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ARTICLE

Microwave assisted extraction as an important technology for valorising orange waste.

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Microwave assisted extraction has been demonstrated as an efficient green technology for the recovery of *D*-limonene from orange waste. Microwave irradiation was shown to be a more efficient method when compared to conventional heating due to its high selectivity for *D*-limonene, significantly shortened extraction durations and *D*-limonene yields twice that of conventional heating. Kinetic analysis of the extraction process indicated a typical two-step diffusion process, an initial stage of extraction from the exterior of the cells (1st stage) and diffusion of solute across the membrane (2nd stage). Diffusion coefficients for the initial stage of extraction from the exterior of cells (1st stage) for both conventional and microwave extraction demonstrated similar trends and activation energies. Interestingly, trans-membrane diffusion coefficient for the microwave assisted extraction at 110 °C was significantly high. Crucially, this was not observed with conventional heating suggesting that microwave radiation favourably interacts with the sample during extraction, causing simultaneous cell rupture and diffusion, resulting in greater yield. This provides an important insight into the development of extraction processes for orange peel.

1. Introduction

Holistic biorefineries are becoming important methods for the conversion of biomass into fuels or chemicals.¹⁻⁴ The use of green extraction technologies is a vital first step in the recovery of metabolites.⁵⁻⁸ Recent work has demonstrated great potential in the valorisation of orange waste as part of a biorefinery.^{9, 10} With approximately 100 million cubic tonnes produced per year, citrus fruit is by far the chief fruit crop in the world, with oranges comprising 60% of the total production.¹¹ The citrus product which stands out is orange juice. Orange juicing is a very wasteful process, with typically 50% waste being generated.¹² 20 million tonnes of unwanted orange peel per year are regularly being produced by the juicing industry every year; a potential goldmine of organic molecules of significant value can be exploited as an alternative natural source of platform molecules.¹³ The composition of orange peel has been studied in a variety of species.¹⁴⁻¹⁶ Typically, waste orange peel consists of water (80%); and sugars, cellulose, hemicellulose, pectin and *D*-limonene which make up the dry matter (20%).¹⁷ Efforts have been made in extracting useful molecules from this waste resource; however there is still uncertainty over the choices and the benefits of the extraction methods.¹⁸⁻²² *D*-limonene is a naturally occurring monoterpene found in many plants and is vital in a variety of industries including cosmetics, food, flavour and fragrance and pharmaceuticals.²³⁻²⁵ The extraction of *D*-limonene from orange peel has been achieved

using steam distillation, cold pressing and solvent extraction.²⁶ However the drawbacks of conventional techniques include long extraction times, high consumption of energy, large amounts of solvent and post-treatment of waste water/solvent.²⁷

Recently, it has been shown that microwave dielectric heating is a very promising method of extraction.^{21, 28-34} Work on the extraction of essential oils from lemons using microwave accelerated distillation has shown that the microwave process results in better yields, shorter extraction times, lower environmental impact and higher quality essential oils when compared to conventional techniques (cold pressing and hydrodistillation).³² Microwave irradiation has also been demonstrated as an effective tool for the recovery of *D*-limonene from oranges,⁹ however the mechanism of microwave assisted extraction of orange peel is yet to be fully determined.

Herein, this investigation considers the microwave assisted extraction (MAE) of *D*-limonene from oranges, focusing on understanding the MW extraction mechanism based on kinetic analysis of the process. The kinetics of extractions were investigated and a mathematical model was adopted to calculate diffusion constants and subsequently determine activation energies for the different extraction methods (microwave vs conventional). The role of microwave radiation in MAE was questioned by designing a system to replicate the conditions of

MAE, with an alternative, conventional heating source. Selecting temperatures close to and exceeding the boiling point of water determined whether an alternative extraction mechanism is observed due to evaporation of water, aided by microwave excitation.

2. Experimental

2.1 Materials

Fresh Valencia oranges were obtained from a local retailer and the same variety of orange was used throughout. The peel was determined by thermogravimetric analysis to have a variable moisture content of up to 60% of the mass combined with other volatile components. The peel samples were prepared using a large sharp knife which gave optimum control of sample size and thickness, approximately 2 mm in thickness. Efforts were made to remove any pith from the peel and all samples were prepared as required to prevent waste and minimise loss of volatile components (Fig. S1 supplementary information). *D*-limonene standard was purchased from Sigma-Aldrich.

