyse the data and mean values were statistically significant ($p < 0.05$). Similarity analysis was performed with Pearson correlation coefficient, Spearman correlation coefficient and Euclidean distance.

3. Results and Discussion

3.1. Comparison of microwave oven and convective oven drying for determination of moisture content in herbs

Accurate and rapid MC determination of fresh or dried plant tissues and their powders is essential for research laboratories and herbal industries. MC determination is important to control shelf-life as well as compositional analysis of herbal products. Often the prescribed method of MC determination by various regulatory agencies is by calculating the weight loss of a sample on (complete) drying at 105ºC in a hot air oven [22, 23]. However, the method has two major limitations, firstly longer time of drying for complete removal of moisture and secondly broader intra-sample variation. In this study, four medicinally valuable plant samples were dried by two different methods; by microwave drying at 720W power and by well-known hot air oven at 105ºC. Both the processes were compared for complete moisture removal. Indeed, the drying rate in the domestic microwave oven was one order of magnitude faster. Figure 1 indicates that the moisture diffusivity in all the samples under microwave drying was about ten times more than that in the hot air oven drying at 105ºC.

In the hot air oven, complete removal of moisture from all four samples took at least 7 h whereas in microwave oven it took less than 16 minutes. Considering the hot air oven method as a gold standard, the moisture content determined for four medicinal plants viz, CA, EGF, ENF and MN using microwave oven was compared with the moisture content determined by hot air oven. The Pearson and Spearman correlation coefficient between the MC determined by both the methods were respectively 0.9 and 0.76 (Table 1).

Table 1
Moisture content comparison of different samples in 105ºC oven drying and Microwave drying (720W)

105ºC Oven drying	Microwave (720W)
0.89	0.89
0.89	0.89
0.87	0.87
0.87	0.87
0.89	0.84
0.89	0.84
0.72	0.77
0.70	0.77

This finding supports that the microwave oven drying is suitable for MC determination of herbal leaves like hot air oven. The method is further examined for the intra-sample variation. MC of an herbal sample (CA) was measured ten times with both the methods and the dispersion of the MC data was compared with a Box-whisker plot (Fig. 2).

The origin of variation in a hot air oven was studied and the heterogeneity of air flow rate and temperature in different locations of the hot air oven was recorded. The samples kept at various trays faced different local air conditions and therefore suffered different extents of drying. It is well known that hot air ovens without forced convection will have spatial heterogeneity of temperature. However, to identify the extent of spatial temperature and air flow distribution, laboratory hot air ovens with forced convection were studied and surprisingly all of them showed significant non-uniformity. The extreme air velocities in two different locations inside the dryer cabinet was observed at 0.1 and 3.6 m/s. Whereas the lowest and highest temperature seen inside the same cabinet was 95ºC and 107ºC. Differences of 10ºC and flowrate differences of one order of magnitude can considerably under-dry or over-dry the samples. Tables 2 and 3 indicates the heterogeneity of temperature and airflow rate inside the dryer cabinet used for the present study. It can be anticipated that the designs of laboratory hot air ovens may not always ensure uniform airflow. Many times, finer mistakes in the design of such ovens may create poor mixing and therefore poor temperature control. Computational fluid dynamics can be used to optimize the design of a hot air oven for narrow temperature and air velocity distribution within the cabinet [24]. Another issue we could identify is solid loss due to high airflow rate in hot air ovens especially for friable materials like leaves, flowers etc. Such issues are less likely in presently available domestic microwave ovens. Though standing wave pattern of microwave inside the oven and dielectric heterogeneity of plant tissues cause some non-uniformity in heating of the sample volume [25]. Ceramic/Stainless steel enamel cavity, appropriate cavity geometry, controlled frequency and turntable plate for holding the samples make most of the domestic microwave oven suitable for uniform heating of plant materials. Therefore, for small volume of samples (5–25 g) uniformity of microwave ovens are superior than that of hot air oven. In this study also microwave oven showed significantly lower intra-sample variation compared to hot air oven (Fig. 2). Moreover, in terms of quality and yield, it is often anticipated that at high temperature essential oil of many medicinal plants may deteriorate. Therefore, distillation method of MC determination is often preferred for such medicinal plants with high oil content [22]. The method is problematic due to difficulty in recovery of the condensate and cleaning the distillation set up.

Table 2
Spatial distribution of temperature and air flow rate in hot air oven

OD (105°C)			TD (50°C)		
Cabinet locations	Flow rate(m/s)	Temperature (°C)	Cabinet locations	Flow rate(m/s)	Temperature (°C)
Near Fan	2.9 ± 0.09	107 ± 1.73	Middle Right (Near Fan)	3.6 ± 0.15	51.2 ± 0.66
Up Middle	0.7 ± 0.06	103 ± 1.73	Middle Middle	0.8 ± 0.09	50.6 ± 1.18
Down Middle	1.5 ± 0.09	97 ± 1.45	Middle Left	0.5 ± 0.09	48.9 ± 1.24
Up Right	0.7 ± 0.15	94 ± 2.03	Top Right	0.4 ± 0.06	48.2 ± 0.66
Down Right	1.2 ± 0.15	95 ± 1.15	Top Middle	0.3 ± 0.06	47 ± 1.36
			Top Left	0.1 ± 0.03	46.7 ± 0.49
			Down Right	1.7 ± 0.20	42.6 ± 1.24
			Down Middle	1.3 ± 0.15	43.2 ± 1.07
			Down Left	0.3 ± 0.06	42.8 ± 1.01
			Infront of Door	0.08 ± 0.01	42 ± 1.13

OD: Oven dried; TD: Convective tray dried; Results were expressed as mean ± standard error of triplicate runs.

Also, the formation of emulsions may be hard to be separated and assessed for oil and moisture content. For fresh plant tissues still, the loss on complete drying is suitable method considering the higher moisture content (70–95%) compared to the oil contents. The oil concentration in plant parts are typically less than 10% except some seeds. However, the commercial Karl Fischer tilt rotors costs couple of thousand USD and often a complex system for regular use in academic or industrial labs. Even 1% moisture content in a standard 5 g sample will cause 0.05 g of change which is achievable for all practical purposes. In case of microwave drying, general concern is volatilization of solids in a sample leading to overestimation of moisture content [26].

