



HAL
open science

Solvent-free microwave extraction of essential oil from aromatic herbs: From laboratory to pilot and industrial scale

Aurore Filly, Xavier Fernandez, Matteo Minuti, Francesco Visinoni, Giancarlo Cravotto, Farid Chemat

► To cite this version:

Aurore Filly, Xavier Fernandez, Matteo Minuti, Francesco Visinoni, Giancarlo Cravotto, et al.. Solvent-free microwave extraction of essential oil from aromatic herbs: From laboratory to pilot and industrial scale. *Food Chemistry*, 2014, 150, pp.193-198. 10.1016/j.foodchem.2013.10.139 . hal-02637346

HAL Id: hal-02637346

<https://hal.inrae.fr/hal-02637346v1>

Submitted on 27 May 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Solvent-free microwave extraction of essential oil from aromatic herbs: From laboratory to pilot and industrial scale

Aurore Filly^a, Xavier Fernandez^b, Matteo Minuti^c, Francesco Visinoni^c, Giancarlo Cravotto^d, Farid Chemat^{a,*}

^a Université d'Avignon et des pays du Vaucluse, INRA, UMR408, GREEN Extraction Team, F-84000 Avignon, France

^b Université de Nice Sophia Antipolis, UMR 7272 CNRS, Institut de Chimie de Nice, Parc Valrose, 06108 Nice, France

^c Milestone srl, Via Fatebenefratelli 1/5, I-26010 Sorisole, Bergamo, Italy

^d Dipartimento di Scienza e Tecnologia del Farmaco, Università di Torino, Via P. Giuria 9, 10125 Torino, Italy

A B S T R A C T

Solvent-free microwave extraction (SFME) has been proposed as a green method for the extraction of essential oil from aromatic herbs that are extensively used in the food industry. This technique is a combination of microwave heating and dry distillation performed at atmospheric pressure without any added solvent or water. The isolation and concentration of volatile compounds is performed in a single stage. In this work, SFME and a conventional technique, hydro-distillation HD (Clevenger apparatus), are used for the extraction of essential oil from rosemary (*Rosmarinus officinalis* L.) and are compared. This preliminary laboratory study shows that essential oils extracted by SFME in 30 min were quantitatively (yield and kinetics profile) and qualitatively (aromatic profile) similar to those obtained using conventional hydro-distillation in 2 h. Experiments performed in a 75 L pilot microwave reactor prove the feasibility of SFME up scaling and potential industrial applications.

Keywords:

Green extraction
Solvent-free microwave extraction
Scaling-up
Essential oil
Rosemary
Pilot scale

1. Introduction

Solvent-free microwave extraction (SFME) was developed in 2004 by Chemat et al. Lucchesie Chemat Smadja (2004a), (2004b). Based on a relatively simple principle, this process consists of the microwave-assisted dry distillation of a fresh plant matrix without adding water or any organic solvent. SFME is neither a modified microwave-assisted extraction (MAE) which uses organic solvents, nor a modified hydro-distillation (HD) which use a large quantity of water (Fig. 1). The selective heating of the *in situ* water content of plant material causes tissues to swell and makes the glands and oleiferous receptacles burst. This process thus frees essential oil, which is evaporated by azeotropic distillation with the water present in the plant material (Li et al., 2013). The water excess can be refluxed to the extraction vessel to restore the original water to the plant material. This process has been applied to several kinds of fresh and dry plants, such as spices (ajowan, cumin and star anise), aromatic herbs (basil, mint and thyme) and citrus fruits. Table 1 summarises the most important essential oils that have been extracted by SFME.

More efficient SFME can be attained on samples that show higher dielectric loss (high water content), because of the strong interaction that microwaves have with the, salt and nutrient containing, physiological water. Thus, the matrix undergoes dramatic swelling and subsequent tissue rupture, enabling the essential oil to flow towards the water layer. This mechanism (I) is also based on the ability of essential oil components to dissolve in water. In fact, solubilisation is the limiting step and solubility becomes the essential parameter in SFME selective extraction. Essential oils contain organic compounds that strongly absorb microwave energy (mechanism II). Compounds with high and low dipolar moments can be extracted in various proportions by microwave extraction. Organic compounds that have a high dipolar moment will interact more vigorously with microwaves and can be extracted more easily in contrast with aromatic compounds which have low dipolar moments.