2.2 Microwave-assisted Extraction (MAE)

Microwave-assisted extractions (MAE) were performed in a CEM II-Discover model (See Figure S2A, supplementary information). 1 g of peel was weighed out into a microwave tube which contained a magnetic follower. 20 ml of hexane was added and the tube was sealed using the microwave tube lid. The tube was exposed to 200 W of microwave radiation. The MAE was performed with a high rate of stirring and with maximum power mode (a setting which would maintain constant microwave power, with cooling achieved using compressed air) switched off, at several hold temperatures (70 °C, 90 °C, 110 °C) in closed vessel mode for a range of times until a constant percentage yield was obtained. The solvent was removed *in vacuo* and *D*-limonene yield determined.

Hexane is categorised as a hazardous air pollutant by the US EPA, is a potential neurotoxin and has is being phase out of many industrial applications.³⁵⁻³⁸ Although it is well recognised that volatile organic solvents such as hexane can be both unselective and environmentally problematic, worldwide such solvents are still traditionally used for extraction.^{35,39} In this current work hexane has only been adopted for research purposes and could be substituted by an alternative greener non-polar low boiling point solvent such as supercritical carbon dioxide (scCO₂). The future aim would be to implement scCO₂ (as the solvent of choice) with microwave activation for the extractions and hexane was selected as it has similar solubility parameters.

2.3 Conventional Heating Extraction

A similar procedure was developed to mimic the conditions of MAE. The conventional heating was carried out using the CEM

I-Discover model (See Fig. S2B, supplementary information). 0.2 g of prepared peel in 4 ml of hexane with an appropriate stirrer follower was placed in the CEM I-Discover tube. Upon commencing the run, the microwave tube was swiftly transferred to a heating plate pre-set at the desired temperature of 70 °C, 90 °C or 110 °C and left to equilibrate until a constant pressure was achieved along with comparable time span with the MAE method. Obtained pressure values were used for internal temperature conformation. Following the extraction, the solvent was removed *in vacuo* and sample yield recorded and % yield calculated for a similar range of times and temperatures.

2.4 HT-GC (High temperature-gas chromatography)

HT-GC analysis was carried out on an Agilent Technologies 6890N Network GC System. A ZB-5HT capillary column (30 m x 250 μm x 0.25 μm nominal) was fitted at constant pressure of 22.35 psi. The carrier gas used was helium. The injector temperature and the flame ionisation detector temperature were maintained at 300 °C. The samples were injected by automated injection (1 μl injection volume) with a split ratio of 40:1. An initial oven temperature of 60 °C was maintained for 1 minute. The temperature was ramped at a rate of 8 °C min⁻¹ until 360 °C.

2.5 HT-GC-MS (High temperature-gas chromatography mass spectrometry)

HT-GC-MS was performed on a Perkin Elmer Clarus 500 GC coupled with a Clarus 500 quadrupole mass spectrometer. This was fitted with a DB5HT capillary column (30m x 250 μm x 0.25 μm nominal) at constant pressure of 22.35 psi. The carrier gas used was helium. The temperature of the injector was 300 °C and the flow rate was set to 1.2 ml/min. The initial oven temperature was maintained at 60 °C for 1 minute. The temperature was then ramped at a rate of 8 °C min⁻¹ until 360 °C and held for 10 minutes. The Clarus 500 quadrupole mass spectra was operated in the electron ionisation mode (EI) at 70 eV, a source temperature of 300 °C, quadrupole at in the scan range of 30 - 1200 amu per second. The data was collected with the PerkinElmer enhanced TurboMass (Ver5.4.2) chemical software.

3. Results and Discussion

Identification of *D*-limonene as the major and only significant product was achieved using a combination of GC (see Fig. S3, supplementary information), GC/MS (Fig. 1). *D*-limonene was identified by GC-MS and use of an external standard; quantified by GC and isolated yield. All the data demonstrate low degree of orange peel decomposition under all experimental conditions.