Table 3
Spatial distribution of temperature in microwave oven (720W)

MW (720W)	1 min	2 min	3 min	4 min	5 min	6 min	7 min	8 min	9 min	10 min
Left Boundary	72 ± 0.88	74 ± 0.33	71 ± 0.58	71 ± 0.33	73 ± 0.67	72 ± 0.33	72 ± 0.33	72 ± 0.58	74 ± 0.58	73 ± 0.88
On Plate	99 ± 0.52	100 ± 0.39	100 ± 0.33	103 ± 0.58	104 ± 0.33	105 ± 0.58	106 ± 0.58	105 ± 0.88	104 ± 0.33	105 ± 0.33
Right Boundary	93 ± 0.58	97 ± 0.58	96 ± 0.58	95 ± 0.58	90 ± 0.58	93 ± 0.58	96 ± 0.58	97 ± 0.88	92 ± 0.88	95 ± 0.88
Upper	112 ± 0.61	104 ± 0.62	105 ± 0.41	107 ± 0.41	105 ± 0.62	107 ± 0.62	105 ± 00.62	103 ± 0.41	103 ± 0.62	109 ± 0.62

MW: Microwave dried; Results were expressed as mean ± standard error of triplicate runs.

Following reaction shows the carbonization (charring) of sugars. For each gram of hexose (equivalent) about 0.6 g of weight loss happens.

$$C_{12}H_{22}O_{11} \rightarrow 11H_2O + 12C$$

We simulated the effect of different percentages (0.5–50%) of volatilization and also the effect of different degrees (0.5–50%) of incomplete drying on the estimated moisture content of a sample (Table SI1 and Table SI2). The standard deviation of all the simulated moisture content values was 0.322%. Therefore, the correct rounding off-figure for representing the moisture content determination was considered upto one decimal place [27]. For the same accuracy of MC values, it was found that with less than 5% volatilization or 5% lesser drying, the MC values does not change significantly for a sample irrespective of its MC. Hence, an herbal product with a sugar/hexose content as high as 8% will show insignificant error in MC even with complete carbonization. Generally, fresh herbal crops like flowers, leaves, rhizomes etc. contain 70–95% moisture. Same simulation showed that no error can be detected in MC determination even if there is 15% under drying or 15% solid volatilization for any sample with more than 70% MC. Therefore, when MC to be determined for fresh (expected MC > 70% in wet basis) and dried (expected MC < 10% in wet basis) herbal substances microwave oven-based method might fail if the thermo-labile compounds respectively

Table 4
Order of time to reach the equilibrium moisture content of herbal samples

Sample Name	Drying time to reach EMC			Initial moisture content (%, wb)	Equilibrium moisture content		
	TD (50°C), h	MW (720W, 90%), minutes	FD (-40°C), h		TD (50°C), h	MW (720W, 90%), minutes	FD (-40°C), h
CA	8	13	48	89.8	1.8	1	0
ENF	12	16	48	89.6	0.2	2	0
EGF	8	9	48	87.5	0.9	0	1
MN	9	15	48	77.9	1	0	1

CA: *Centella asiatica*; EGF: *Eryngium foetidum*; ENF: *Enhydra fluctuans*; MN: *Marsilea minuta*; TD: Convective tray dried; MW: Microwave dried; FD: Freeze dried; EMC: Equilibrium moisture content; wb: wet basis

crosses 15% and 5% considering 5 g of sample size. The thermo-labile compounds may be essential oils, sugars or other heat-sensitive compounds. In addition to non-uniform energy distribution, another reason for the lack of repeatability was found to be heterogeneity of samples. Many a times fresh herbal samples may contain different tissues (e.g., stem and leaves together) which will have different drying behaviour and moisture content.

3.2. Drying characteristics of four herbs in three different types of dryer and properties of their powder

In a separate set of experiment, microwave drying was compared with two drying methods; a commercially popular drying method i.e., convective tray drying (at 50°C) and the other one is a peer accepted sophisticated drying technique, i.e. freeze drying. Convective drying is very common form of drying in industries. However, it is a slow and poor drying process in terms of bioactives. On the other hand, freeze drying is a costly process to be adopted for common usage. In the present trial, microwave drying was acceded to check its suitability to prepare dried herbs for further used as herbal beverages (decoction and infusion), ingredients for curries or cuisines or component of herbal

medicine preparation (e.g., hydroalcoholic extract) and quality analysis of herbal products. For the three drying methods, moisture content of the sample was estimated for different time intervals till the constant weight of the sample was reached. The order of time to reach the equilibrium moisture content was microwave drying (8–12 min) < low temperature convective drying (50ºC) (9–16 h) < freeze drying (36–48 h) (Table 4). As expected, the drying time was dependent on the herb variety since the surface area and thickness of the leaf and the residual stem as well as the internal cell structures, were different. EGF and ENF took respectively fastest and slowest time to reach EMC in both convective and microwave drying. For freeze drying, we could take weight change only after every 12 h and all the four samples reached EMC between 36–48 h (Fig. SI1). Since the sublimation and subsequent diffusion rate of water molecules in sub zero temperature was much slower than that duirng drying at 50ºC or higher temperature, freeze drying took longest time to dry. However, in all three methods the equilibrium moisture content was quite low and the highest EMC was observed for *Enhydra fluctuans* i.e., 2% in case of microwave drying (Table 4). This indicates that microwave drying is the fastest method for drying herbs to achieve a desired moisture content. For consistent results (sensory quality, bioactivity etc.) of an infused beverage, soup, sprinkle, medicinal decoction etc. herbs are often used in a powdered form where its soluble components get extracted in the (aqueous) solvent. Both qualitative and quantitative extraction of the molecules depends on particle size as well as its porosity of the dried herbal powders. Specific drying technique i.e., moisture removal mechanism, temperature of drying and rate of moisture removal of the herbal product controls not only the composition of the molecues (degradation or derivatization of the small compounds) but also their milled powder characteristics (particle size and porosity). From the sieve analysis of the powders obtained from four different plant

Table 5
Particle size distribution of herbal powders

Sample Name	Average particle size (µm) (2000-63)			Average particle size (µm) (250 – 63)		
	TD (50°C)	MW (720W)	FD (-40°C)	TD (50°C)	MW (720W)	FD (-40°C)
CA	716.48 ± 6.48	663.76 ± 2.52	735.02 ± 0.39	305.33 ± 0.89	276.89 ± 0.53	287.17 ± 0.79
ENF	707.65 ± 13.58	676.25 ± 0.97	688.34 ± 0.17	309.60 ± 4.28	302.09 ± 0.59	295.19 ± 0.87
EGF	641.77 ± 16.59	660.17 ± 2.74	694.13 ± 1.76	295.22 ± 5.99	294.51 ± 1.13	301.43 ± 1.13
MN	614.25 ± 5.80	633.16 ± 5.95	661.41 ± 2.01	292.11 ± 1.66	292.09 ± 3.21	304.33 ± 0.04

CA: *Centella asiatica*; EGF: *Eryngium foetidum*; ENF: *Enhydra fluctuans*; MN: *Marsilea minuta*; TD: Convective tray dried; MW: Microwave dried; FD: Freeze dried; Results were expressed as mean ± standard error of triplicate runs.

leaves dried with three different types of drying methods but milled under same conditions showed that the particle size distribution was not greatly influenced by the method of drying but varied with the type of the plant material (Table 5).