The purpose of the present study is to optimise the SFME recovery of essential oil from rosemary on a laboratory scale and apply the same conditions to a pilot scale.

Comparisons have been made between SFME (on laboratory and pilot scales) and conventional HD as well as in terms of extraction time, yield, chemical composition and quality of essential oil that environmentally friendly.

* Corresponding author. Tel.: +33 0490144465.

E-mail address: Farid.Chemat@univ-avignon.fr (F. Chemat).

Table 1
most important products extracted by SFME.

Common name	Scientific name	SFME operating conditions	Refs.
Orange	<i>Citrus sinensis</i> L.	T = 30 min, m = 200 g, P(atm) = 200 W	Ferhat, Meklati, Smadja, and Chemat (2006)
Marjoram	<i>Origanum vulgare</i> L.	T = 35 min, m = 150 g soaked in water during 1 h, P(atm) = 500 W	Bayramoglu, Sahin, and Sumnu (2008)
Laurel	<i>Laurus nobilis</i> L.	T = 85 min, m = 150 g soaked in water during 1 h, P(atm) = 622 W	Bayramoglu, Sahin, and Sumnu (2009)
Orange	<i>Citrus sinensis</i> L.	T = 10 min, m = 200 g, P(atm) = 200 W	Ferhat, Meklati, Visinoni, Abert Vian, and Chemat (2008)
Lemon	<i>Citrus limon</i> L.	T = 30 min, m = 200 g, P(atm) = 200 W	Ferhat, Meklati, and Chemat (2007)
Basil	<i>Ocimum basilicum</i> L.	T = 30 min, m = 250 g, P(atm) = 500 W	Lucchesie et al. (2004a), (2004b)
Mint	<i>Mentha crispa</i> L.	T = 30 min, m = 250 g, P(atm) = 500 W	
Thyme	<i>Thymus vulgaris</i> L.	T = 30 min, m = 250 g, P(atm) = 500 W	
Caraway	<i>Carum ajowan</i> L.	T = 60 min, m = 250 g soaked in water during 1 h, P(atm) = 500 W	Lucchesie et al. (2004a), (2004b)
Cumin	<i>Cuminum cyminum</i> L.	T = 60 min, m = 250 g soaked in water during 1 h, P(atm) = 500 W	
Anise or star anise	<i>Illicium verum</i>	T = 60 min, m = 250 g soaked in water during 1 h, P(atm) = 500 W	
Cardamom	<i>Elletaria cardamomum</i> L.	T = 75 min, m = 100 g soaked in water, P(atm) = 390 W	Lucchesie, Smadja, Bradshaw, Louw, and Chemat (2007)
Rosemary	<i>Rosmarinus officinalis</i> L.	T = 40 min, m = 250 g, P(atm) = 500 W	Okoh, Sadimenko, and Afolayan (2010)
Rosemary	<i>Rosmarinus officinalis</i> L.	T = 30 min, m = 200 g, P(atm) = 200 W	Tigrine-Kordjani, Meklati, and Chemat (2006)
Laurel	<i>Laurus nobilis</i> L.	T = 50 min, m = 140 g soaked in water during 1 h, P(atm) = 85 W	Uysal, Sozmen, and Buyuktas (2010)
Lemon balm	<i>Melissa officinalis</i> L.	T = 50 min, m = 280 g soaked in water, P(atm) = 85 W	

2. Experimental

2.1. Plant material

Fresh rosemary plants (*Rosmarinus officinalis*) were purchased from Midiflore (Aromatic plant, Hyeres, France). They were composed of stems, leaves and flowers. Only fresh plant material was used in all of the extractions. The initial moisture of this rosemary was 70%. In fact the dry mass ratio (DMR) was determined through the use of a moisture analyser (OHAUS MB35). 5 g of sample were heated 45 min at 110 °C to obtain the mass stability. This method gives us the water content of the sample.