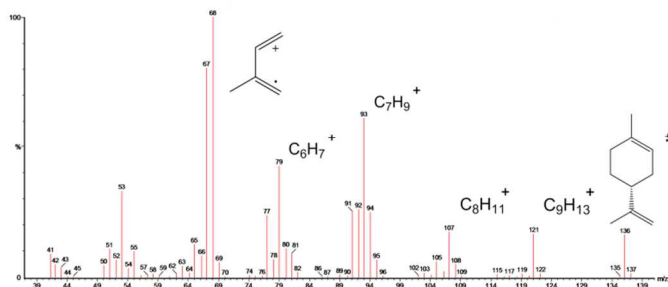


Fig. 1 Mass spec. of extracted *D*-limonene

Solvent extraction is heavily dependent on diffusion rates, which can be interpreted through the use of a mathematical diffusion based model.⁴⁰ This enables the possibility of measuring diffusion coefficients and further improving our knowledge of extraction methods. Two constants of diffusion can be determined for extraction processes, the first is diffusion from the exterior of the material (1st stage) and the second resulting from diffusion across a membrane (2nd stage).⁴⁰⁻⁴³ An extraction constant for the 1st stage is calculated from the initial period of extraction and corresponds to accessible solute formed during sample preparation. The second constant represents less easily accessible solute which must diffuse across membranes before it can be accessed and subsequently rapidly extracted (2nd stage). When the extraction consists of a two stage mass transfer process, the model (originally based on Fick's law) can be expressed as:⁴⁰

$$\frac{c_{\infty}-c}{c_{\infty}} = \frac{6}{\pi^2} \left[f_1 \exp \left\{ -\frac{\pi^2 D_1 t}{R^2} \right\} + f_2 \exp \left\{ -\frac{\pi^2 D_2 t}{R^2} \right\} \right] \quad (1)$$

where c is the concentration at time t , c_{∞} is the concentration at 'infinite' time for a method, when all possible barriers are overcome and R is the size of the particle, D_1 and D_2 are diffusion coefficients at the 1st and 2nd stages and f_1 and f_2 are the fractions of the solute at these stages respectively. The parameter D_2 is obtained from the slope and the parameter f_2 from the intercept of the curve where $\ln[c_{\infty}/(c_{\infty}-c)]$ is plotted as function of time t .^{40, 42}

The exponential curves for the conventional heating extraction technique at different temperatures are shown in Fig. 2A. The exponential curve shape is a first order trend, as rapid extraction occurs during the early stages, but the rate slowly decreases over time, eventually to a constant level when the maximum yield has been achieved. The exponential curves for MAE at different temperatures are found in Fig. 2B. Little variation was observed between repeats in the raw data (see supplementary information) suggesting a consistent procedure and even extraction. Microwave heating was limited to only 30 minutes after which time a significant yield of decomposition products started to form. The decomposition of pectin and cellulose occurs at 160-180 °C and hence no degradation products were observed within the first 30 minutes since the

extractions were carried out at 110 °C.^{10,44} Decomposition post-30 minutes include HMF and polysaccharide decomposition products. Fig. 2 shows the yields of *D*-limonene extracted at different temperatures after 30 minutes as well as the maximum predicted yield for MAE at 110 °C, calculated to be 14.1 wt%. The results indicate an increase in % average yield with increasing temperature. This can be attributed to differing amounts of inaccessible *D*-limonene depending on a combination of two factors. Firstly, the higher temperature runs require more microwave heating, which results in a rapid and significant amount of direct cell damage, resulting in a greater amount of accessible *D*-limonene.

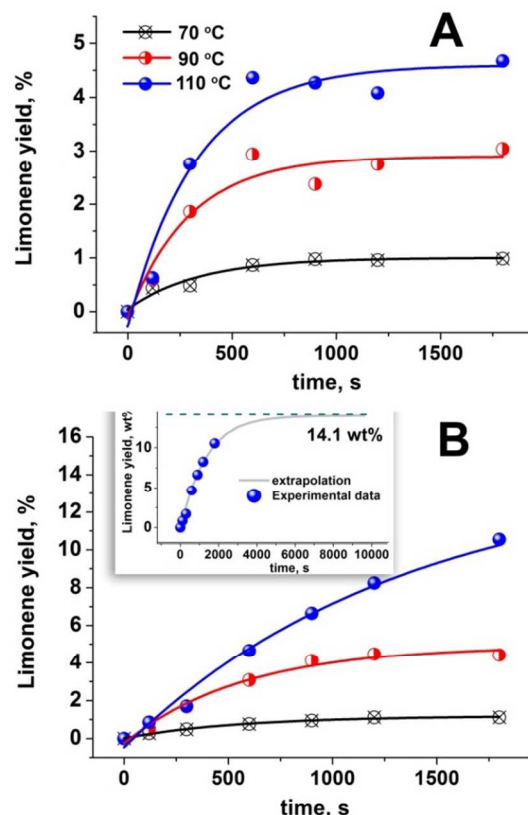


Fig. 2 Kinetics of A) Conventional Heating process and B) Microwave extraction at 70 °C, 90 °C and 110 °C.