Table 6
Comparative study of different methods of drying

Sample Name	TD (50°C)			MW (720W)			FD (-40°C)		
	Bulk Density (kg/m^3)	Tapped Density (kg/m^3)	Apparent Porosity (%)	Bulk Density (kg/m^3)	Tapped Density (kg/m^3)	Apparent Porosity (%)	Bulk Density (kg/m^3)	Tapped Density (kg/m^3)	Apparent Porosity (%)
CA	125.00 ± 00	163.33 ± 3.33	18.00 ± 2.00	236.89 ± 7.01	283.70 ± 2.01	34.04 ± 0.24	217.49 ± 4.73	246.95 ± 3.05	29.63 ± 0.37
ENF	270.47 ± 7.31	313.73 ± 19.61	25.10 ± 1.57	272.73 ± 12.99	312.50 ± 0.00	34.38 ± 3.12	226.0 ± 1.28	266.71 ± 3.56	23.97 ± 2.35
EGF	200.08 ± 4.00	227.74 ± 10.35	24.95 ± 1.14	215.08 ± 2.31	253.21 ± 3.21	32.88 ± 2.12	221.0 ± 1.22	241.0 ± 2.90	26.54 ± 2.73
MN	233.99 ± 4.11	285.95 ± 8.17	22.88 ± 0.65	289.92 ± 4.20	305.36 ± 2.33	30.54 ± 0.23	241.28 ± 8.72	283.82 ± 6.04	22.71 ± 0.48

CA: *Centella asiatica*; EGF: *Eryngium foetidum*; ENF: *Enhydra fluctuans*; MN: *Marsilea minuta*; TD: Convective tray dried; MW: Microwave dried; FD: Freeze dried; Results were expressed as mean ± standard error of triplicate runs.

Usually with decreasing moisture content, there should be a decrease in bulk density as well as the tap density of the dried powder but we could observe the density values varied according to the method of drying and not just the moisture content [28, 29]. Among all the dried materials, the highest bulk density powder was of *Marsilea minuta* (289.9 kg/m^3) when dried in the microwave oven (Table 6). However, the lowest bulk density powder could be seen for *Centella asiatica* (125.0 kg/m^3) when dried with convective drying at 50ºC. Also the apparent porosity i.e., the ratio of tapped density to true density of the dried powder from microwave was higher than that of freeze drying and lowest in low temperature convective drying (50ºC). Generally, tapped density is more for regular shaped particles like sphere cubes etc., than irregular shaped particles like needle shaped or fibrous one. In the present study, the tapped density does not follow a specific trend and the lowest and highest tap densities were found to be for *Centella asiatica* and *Enhydra fluctuans.* Owing to the difference in their tissue structure they gave rise to particles of different shapes as well as pore pattern. Also the structural components like lignin, cellulose, hemicellulose and pectin can vary greatly for CA, EGF, ENF, and MN which control the true density of the leaf powder particle specifically in dried form. Since lignin and cellulose have less affinity to moisture than hemicellulose and pectin which influence the drying behaviour greatly. Such difference in composition reflects in the particle size. For all four plants depending on the method of drying, 30–50% of the powdered samples are in the range of 250 µm to 106 µm. Etti et al.[30] and Fitzpatrick et al.[31] reported that all the pure herbal powders with particle sizes below 100 µm made them cohesive. Hence, the tiny particles will form interparticular binding to make their flow difficult [32]. Since particle size distribution and porosity dictates its functional properties; adsorption-desorption behaviour, extractability of solubles from the particles, enzymatic digestion, shelf-life, compaction and flowability etc. microwave drying can be used as a better method than low temperature convective drying or even freeze drying to obtain dried powder with better porosity and smaller particle size.

3.3. Effect of three different drying on extractability of alcohol soluble components and antioxidant activity of the resultant extract

In terms of better retention of bioactive compounds in a herb, freeze-drying is generally considered as the most reliable method for drying for their processing and analysis. In this study, we wanted to confirm two possibilities;

whether the drying method can influence the matrix structure and therefore total extractability of a specific soluble (e.g., methanol) fraction in terms of TSS and any specific functional property like antioxidant activity of the millieu of molecules in the extract. The TSS of the four-leaf samples listed in the Fig. 3a were dried in three different drying methods. For extraction, methanol was used since most primary and secondary metabolites are soluble in methanol and it has good penetration into the cells. All the four leaves dried using microwave and freeze dryer had a 10–20% higher amount of TSS compared to convective tray dried sample at 50ºC. However, there is no significant difference found between freeze-dried and microwave dried samples of EGF, ENF and MN. In CA, we have found 18% higher TSS than freeze-dried samples. Nevertheless, the comparable amount of TSS of the microwave with freeze-dried showed that the drying method did not alter the porous matrix of the herbs. Singh et al.[33] also reported that microwave (0.03–0.78) and freeze (0.03–0.88) dried samples have more or less the same porosity for potato, whereas in the case of convective drying, it is in the narrow range of 0.03 to 0.20. Apart from TSS, the so-called total phenolic content in terms of gallic acid equivalent of methanolic extract was similar in both microwave and freeze drying, on the other hand, low temperature convective dried samples had 25–45% lesser TPC values (Fig. 3b). The total flavonoid content of the methanolic extracts from different dried samples of the four plants followed almost same pattern as TPC (Fig. 3c). However, the antioxidant capacity in terms of Fe^{3+} reduction (IRP), free radical scavenging (ARSA) and lipid peroxidation inhibition (LPOX) out of the four herbs, CA and ENF are in the same order and showed high antioxidant potential (Fig. 3d-3f) whereas other two plants had significantly lesser antioxidant potential. Therefore, particular antioxidant capacity (e.g., Fe^{3+} reduction or free radical scavenging capacity) of the plants were dependent on both the herb variety and the methods of drying. Potisate et al.[34] reported that approximately 43–62% increase in quercetin and kaempferol levels in the *M. oleifera* leaves after drying in a freeze dryer(-85ºC) as well as in microwave (150, 450, 900W) compared to dried in a convective dryer at 50ºC, also a reduction in phytochemicals was observed at 60ºC in convective tray dryer since multiple reaction can take place at that high temperature. Similarly, Max industrial microwave did a comparative study on *M. oleifera* leaves and reported an increase in both micronutrients and macronutrients on microwaving. There is an increase in sulphur (0.72%), iron (16.5%), copper (14.7%), manganese (10.2%), vitamin C (46.7%), vitamin E (33.02%), vitamin B2 (47.9%) and folate (14.3%) compared to convective tray dryer at 40ºC whereas, there is a minimum decrease in phosphorus (5%), potassium (7%), calcium (6.7%), zinc (1.6%) and vitamin A (6.6%) content. Such findings support that not only both microwave and freeze drying is superior than low temperature convective drying but also quality of microwave dried leaves is closer to freeze dried w.r.t. extractability and antioxidant properties of the herbs.