DMR = 100 – moisture percent of sample

2.2. Laboratory SFME apparatus and procedure

SFME was performed in a laboratory microwave oven (NEOS, Milestone, Italy). This is a 2.45 GHz multimode microwave reactor with a maximum power of 900 W delivered in 10 W increments. During experiments, time, temperature, pressure and power were controlled by the software. The experimental SFME variables were optimised in order to maximise the essential oil yield. In a typical SFME procedure performed at atmospheric pressure, 150 g of fresh plant material was heated using a fixed power of 150 W without adding any solvent or water. Essential oil and aromatic water was simply separated by decantation. The essential oil was collected, dried under anhydrous sodium sulphate and stored at 4 °C until subsequent analysis.

2.3. Hydro-distillation apparatus and procedure

One kilogram of fresh rosemary was submitted to hydrodistillation using Clevenger-type apparatus, (Clevenger, 1928) according to the European Pharmacopoeia, and extracted with 7 L of water for 2 h (until no more essential oil was obtained). The essential oil was collected, dried under anhydrous sodium sulphate and stored at 4 °C until used.

2.4. Pilot scale SFME apparatus and procedure

The MAC-75 apparatus is a multimode microwave reactor. It contains 4 magnetrons (4 × 1500 W, 2450 MHz) with a maximum power of 6000 W delivered in 500 W increments. The stainless steel microwave cavity has a capacity of 150 L and contains a removable, rotating PTFE drum that allows up to 75 L of plant material to be loaded. The rotation ensures a homogeneous

microwave distribution to the material inside the drum. The drum circumference is entirely perforated to allow the vapour and liquid to pass. The cavity has 6 external tube connections (one in the top, one in the bottom and 4 in the sides) and is wrapped in removable thermal insulation. The absorption of microwave power is controlled by sensors placed on wave guides. The system automatically adjusts the power delivered if absorption is too low. The temperature is monitored by a Resistance Temperature Detector (PT-100) inserted into the cavity. The cavity is able to work in deep vacuum or as an open vessel. The functional deep vacuum is need with plant material particularly. Interlocks on the door prevent accidental opening during the process or when the cavity contains liquid. The device is controlled by an industrial touch screen control terminal with an intuitive graphic user interface.

2.5. GC and GC-MS identification

2.5.1. Gas chromatography by flame ionic detector (FID)

GC analysis was carried out using an Agilent 6850 gas chromatograph, under the following operation conditions: vector gas, Helium; injector and detector temperatures, 250 °C; injected volume, 1 l; split ration 1/100; HP1 column (J&W Scientific), polydimethylsiloxane (10 m × 1 mm i.d., film thickness × 0.4 m; constant flow 0.3 mL/min). Temperature program 60–250 °C at 4 °C/min and 250 °C for 80 min. Retention indices were determined with C₆–C₂₇ alkane standards as reference. Relative amounts of individual components are based on peak areas obtained without FID response factor correction. Three replicates were performed for each sample. The average of these three values and the standard deviation were determined for each component identified.

2.5.2. Gas chromatography-mass spectrometry analysis

GC-MS analysis was carried out using an Agilent 6890N coupled to an Agilent 5973 MS (Agilent, Massy, France). Samples were analysed on a fused-silica capillary column HP-1MS™ (polydimethylsiloxane, 50 m × 0.25 mm i.d. × film thickness 0.25 µm; Interchim, Montluçon, France) and INNOWAX (polyethyleneglycol, 50 m × 0.20 mm i.d. × film thickness 0.4 µm; Interchim, Montluçon, France). Operation conditions: carrier gas, helium; constant flow 1 mL min⁻¹; injector temperature, 250 °C; split ratio, 1:150; temperature program, 45–250 °C or 230 °C, at 2 °C/min then held isothermal (20 min) at 250 °C (apolar column) or 230 °C (polar column), ion source temperature, 230 °C; transfer line temperature, 250 °C (apolar column) or 230 °C (polar column), ionisation energy, 70 eV; electron ionisation mass spectra were acquired over the mass range 35–400 amu.



Fig. 1. Solvent free microwave extraction: from laboratory to pilot scale.