The second factor to consider is the effect of the vibration of water molecules. Free water molecules located in the glands and vascular systems of plants interact strongly with microwave radiation and this vibration results in dramatic expansion leading to further damage to cellular structures and tissue rupture.³² It is postulated that should the water molecules boil, a rapid structural damage will occur to the peel, releasing previously inaccessible molecules for subsequent extraction. Greater proportion of water observed in the microwave tube during the extraction support these suggestions, as well as the dramatic change in appearance of the peel at 110 °C MAE sample over extended time. This phenomenon was not observed in any of the other temperatures or methods. The progressive

dehydration displayed in Fig. 3 is a result of cell destruction and loss of water and leaching of *D*-limonene.

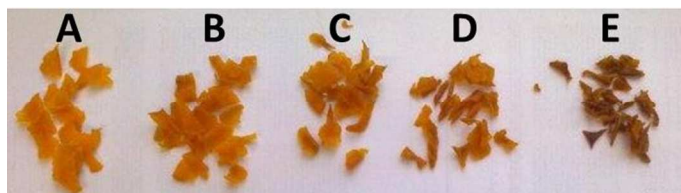


Fig 3. Orange peel after (a) 5, (b) 10, (c) 15, (d) 20 and (e) 30 minutes MAE at 110 °C

A graph showing the linear fitting of the data to a one stage extraction model has been provided (see supplementary information, Fig. S4). This fitting demonstrates significant errors ($R^2 = 0.77$) and as such does not support a single process hypothesis.

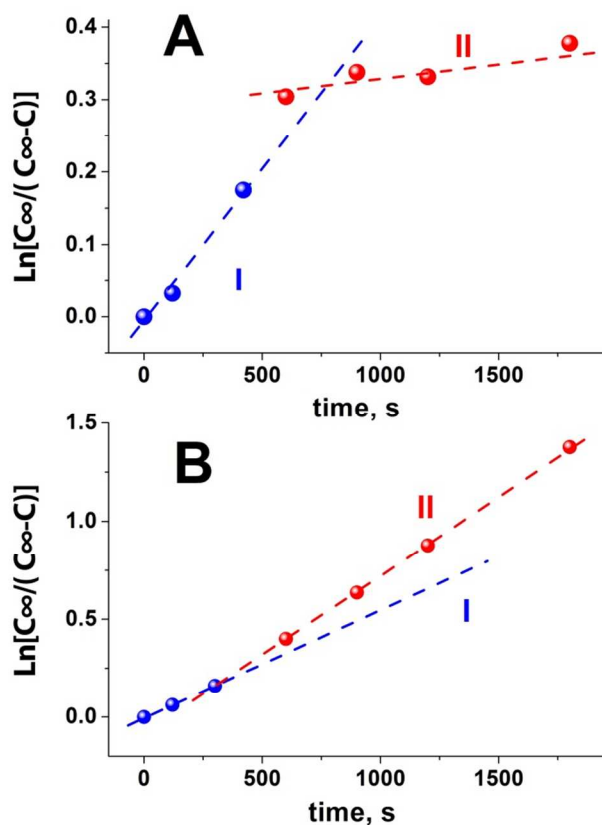


Fig 4. Orange peel extraction kinetics $\ln(c_{\infty}/(c_{\infty}-c))$ against extraction time of A) CH at 110 °C and B) microwave-assisted extraction at 110 °C

Fig. 4 illustrates the kinetics of the MAE at 110 °C, which suggests a two-stage extraction process. In order to calculate the diffusion coefficients via the mathematical model (Equation 1), the extract concentration at each time must be known (Fig. 2) and the concentration at infinite time must be approximated (Fig. 2B). Plotting a graph of $\ln(c_{\infty}/(c_{\infty}-c))$ against extraction

time allows determination of the diffusion coefficients.^{40,42} The value of c_{∞} was estimated by determining the maximum possible yield (see Fig 2B) at 110 °C.

Table 1 – Values of diffusion constants and other constants calculated for each method, temperature and parallel diffusion process.