3.4. Effect of drying on polyphenol oxidase

To strengthen the conclusion of section 3.3 that microwave and freeze-dried herbs had similar TPC and TFC and both values were higher than convective dried condition, we assayed the native polyphenol oxidase assay for all four leaves. Figure 4 shows that out of four types of drying, microwave dried samples lost the PPO enzymatic activity similar to that of 105ºC whereas in all four leaves the PPO could survive in significant amount in both freeze-drying and low temperature convective drying at 50ºC. This supports the fact that at a low temperature drying there is enough PPO enzymatic activity that for the long period of drying the oxidative enzyme might degrade some of the phenolic compounds present in the leaves. However, it is important to know the magnitude of oxidase enzymes activity and how it would affect the degradation of phenolics within the leaves.

Because during freeze drying the PPOs might not react in sub-zero condition (-40ºC) even if high residual PPO activity is traced in the dried product. Depending on the variety, the activity level varied between the drying methods. For example, EGF showed more PPO activity in freeze dried samples but ENF showed more activity in 50ºC dried sample. According to Loh et al.[35] as polyphenol oxidase activity increased, the percentage loss in TPC also

increased; however, there was no obvious trend observed for the peroxidase enzyme. Reports also stated that enzymatic activities generally decreases with decreasing water activity [36]. It was observed that all the dried leaves (a_w between 0.1–0.3) have low water activity (Table SI3). Lin et al.[37] reported that the release of active oxidative enzymes (PPO and POD) could cause enzymatic degradation and therefore reduce the number of extractable phenolics when leaf tissues were damaged. As PPO enzymes are involved in the production of quinones from monophenols and diphenols, it is logical to expect that high PPO activity would degrade more phenolics in the plant leaf samples [35]. Moreover most plant tissues contain isoenzymes of PPOs with different substrate affinity and thermal stablity. This is probably the reason in different drying condition specific polyophenols may be present or absent. Microwave dried leaves of *Catharanthus roseus, Backhousia citriodora, G. pseudochina, M. communis* contained higher concentration of gallic acid, caffeic acid, rutin, myricetin 3-o-rhamnoside, quercetin 3-o-glucoside, quercetin 3-o-rhamnoside, myricetin, quercetin, kaempferol, and chlorogenic acid [38–41]. Therefore, further investigation of polyphenol distribution under different drying conditions will provide valuable insights into the impact of processing methods on the phytochemical composition of the herbs.

3.5. Effect of drying on polyphenols of selected four herbs using HPLC

The signature chromatogram profiles of the extracts from CA, EGF, ENF and MN leaves dried with freeze-drying and microwave and convective drying processes are shown in Table SI4 (a) – SI4 (d). The normalized HPLC chromatogram confirmed that the freeze-dried and the microwave dried samples contained higher amounts of phenolics than those in the convective dried samples and for most compounds (identified as well as unidentified peaks) the general order of concentration in all four herbs was freeze drying > microwave drying > low temperature convective drying. Moreover, there was an increased concentration of chlorogenic acid, rutin, ethyl protocatechuate, naringin, and myricetin

recorded in the microwave, as well as freeze-dried CA leaves over convective drying. Whereas apigenin was not identified in microwave dried sample of CA but its concentration was much higher in freeze-dried sample than the convective dried one. Others have also reported superiority of microwave and freeze drying for polyphenol extraction/retention in several plant materials [42–44]. Apart from altering leaf powder, particle microstructure and PPO enzyme inactivation, microwave drying can cause releasing of free phenolic compounds from the bound phenolic compounds [45–47]. For example, caffeic acid one of the intermediate in lignification can exist as caffeoyl shikimic acid, caffeic aldehyde, and caffeoyl alcohol which may not be the extractable. These compounds can be transformed during microwave heating and become extractable [43, 47, 48]. In this study, both freeze-drying and microwave drying could retain more phenolic compounds from the CA, ENF, EGF, and MN. Also, similarity analysis with Pearson correlation coefficient and Euclidian distance of the four plants showed that microwave dried samples are close to freeze dried samples (Table 7).

Table 7
Similarity indices of the three types of drying on HPLC spectra of four types of herbal plants

Name Sample	Similarity marker	TD (50°C)_MW (720W)		MW (720W)_FD(-40°C)		TD (50°C)_FD(-40°C)	
		Pearson correlation coefficient	Euclidean distance	Pearson correlation coefficient	Euclidean distance	Pearson correlation coefficient	Euclidean distance
CA	Area (mAU*s)	0.05	1224.0	0.97	241.2	0.07	1181.9
	Height (mAU)	0.11	162.2	0.98	29.1	0.09	149.8
ENF	Area (mAU*s)	0.44	2772.5	0.87	1919.5	0.14	4091.9
	Height (mAU)	0.51	181.1	0.79	156.1	0.14	278.2
EGF	Area (mAU*s)	-0.17	1929.0	0.84	906.7	-0.09	1433.9
	Height (mAU)	-0.16	113.0	0.74	63.0	-0.12	100.9
MN	Area (mAU*s)	0.15	577.8	0.92	304.8	0.03	781.8
	Height (mAU)	0.01	111.7	0.92	52.2	-0.12	146.6

CA: *Centella asiatica*; EGF: *Eryngium foetidum*; ENF: *Enhydra fluctuans*; MN: *Marsilea minuta*; TD: Convective tray dried; MW: Microwave dried; FD: Freeze dried

Nevertheless, according to the area under the curve and height of the HPLC chromatogram for both identified and unidentified compounds, it was observed that most of the compounds present in the samples are increasing due to microwave drying. Therefore, microwave drying can be a fast-drying method for isolating a good amount of bioactive compounds from these selected plant species.