2.5.3. Identification of the components

Identification of the components was based on computer matching against commercial libraries (Wiley, MassFinder 2.1 Library, NIST98), laboratory mass spectra libraries built up from pure substances, and MS literature data (Chabard, 2011; Jalali-Heravi, Moazeni, & Sereshti, (2011) Nabil et al., 2009; Sui, Liu, MA, Zu, Zhang, & Wang, 2012; Szumny, Figiel, Gutiérrez-ortiz, Carbonell-Barrachina 2010; Tigrine-Kordjani, Meklati, & Chemat, 2012; Zaouali, Boucaine, & Boussaid, 2012) combined with a comparison of GC retention indices (RI) on a polar and polar columns. RIs were calculated with the help of a series of linear alkanes C₆–C₂₇ on apolar and polar columns (HP-1MS™ and HP-INNOWAX). Compounds available in the laboratory were confirmed by external standard compound co-injection.

3. Results and discussion

Classic hydrodistillation remains the most common essential oil extraction method both in the laboratory and on an industrial scale. The main drawbacks are the long extraction time involved and the risk of thermal degradation. A number of studies on solvent-free *in situ* microwave-generated hydrodistillation highlighted the efficiency and the wide applicability of this technique. We have recently compared the ability of traditional hydrodistillation and SFME to extract three common mint species (*Mentha spicata* L. var. *rubra*, *Mentha spicata* L. var. *viridis* and *Mentha x piperita* L.) using either fresh plant or rehydrated material (Orio et al., 2012). While the quality of the isolated oils was comparable, SFME was faster and, as such, gave reduced energy

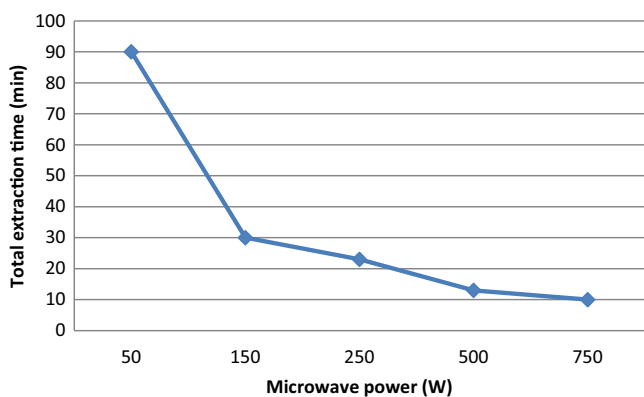


Fig. 2. Relationship between microwave irradiation power and required extraction time.

consumption and overall process cost. The differences in the oil composition obtained with this environmentally friendly technique are related to the water solubility of the components. The reduction in costs and CO₂ emissions makes the scale-up of this technique extremely appealing. This challenging task could be pursued by means of a new pilot scale SFME apparatus, a multimode microwave reactor (MAC-75) designed for this specific application.

3.1. Preliminary study: optimisation of microwave power

An appropriate microwave irradiation power setting is important in essential oil extraction as high power can degrade volatile compounds and the plant material itself (Ma et al., 2011). Thus, the relationship between time and irradiation power in SFME

was studied at 50, 150, 250, 500 and 750 W power settings (Fig 2). With the aim of assessing the power setting's influence on essential oil composition, all extracts were collected and analysed using gas-chromatography with a flame ionisation detector GC-FID and gas chromatography coupled with mass spectrometry GC-MS. A microwave irradiation power of 150 W for 150 g of fresh rosemary plant, or 1 W/g was the optimum microwave power density. Essential oil extraction was completed and the loss of volatile compounds avoided after 30 min of microwave irradiation. Extraction is performed at 100 °C and at atmospheric pressure. At 250, 500 and 750 W power settings allow shorter extraction time but degradation of more essential oil's compounds have been observed. At power settings of 250 and 500 W, there is a loss of oxygenated compounds and the smell of the essential oil is less typical of the plant; aromatic, fruity, slightly camphor. The matrix burns before essential oil is extracted at a power setting of 750 W.