Extraction Method	T, °C	D ₁ m ² s ⁻¹ x 10 ⁻¹¹	Standard Deviation (±) m ² s ⁻¹ x 10 ⁻¹¹	D ₂ m ² s ⁻¹ x 10 ⁻¹¹	Standard Deviation (±) m ² s ⁻¹ x 10 ⁻¹¹
MAE	70	4.6	0.7	1.8	0.4
MAE	90	17.1	0.9	5.9	1.1
MAE	110	26.9	2.9	33.0	2.5
CH	70	2.8	0.4	2.4	0.9
CH	90	6.2	1.0	3.4	0.3
CH	110	15.3	2.1	4.2	0.8

Obtained diffusion coefficients (Table 1) increase with temperature for both the microwave-assisted and conventional heating (CH). The standard deviations have been determined from linear regression analysis using Origin 8.1 software. The diffusion constants seem to be in accordance with other green technologies such as ultra-sound and supercritical fluid extraction.^{41,43} Both CH and MAE exhibit similar trends in terms of larger diffusion constants at greater temperatures, due to an increased solubility with heating. The difference in heating methods influenced the initial extraction rate significantly. For example, for both extraction techniques carried out at the same temperatures microwave heating has a greater initial rate of extraction compared with CH. Furthermore the rate for CH rapidly declines once all of the easily accessible *D*-limonene is removed. In addition, the MAE constants of diffusion for the 2nd stage are notably greater than CH, particularly at high temperatures (110 °C). This can be observed from Fig. 4, where the 2nd stage (trans-membrane diffusion) for the MAE is much quicker than that of the CH. As expected, in most cases, the 1st stage had higher diffusion coefficients (D_1) than the 2nd stage (D_2). However, this was not observed for the MAE at 110 °C, where D_2 was greater than D_1 and crucially this was not the case for the CH at 110 °C.

Table 2 - Calculating activation energies using kinetic data

Process	Diffusion Constant	Activation Energy kJ mol ⁻¹	R ²	Standard Deviation (±) kJ mol ⁻¹
MAE	D ₁	48.2	0.999	0.9
MAE	D ₂	79.0	0.962	11
CH	D ₁	46.6	0.991	3.0
CH	D ₂	14.5	0.989	1.1

In order to explain the variation in diffusion coefficients, the Arrhenius equation was applied to the data to calculate the activation energies required for the extraction process (Table 2). The activation energies were calculated using three data

points (see supplementary information). Both CH and MAE have similar activation energies for the 1st stage, consistent with diffusion from glands near the surface of the peel and sample preparation. However, the values obtained are higher than a typical value for a pure diffusion process, which are typically being quoted at lower values of 20 kJ mol⁻¹ or less. Similar activation energies for both MAE and CH indicate that the accessibility or penetration through surface matter (and therefore to *D*-limonene) occurs via a similar mechanism for both heating methods, but the MAE provides greater access to the *D*-limonene resulting in a high diffusion coefficient D_1 . This could be a result of an increase in the rate of limonene mass transfer through the peel surface as a result of water molecule activation in the presence of microwave irradiation.⁴⁵

In contrast diffusion coefficients and activation energies varied significantly between the two heating methods in the 2nd stage. The calculated activation energy values of the CH 2nd stage are consistent for an entirely diffusion controlled process. The high activation energy for MAE (79 ± 11 kJ mol⁻¹) obtained for D_2 is a result of diffusion out of the ruptured cells rather than diffusion through the cell membrane. When microwave heating is applied, the oil glands situated in the orange peel are subjected to massive thermal stresses and localised high pressures.³² The build-up of pressure in the glands far exceeds their capacity to expand which leads to the rupturing of the glands at a rate that is much faster than CH.³² It also explains why there is a much higher % of *D*-limonene extracted for MAE when compared to CH. One of the explanations for the observed two stage process is that extraction takes place from oil glands close to the surface and also limonene extraction/diffusion from oil glands located in the interior of the peel (at a much faster rate with MAE).³² However further work is needed to clarify these observations.

The maximum yield of *D*-limonene obtained after 30 minutes at 110 °C was found to be 11.1% which is significantly higher than the 4.7% obtained for the CH (Fig. 2). Furthermore, a soxhlet extraction was carried out using hexane so as to compare % yield of *D*-limonene. The % yield for the Soxhlet extraction, after 7 hours, was 5.4% further giving evidence that microwaves favourably interact with the sample (Table S1, supplementary information). Therefore, it can be concluded that the effects of microwave heating directly or indirectly (via water molecule excitation) break down cellular structures within the peel throughout extraction, as such extraction rates could not be obtained by mere diffusion controlled extraction through cell membranes.