3.6. Chemical profiling of one of the selected herbs for similarity of drying process

LC-MS analysis was performed for three different drying methods to identify phenolic compounds present in *Centella asiatica* methanolic extracts. A total of 31 compounds were identified in any of the three dried extracts, which belonged to 9 different classes: caffeoylquinic acids, hydrocinnamic acid, tannins, flavonoids, terpenoids, stilbene, and fatty acids (refer to Table 8). The results showed that 19% of these compounds were present in all three types of drying. When compared to freeze-dried, the convective-dried sample shared 27% common compounds, while microwave-dried samples showed 46% common compounds in *Centella asiatica* extract. Furthermore, microwave-dried samples had 38% compounds in common to convective-dried samples. All the identified compounds had been previously reported in different *Centella asiatica* extracts. For instance, the study identified five phenolic acids known as caffeoylquinic acids (CQAs), which had been previously reported in *Centella asiatica* by Long et al.[49]. In addition to phenolics, the flavonoid naringin was detected in all three drying methods, whereas luteolin-7-glucuronide and quercetin were only found in convective drying and microwave drying. A significant group of compounds, including madecassoside, oleuropein, asiaticoside, and madecassic acid, were detected in all three drying processes. However,

compounds such as 3,5-di-o-caffeoylquinic acid, piceatannol, p-coumaric acid, ferulic acid derivative, chlorogenic acid, and 3,4-dicaffeoylquinic acid were exclusively found in microwave-dried and freeze-dried *Centella asiatica* extracts. Moreover, tannins like trigalloylquinic acid were detected in all three drying methods. It is important to note that this untargeted metabolomics approach only represents a small fraction of the metabolome, and a collection of chromatographic methods is

Table 8
Chemical profiling of Centella asiatica methanolic extracts

Sl. No.	Rt (min)	Parent ion (m/z)	MS/MS fragments	Tentative identity of compound	TD (50°C)	MW (720W)	FD (-40°C)	Compound Class
1.	2.46	343	153, 201	Piceatannol	×	✓	✓	Stilbene
2.	2.68	632	128, 341, 539, 632	Oleuropein	✓	✓	✓	Terpenoids
3.	21.76	1033	546, 740, 973	Madecassoside	✓	✓	✓	
4.	22.79	1017	179, 538.3, 740, 957	Asiaticoside	✓	✓	✓	
5.	24.80	713.2	134, 375.2, 585.1	Asiatic acid	✓	✓	×	
6.	27.79	-	503	Madecassic acid	✓	✓	✓	
7.	3.79	180.1	130.2	Caffeic acid	×	✓	×	Hydrocinnamic acid
8.	7.32	-	164.2	P-coumaric acid	×	✓	✓	
9.	28.56	-	143, 293	Cinnamoyl-glucose	✓	×	×	
10.	22.05	1018	193.1, 538.6, 887	Ferulic acid derivative	×	✓	✓	
11.	12.67	-	113, 203.2	Chlorogenic acid	×	✓	✓	Caffeoylquinic Acids
12.	13.36	707	191, 353, 467, 707	1,5-Di-O-Caffeoylquinic acid	×	×	✓	
13.	16.95	515	335, 191.1, 161	3, 4-Dicaffeoylquinic acid	×	✓	✓	
14.	23.94	1060	113, 375.4, 565.5, 740.8, 1000	Neochlorogenic acid	×	✓	×	
15.	18.29	1031.7	161.1, 353, 515.4, 615.4	3, 5-Di-o-caffeoylquinic acid	×	✓	✓	
16.	18.60	-	285, 461.1	Luteolin-7-glucoronide	✓	✓	×	Flavonoids
17.	19.60	565.5	489.3, 511.4, 565.3	Naringin	✓	✓	✓	
18.	21.36	737.6	713, 723	Quercetin derivative	✓	✓	×	
19.	16.07	601	161, 233	Eriodictyol 7-(6-galloylglucoside)	×	×	✓	
20.	20.20	587	187, 429, 489	Catechin derivative 1	✓	×	×	

Sl. No.	Rt (min)	Parent ion (m/z)	MS/MS fragments	Tentative identity of compound	TD (50ºC)	MW (720W)	FD (-40ºC)	Compound Class
21.	20.77	713	333.1, 429, 489	Catechin derivative 2	✓	×	×	
22.	25.73	-	285.1	Kaempferol	✓	×	×	
23.	36.97	-	277.2	Myricetin	✓	×	✓	
24.	33.04	-	281	Linoleic acid	×	×	✓	Fatty acid
25.	33.74	837.6	279.2	Linolelaidic acid	✓	×	×	
26.	34.13	695	205, 249.2, 389, 452, 695	Palmitic acid	✓	×	✓	
27.	33.07	737	105, 213, 273, 391, 487	Pelargonidin isomer	✓	✓	×	Anthocyanidin
29.	18.08	613	161, 353, 477, 515, 613	Trigalloylquinic acid	✓	✓	✓	Tannins
30.	25.30	-	127	Pyrogallol	×	×	✓	Other polyphenols
31.	35.09	815	-	Unknown	×	×	✓	
Rt: Retention time; TD: Convective tray dried (50ºC), MW: Microwave dried (720W); FD: Freeze dried (-40ºC)								

necessary for a comprehensive understanding of the global metabolome.

The results also indicated the preferential distribution of certain compounds in convective-dried, microwave-dried and freeze-dried *Centella asiatica* methanolic extracts.