3.2. Kinetics

An SFME extraction time of 30 min on the laboratory and pilot scale provides yields 0.54% and 0.50%, respectively which are comparable to HD 0.57% after 2 h. The yield is defined as the percentage of weight of essential oil extracted from the initial mass of rosemary used. Fig. 3 show the variation in extraction yield according to extraction time. Four phases are observed: step 0 represents the heating phase, ranging from room temperature to 100 °C; step 1 is represented by an increasing line which indicates the first quantities, located at the surface of vegetable particles, extracted. This is followed by a second increasing line, step 2, representing the internal diffusion of the essential oil from the middle of the particles towards the external medium caused by the internal warming of the water located in the plant cells. The last step corresponds to a horizontal line which marks the end of the extraction

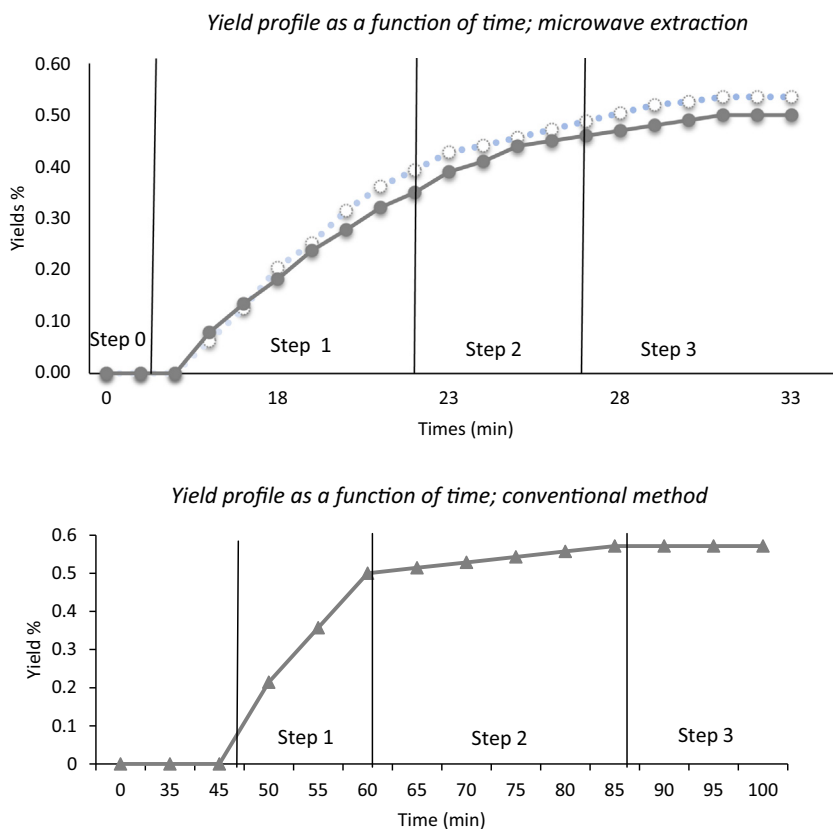


Fig. 3. Yield profile as a function of time. ○ SFME laboratory, ● SFME pilot, and ▲ conventional.

Table 2

Yields, extraction time, and chemical compositions of rosemary essential oils.