Conclusions

It was shown using a mathematical model that *D*-Limonene extraction consisted of a two stage diffusion process for both heating methods: initial extraction from the exterior of cells (1st stage) followed by trans-membrane diffusion (2nd stage). It was found that microwave extraction was found to be more

efficient for both stages of the process. In the 1st stage there was water molecule activation in the presence of microwave irradiation leading to a higher *D*-limonene mass transfer. In the 2nd stage, trans-membrane diffusion was accelerated as a result of simultaneous gland rupture and diffusion. This leads to a greater overall yield due to increased amounts of accessible *D*-limonene.

Notes and references

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- 1 J. H. Clark, V. Budarin, F. E. I. Deswarte, J. J. E. Hardy, A. J. Hunt, F. M. Kerton R. Luque, D. J. Macquarrie, K. Milkowski, A. Rodriguez, O. Samuel, S. J. Tavener, R. J. White, A. J. Wilson, *Green Chem.*, 2006, **8**, 853-860.
- 2 P. S. Shuttleworth, M. De bruyin, H. L. Parker, A. J. Hunt, V. L. Budarin, A. S. Matharu and J. H. Clark, *Green Chem.*, 2014, DOI: 10.1039/C3GC41555D.
- 3 J. H. Clark, L. A. Pfaltzgraff, V. L. Budarin, A. J. Hunt, M. Gronnow, A. S. Matharu, D. J. Macquarrie and J. R. Sherwood, *Pure Appl. Chem.*, 2013, **85**, 1625-1631
- 4 J. R. Dodson, V. L. Budarin, A. J. Hunt, P. S. Shuttleworth and J. H. Clark, *J. Mater. Chem. A*, 2013, **1**, 5203-5207.
- 5 V. L. Budarin, P. S. Shuttleworth, J. R. Dodson, A. J. Hunt, B. Lanigan, R. Marriott, K. J. Milkowski, A. J. Wilson, S. W. Breeden, J. Fan, E. H. K. Sin and J. H. Clark, *Energy Environ. Sci.*, 2011, **4**, 471-479.
- 6 A. J. Hunt, E. H. K. Sin, R. Marriott and J. H. Clark, *ChemSusChem*, 2010, **3**, 306-322.
- 7 E. H. K. Sin, R. Marriott, A. J. Hunt and J. H. Clark, *Comptes rendus chimie*, 2013, DOI: 10.1016/j.crci.2013.12.001
- 8 M. Arshadi, A. J. Hunt and J. H. Clark, *RSC Adv.*, 2012, **2**, 1806-1809
- 9 L. A. Pfaltzgraff, M. De bruyin, E. C. Cooper, V. Budarin and James H. Clark, *Green Chem.*, 2013, **15**, 307-314
- 10 A. Mariana Balu, V. Budarin, P. S. Shuttleworth, L. A. Pfaltzgraff, K. Waldron, R. Luque, J. H. Clark, *ChemSusChem*, 2012, **5**, 1694-1697
- 11 *Utilization of By-Products and Treatment of Waste in the Food Industry.*, ed. V. Oreopoulou and W. Russ, Springer, New York, 2006, 209 - 232.
- 12 R. J. Braddock, *Food Technol.*, 1995, **49**, 74 - 77.
- 13 K. Rezzadon, S. Benedetti and E. R. Amante, *Food. Bioprod. Process.*, 2012, **90**, 606 - 614.
- 14 G. M. Kamal, F. Anwar, A. I. Hussain and V. M. Ashraf, *Int. Food. Res.*, 2011, **18**, 1275 - 1282.
- 15 J. A. Manthey and K. Grohmann, *J. Agric. Food. Chem.*, 1996, **44**, 811 - 814.
- 16 A. Bocco, M. E. Cuvelier, H. Richard and C. Berset, *J. Agric. Food Chem.*, 1998, **46**, 2123 - 2129.
- 17 V. A. Bampidis, P. H. Robinson, *Anim. Feed Sci. Technol.* 2006, **128**, 175 - 217.