4. Conclusion

To convert the herbs into food products and also to assay different bioactives, microwave drying was found to be an effective drying process. For leaf kind of product, microwave drying was equivalent to 105ºC oven drying for moisture content determination (loss on drying type) as well as quantifying phenolics. Also, this study revealed that low temperature convective drying may have significant variation among samples apart from having longer analysis time. The TPC and TFC content of the four herbs followed the following order ENF > CA > MN > EGF. The trend for *in vitro* antioxidant properties was also similar except for CA which showed the highest reducing power, capacity to scavenge free radical and lipid peroxidation inhibition. This study also revealed depending on the type of herb, selective extraction can happen when the drying process is switched from convective to microwave or freeze dried. Since microwave drying is a non-isothermal drying unlike convective drying or specifically conventional tray drying (say 50°C) the herbs can experience the different extent of damage to tissue structure, PPO inactivation and solubilization of complex polyphenols depending on the heating history, which in turn can decide the composition of the biomolecules in the solvent extract from the dried herb. While performing microwave drying, the parameters of the sample e.g., size, examination of dielectric parameters and their temperature dependence, penetration depth, the temperature distribution inside the sample, etc. and parameters of the equipment, e.g., power rating of all microwave components, applicator suitable for the intended process, pulse or, forward power, reflected power, single or multimode applicator, temperature control, safety, etc. Therefore, it is important to choose an optimal microwave

power for each herb to retain its bioactives and dry it to a desired quality like sensory property, water activity, millability etc.

Abbreviations

AA: Ascorbic Acid

ABTS: 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)

AOAC: Association of Official Analytical Collaboration

AOCS: American Oil Chemists' Society

ARSA: ABTS radical scavenging activity LPOX: Lipid peroxidation inhibition

a_w: Water Activity

BDM: Bone Dry Mass

CA: *Centella asiatica*

CAGR: Compound Annual Growth Rate

CQA: Caffeoylquinic Acid

d.b.: dry basis

D_{eff}: Effective moisture diffusivity

dw: Dry weight

EGF: *Eryngium foetidum*

EMC: Equilibrium Moisture Content

ENF: *Enhydra fluctuans*

ESI: Electrospray Ionization

FAO: Food and Agricultural Organization

FD: Freeze dried

FSSAI: Food Safety and Standards Authority of India

GAE: Gallic Acid

HPLC: High-performance liquid chromatography

IQR: Interquartile range

IR: Infrared

IRP: Iron Reducing Power

ISO: International Organization for Standardization

LC-MS: Liquid chromatography–mass spectrometry

LOD: Loss on Drying

MC: Moisture content

MDA: Malondialdehyde

MN: *Marsilea minuta*

M_R: Moisture Ratio

MW: Microwave dried

OD: Oven dried

OECD: Organization for Economic Co-operation and Development

POD: Peroxidase

PPO: Polyphenol oxidase

PVP: Polyvinylpyrrolidone

QE: Quercetin

SE: Standard Error

TBA: Thiobarbituric Acid

TCA: Trichloroacetic Acid

TD: Convective Tray dried

TE: Trolox

TFC: Total Flavonoid content

TPC: Total Phenolic Content

TSS: Total Soluble Solids

USD: United States dollar

WHO: World Health Organization

Declarations

Supporting Information

Supplementary information is enclosed.

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Author Contribution

Esha Bala: Experimentation, Formal analysis, Data curation, Methodology, Conceptualization, Investigation, Validation, Formal analysis, Writing – original draft. **Saurav Dey:** Data curation, LC-MS Methodology. **Sanjukta Patra:** Supervision, Validation, Formal analysis, Writing – review & editing. **Siddhartha Singha:** Supervision, Conceptualization, Formal analysis, Visualization, Validation, Methodology, Resources, Formal analysis, Writing – review & editing.

Data Availability

Data will be available as per request.

Declaration of Competing Interest

The authors have no competing interests to declare that are relevant to the content of this article.

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Figures

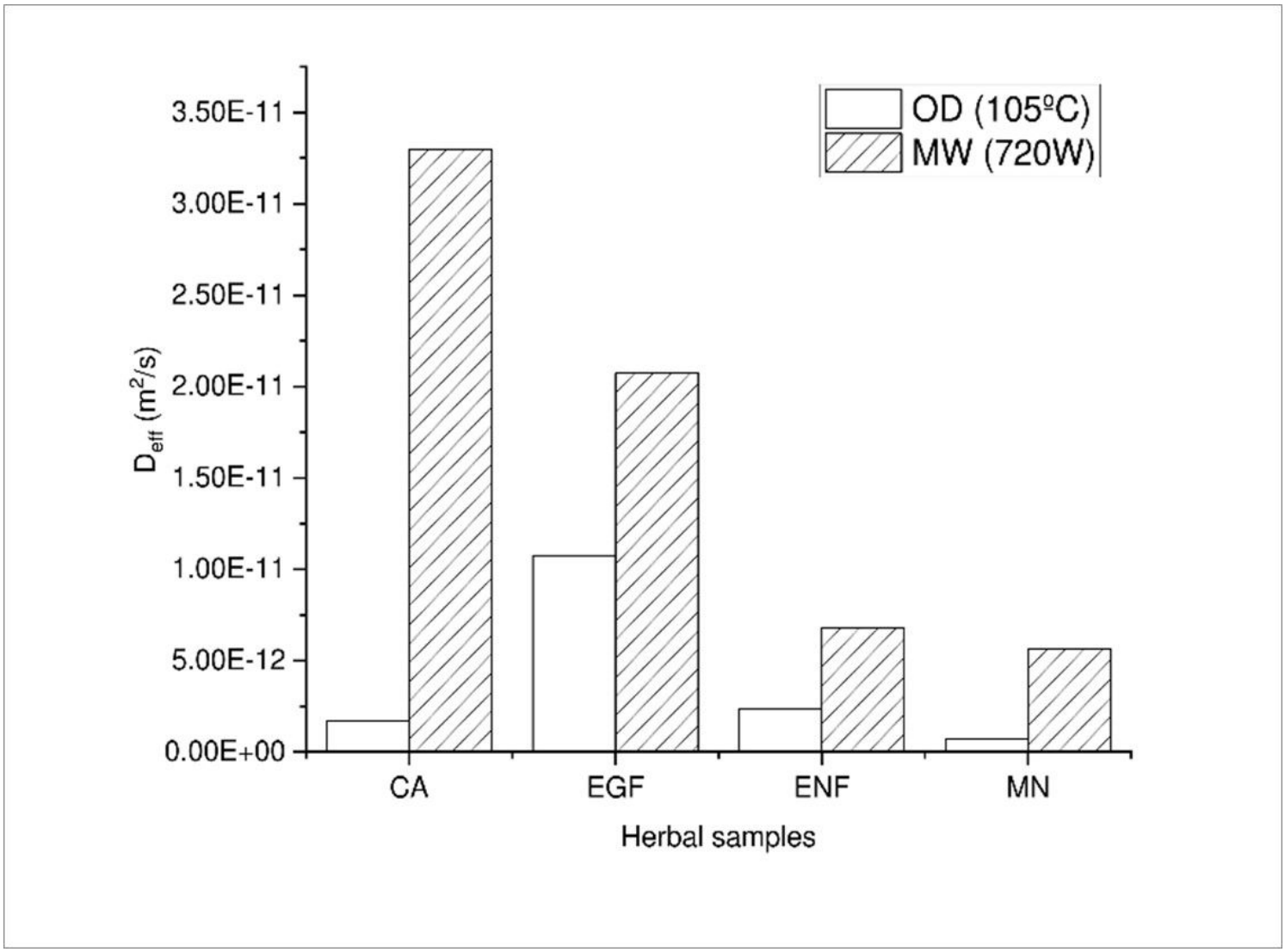

Figure 1

Moisture diffusivity of four herbs under microwave drying (720W) and hot air drying (105°C)