Compounds ^a	RI ^b	Hydro-distillation (%) ^c	SFME (%)	MAC-75 (%)
<i>Monoterpenes</i>				
Tricyclene	922	0.6	0.4	0.6
α -Thujene	929	0.7	0.5	0.6
α -Pinene	938	17.8	14.8	18.6
Camphene	945	8.0	6.4	7.4
Verbenene	949	0.1	0.1	0.1
Sabinene	968	0.1	–	–
β -Pinene	973	4.7	4.3	4.3
β -Myrcene	983	1.5	1.3	1.3
α -Phellandrene	998	3.1	2.9	2.5
δ -3-Carene	1002	0.1	0.1	0.1
α -Terpinene	1009	0.7	0.7	0.5
<i>p</i> -Cymene	1014	0.4	0.4	0.4
Limonene	1025	23.4	21.2	22.2
γ -Terpinene	1050	1.7	1.6	1.5
Terpinolene	1080	1.0	0.9	0.6
<i>Oxygenated monoterpenes</i>				
Eucalyptol (1,8Cinéole)	1022	2.8	4.0	3.5
Sabinene hydrate cis	1062	0.4	0.6	0.3
Linalool	1088	0.5	0.4	0.1
Chrysanthenone	1095	0.2	0.3	0.1
Fenchol	1096	0.1	0.1	0.1
(E) <i>p</i> -2-menthen-1-ol	1110	0.2	0.1	–
Camphor	1123	13.8	14.8	14.3
<i>cis</i> Verbenol	1124	0.1	0.1	0.1
<i>trans</i> Verbenol	1120	0.2	0.1	0.1
Pinocarvone	1132	0.3	0.3	–
Borneol	1150	2.9	2.9	2.5
Terpin-4-ol	1160	1.4	1.1	1.2
α -Terpineol	1173	2.2	2.1	2.1
Verbenone	1183	1.5	1.9	1.3
<i>trans</i> Piperitone	1189	0.1	0.2	–
<i>trans</i> Carveol	1201	–	0.3	–
<i>trans</i> Pipetitol	1205	0.1	0.2	–
Piperitone	1222	0.1	–	–
Geranial (E)	1252	0.1	0.2	–
Bornyl acetate	1270	5.7	6.0	6.1
Methyl eugenol	1369	0.2	0.1	–
<i>Sesquiterpenes</i>				
β -Caryophyllene	1409	1.8	1.6	1.5
(E) β -Farnesene	1422	–	0.1	–
α -Humulene	1420	0.2	0.7	0.5
Germacrene D	1476	0.1	–	–
β -Bisabolene	1496	–	0.3	–
β -Sesquiphellandrene	1508	–	0.1	–
<i>Oxygenated sesquiterpenes</i>				
Caryophyllene oxide	1568	0.8	0.4	0.2
Isoaromadendrene epoxide	1590	0.1	–	–
α -Bisabolol	1662	0.1	–	–
Extraction time	90 min		30 min	30 min
Yield %	0.57%		0.54%	0.50%
Total oxygenated compounds	33.9		36.2	32
Total non-oxygenated compounds	66.0		58.3	62.7

^a Essential oil compounds sorted by chemical families.^b Retention indices relative to C₆–C₂₇ n-alkanes calculated on non-polar HP1MSTM capillary column.^c % Percentage calculated by GC-FID on non polar HP1MSTM capillary column.

* Compounds known in the rosemary.

process. 80% (after step 1) of final yield is obtained within 24 min using the SFME process (laboratory and pilot scale) and the same proportion is collected after 60 min using the conventional method. The end of the extraction process is reached after 30 min for the microwave process and 90 min using HD.

3.3. Quality and quantity of essential oil

A total of 45 major compounds (in agreement with the literature) were identified in rosemary essential oil extracted using the two techniques. The principal volatile compounds are limonene and α -pinene followed by camphor, camphene, bornyl

acetate, β -pinene, borneol, eucalyptol, α -terpineol, β -caryophyllene and terpin-4-ol, however, their proportions depend on the isolation technique used (Table 2). The oxygenated compounds are more odoriferous than monoterpene hydrocarbons and, hence, the most valuable. Substantial amounts of oxygenated compounds (36.2% or 32% versus 33.9%) and lower amounts of monoterpene hydrocarbons (58.3% or 62.7% versus 66%) are present in the essential oil of rosemary extracted by SFME (Lab or pilot) in comparison with HD. The higher proportion of oxygenated compounds obtained using SFME is probably due to the fact that it causes less intense thermal and hydrolytic effects than HD which uses a large quantity of water. Furthermore, oxygenated compounds have a high dipolar moment and will interact more vigorously with microwaves and can therefore be extracted more easily than monoterpene hydrocarbons which have low dipolar moments.

Essential oils obtained using the MAC-75 were quantitatively and qualitatively (aromatic profile) similar to those obtained by SFME. Only the most minor compounds present in the SFME oil are not found in the up-scaled sample.

3.4. Up-scaling, cost and environmental impact

While conventional procedures such as hydro-distillation are often highly time and/or energy consuming, microwave extraction provides numerous advantages from an industrial point of view. Microwaves have wide-ranging large scale commercial applications as a processing technology and can provide high returns on capital investment. Improvements in product efficiency, process enhancement and low maintenance costs are achievable on a commercial scale.