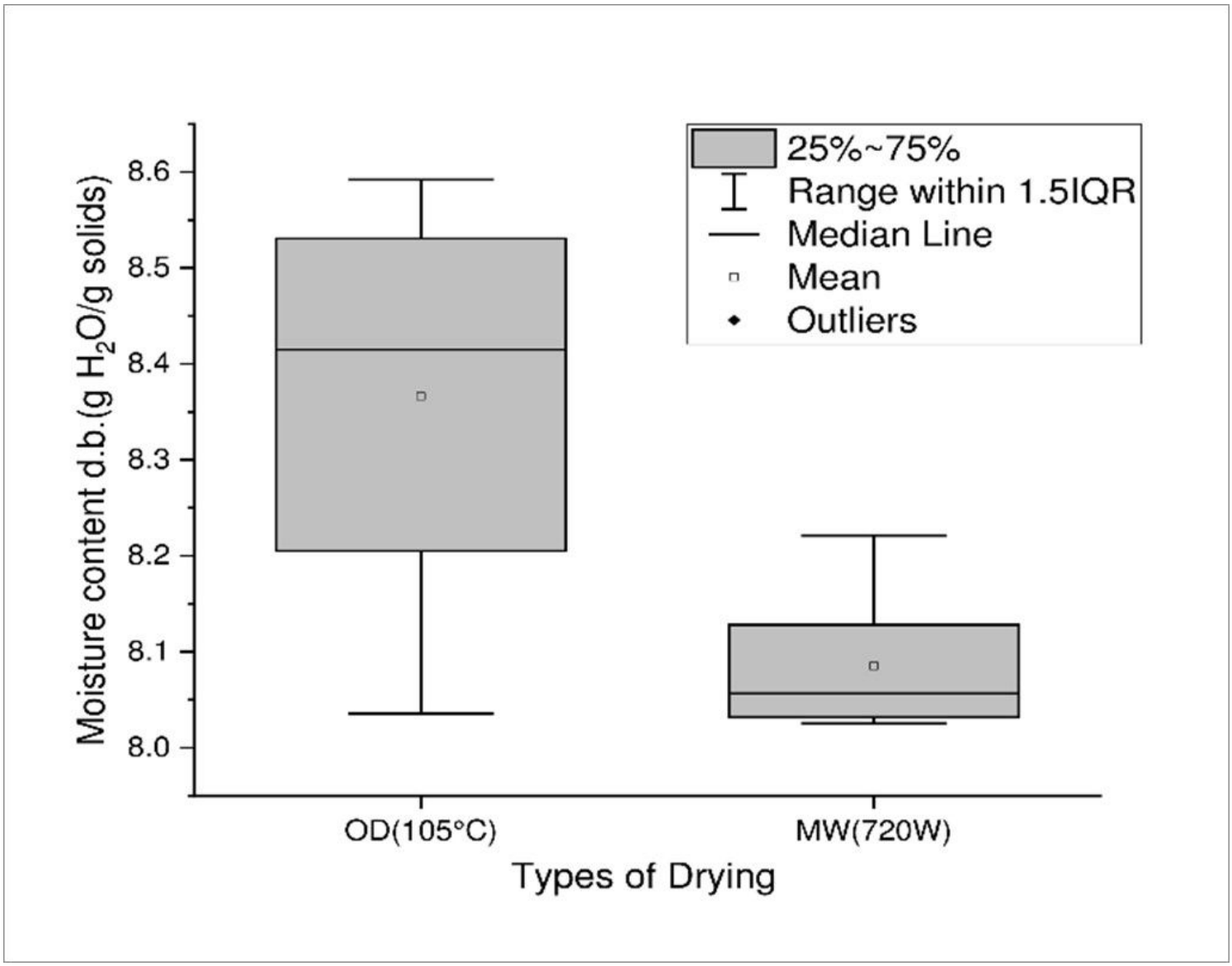

Figure 2

Dispersion of the moisture content of 105ºC and microwave drying with a Box-whisker plot.

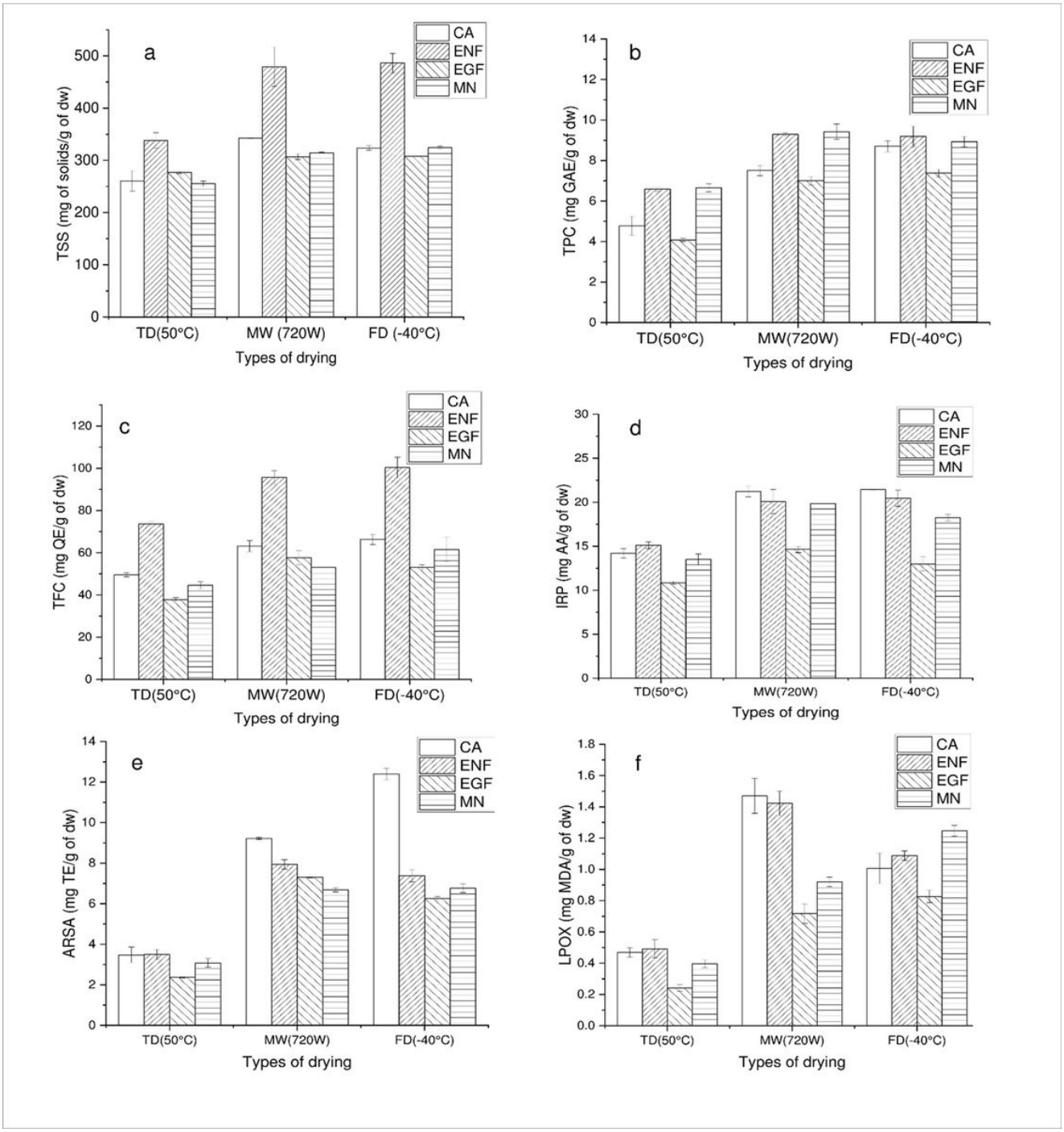

Figure 3

Effect of three different types of drying on extractability of alcohol soluble components and its antioxidant activity. (a) Total soluble solids (TSS); (b) Total phenolic content (TPC); (c) Total flavonoid content (TFC); (d) Iron reducing power (IRP); (e) ABTS radical scavenging activity (ARSA); (f) Lipid peroxidation inhibition (LPOX). Results were expressed as mean ± standard error of triplicate runs

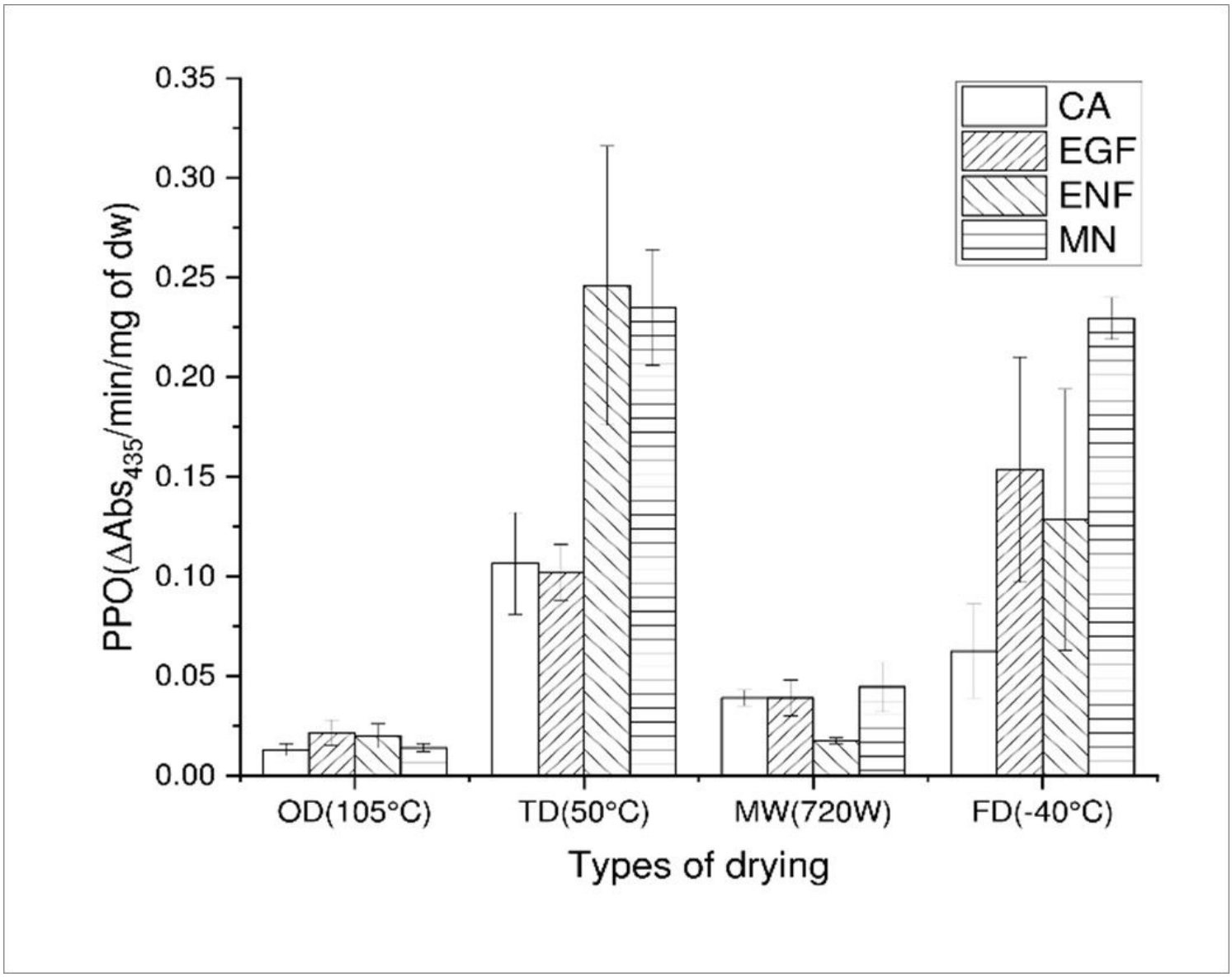

Figure 4

Polyphenol oxidase activity (ΔA435/min/g of dry powder) of different dried samples

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