To recover essential oil from fresh rosemary with yields comparable to conventional extraction procedure, the microwave extraction is performed in 30 min without adding any solvent or water. It is a rapid technique and one that consumes less energy and is advantageous from an environmental point of view. For this purpose, a pilot study has been performed with 3 kg of fresh rosemary plant; microwave irradiation power was 3 kW over 30 min. Essential oil yields in the MAC-75 were relatively comparable to the lab scale experiments (Table 2). The first experiment in a large scale microwave reactor appears to be promising. Thus the important role and the real potential of microwaves in industry begin to become clear.

The reduced cost of extraction is clearly advantageous for the proposed SFME method in terms of energy and time. The energy required to perform the two extraction methods are 4.5 kW h per gram of essential oil for HD and 0.25 kW h per gram of essential oil for SFME. The power consumption was determined with a Wattmeter at microwave generator entrance and the electrical heater power supply. At the same time, the calculated quantity of carbon dioxide released into the atmosphere is dramatically higher in HD (3600 g CO₂/g of essential oil) than in SFME (200 g CO₂/g of essential oil). These calculations have been made according to obtain 1 kW h from coal or fuel, 800 g of CO₂ will be rejected in the atmosphere during combustion of fossil fuel (Chemat & Cravotto, 2013). Hydro-distillation requires an extraction time of 120 min to heat the water and plant material to the extraction temperature, followed by evaporation of water and essential oil, while the SFME method requires only 30 min of fresh aromatic herb heating and the evaporation of the *in situ* water and essential oil of the plant material.

4. Conclusion

SFME offers important advantages over traditional hydro-distillation. It is quicker, more effective and has a more environmentally

friendly approach, making SFME a promising tool for the extraction of essential oils from aromatic plants. When compared to conventional hydro-distillation, optimised microwave treatment shows an increase in oxygenated compound content which are more odoriferous than monoterpene hydrocarbons. This study SFME a laboratory and a pilot shows the potential applicability of the technique in industry.

Acknowledgments

This scientific study is carried out within the framework of the Alcotra Eco-Extraction Transfrontalière project which brings together private and public-sector stakeholders, (University of Avignon, European University of Fragrances & Flavours, FranceAgriMer, University of Turin and Technogrande).

We would also like to warmly thank our co-funding partners, i.e. the European Union (FEDER), the French and Italian governments, the Piemonte region as well as ADEME and the Conseil Régional Provence-Alpes-Côtes d'Azur through the Etat-Region-ADEME framework programme. Their financial support has helped partners successfully achieve the project's scientific objectives.

Aurore Filly thanks Region PACA (Provence Alpes Côte d'Azur) and PASS (Pôle Arômes Senteurs et Saveurs) for her doctoral grant.

References

- Bayramoglu, B., Sahin, S., & Sumnu, G. (2008). Solvent-free microwave extraction of essential oil from oregano. *Journal of Food Engineering*, 88, 535–540.
- Bayramoglu, B., Sahin, S., & Sumnu, G. (2009). Extraction of essential oil from laurel leaves by using microwaves. *Separation Science and Technology*, 44, 722–733.
- Chabard J.L. " Base de données ESO: Essential oils of rosemary (*Rosmarinus officinalis* L.) the chemical composition of oils of various origins (Marrocco, Spain, France). Chemat, F., & Cravotto, G. (2013). Microwave-assisted extraction for bioactive compound. Springer: New York.
- Ferhat, M. A., Meklati, B. Y., & Chemat, F. (2007). Comparison of different isolation methods of essential oil from Citrus fruits: Cold pressing, hydrodistillation and microwave 'dry' distillation. *Flavour and Fragrance Journal*, 22, 494–504.
- Ferhat, M. A., Meklati, B. Y., Smadja, J., & Chemat, F. (2006). An improved microwave clever apparatus for distillation of essential oils from orange peel. *Journal of Chromatography A*, 1112, 121–126.
- Ferhat, M. A., Meklati, B. Y., Visinoni, F., Abert Vian, M., & Chemat, F. (2008). Solvent free microwave extraction of essential oils Green chemistry in the teaching laboratory. *Chimica Oggi Chemistry Today*, 26, 48–50.

- Jalali-Heravi, M., Moazeni, R. S., & Sereshti, H. (2011). Analysis of Iranian rosemary essential oil: Application of gas chromatography–mass spectrometry combined with chemometrics. *Journal of chromatography A*, 1218, 2569–2576.
- Y. Li, A.S. Fabiano-Tixier, M. Abert, Vian, F. Chemat. (2013) Solvent free microwave extraction of bioactive compound provides a tool for green analytical chemistry, *Trends in analytical chemistry*, 47.
- Lucchesie, M. E., Chemat, F., & Smadja, J. (2004a). Solvent-free microwaves extraction of essential oil from aromatic herbs: Comparison with conventional hydro-distillation. *Journal of Chromatography A*, 1043, 323–327.
- Lucchesie, M. E., Chemat, F., & Smadja, J. (2004b). Solvent-free microwaves extraction of essential oil from spices. *Flavour and Fragrance Journal*, 19, 134–138.
- Lucchesie, M. E., Smadja, J., Bradshaw, S., Louw, W., & Chemat, F. (2007). Solvent free microwave extraction of *Elleteria cardamom* L.: A multivariate study of a new technique for the extraction of essential oil. *Journal of Food Engineering*, 79, 1079–1086.
- Ma, C., Liu, T., Yang, L., Zu, Y., Chen, X., Zhang, L., et al. (2011). Ionic liquid-based microwave-assisted extraction of essential oil and biphenyl cyclooctene lignans from *Schisandra chinensis* Baill fruits. *Journal of the chromatography A*, 1218, 8573–8580.
- Nabil, B., Vian- Abert, M., Ferhat, M. A., Petitcolas, E., Meklati, B. Y., & Chemat, F. (2009). Comparison of two isolation methods for essential oil from rosemary leaves: Hydrodistillation and microwave hydrodiffusion and gravity. *Food Chemistry*, 114(1), 355–362.
- Okoh, O. O., Sadimenko, A. P., & Afolayan, A. J. (2010). Comparative evaluation of the antibacterial activities of the essential oils of *Rosmarinus officinalis* L. obtained by hydrodistillation and solvent free microwave extraction methods. *Food Chemistry*, 120, 308–312.
- Orio, L., Cravotto, G., Binello, A., Pignata, G., Nicola, S., & Chemat, F. (2012). Microwave-assisted hydrodistillation and hydrodistillation of fresh and dried mint leaves: a comparison study. *Journal of the Science of Food and Agriculture*, 92, 3085–3090.
- Sui, X., Liu, T., MA, C., Zu, Y., Zhang, Li, & Wang, H. (2012). "Microwave irradiation to pretreat rosemary for maintaining antioxidant content during storage and to extract essential oil simultaneously. *Food Chemistry*, 131, 1399–1405.
- Szumny, A., Figiel, A., Gutiérrez-ortiz, A., & Carbonell-Barrachina, angel A. (2010). Composition of rosemary essential oil (*Rosmarinus officinalis*) as affected by drying method. *Journal of food engineering*, 97, 253–260.
- Tigrine-Kordjani, N., Meklati, B. Y., & Chemat, F. (2006). Microwave 'dry' distillation as an useful tool for extraction of edible essential oils. *International Journal of Aromatherapy*, 16, 141–147.
- Tigrine-Kordjani, N., Meklati, B. Y., & Chemat, F. (2012). Kinetic investigation of rosemary essential oil by two methods: Solvent-free microwave extraction and hydrodistillation. *Food Analytical Methods*, 5(3), 596–603.
- Uysal, B., Sozmen, F., & Buyuktas, B. S. (2010). Solvent free microwave extraction of essential oils from *Laurus nobilis* and *Melissa officinalis*: Comparison with conventional hydrodistillation and ultrasound extraction. *Natural Product Communications*, 5, 111–114.
- Zaouali, Y., Boucaïne, T., & Boussaid, M. (2010). Essential oils composition in two *Rosmarinus officinalis* L. varieties and incidence for antimicrobial and antioxidant activity. *Food and Chemistry Toxicology*, 48, 3144–3152.

Comment citer ce document :

Filly, A., Fernandez, X., Minuti, M., Visinoni, F., Cravotto, G., Chemat, F. (Auteur de correspondance) (2014). Solvent-free microwave extraction of essential oil from aromatic herbs: From laboratory to pilot and industrial scale. *Food Chemistry*, 150, 193-198. DOI :

10.1016/i.foodchem.2013.10.139