- 18 B. Mira, M. Blasco, A. Berna and S. Subirats, *J. Supercrit. Fluids.*, 1999, **14**, 95 – 104.
- 19 A. Berna, A. Tarrega, M. Blasco and S. Subirats, *J. Supercrit. Fluids.*, 2000, **18**, 227 – 237.
- 20 M. K. Khan, M. Abert-Vian, A. S. Fabiano-Tixier, O. Dangles and F. Chemat, *Food Chem.*, 2010, **119**, 851 – 858.
- 21 A. Farhat, A. S. Fabiano-Tixier, M. El Mantaoui, J. F. Maingonnat, M. Romdhane and F. Chemat, *Food Chem.*, 2011, **125**, 255 – 261.
- 22 X. Guo, D. Han, H. Xi, L. Rao, X. Liao, X. Hu and J. Wu, *Carbohydr. Polym.*, 2012, **88**, 441 – 448.
- 23 M. L. Lota, D. de Rocca Serra, C. Jacquemond, F. Tomi and J. Casanova, *Flavour. Frag. J.*, 2001, **16**, 89 – 96.
- 24 M. Lahlou, *Flavour. Frag. J.*, 2004, **19**, 159 – 165.
- 25 A. E. Edris, *Phytother. Res.*, 2007, **21**, 308 – 323.
- 26 W. Q. Hull, C. W. Lindsay and W. E. Baier, *Ind. Eng. Chem.*, 1953, **45**, 876 – 890.
- 27 F. M. Kerton and R. Marriott, *Alternative Solvents For Green Chemistry*, RSC Publishing, London, 2 edn., 2013, 123.
- 28 J. A. Manthey, K. Grohmann, *J. Agric. Food Chem.*, 1996, **44**, 811– 814.
- 29 M. Letellier and H. Budzinski, *Analisis*, 1999, **27**, 259 – 271.
- 30 F. Chemat, M.E. Lucchesi, J. Smadja, L. Favretto, G. Colnaghi and F. Visinoni, *Anal. Chim. Acta.*, 2006, **555**, 167 – 170.
- 31 M.A. Ferhat, B.Y. Meklati, J. Smadja and F. Chemat, *J. Chromatograph. A.*, 2006, **1112**, 121 – 126.
- 32 M.A. Ferhat, B.Y. Meklati and F. Chemat, *Flavour. Frag.*, 2007, **22**, 494 – 504.
- 33 M. Abert Vian, X. Fernandez, F. Visinoni, F. Chemat, *J. Chromatograph. A.*, 2008, **1190**, 14 – 17.
- 34 C.C. Teo, S.N. Tan, J.W. Hong Yong, C.S. Hew and E.S. Ong, *J. Chromatograph. A.*, 2008, **1182**, 34 – 40.
- 35 J.M. DeSimone, *Science*, 2002, 297, 799–803.
- 36 H.H. Schumburg, P.S. Spencer, *Brain*, 1976, **99**, 183–192.
- 37 P.S. Spencer, H.H. Schumburg, *Proc. R. Soc. Med.*, 1977, **70**, 37–38.
- 38 D. Prat, O. Pardigon, H.W. Flemming, S. Letestu, V. Ducandas, P. Isnard and P. Hosek, *Org. Process Res. Dev.*, 2013, **17**, 1517–1525
- 39 E.H.K. Sin, R. Marriott, A.J. Hunt and J.H. Clark, *Comptes Rendus Chimie*, 2014, In press, DOI:10.1016/j.crci.2013.12.001
- 40 S.C. Ma, X.L. Wang and Y.R. Liang, *Afr. J. Pharm. Pharmacol.*, 2012, **6**, 1410 – 1416.
- 41 M. Skerget, M. Bezjak, K. Makovsek and Z. Knez, *Acta. Chim. Slovaca*, 2010, **57**, 60 – 65.
- 42 L. Wang and C. L. Weller, *Trends Food Sci. Tech.*, 2006, **17**, 300 – 312.
- 43 S. S. Petrovic, J. Ivanovic, S. Milovavonic and I. Zizoviv, *J. Serb Chem. Soc.*, 2012, **77**, 799 – 813.
- 44 J. Fan, M. De Bruyn, V. L. Budarin, M. J. Gronnow, P. S. Shuttleworth, S. Breeden, D. J. Macquarrie and J. H. Clark, *J. Am. Chem. Soc.*, 2013, **135**, 11728 - 11731.
- 45 Microwave-assisted Extraction for Bioactive Compounds Theory and Practice, ed. F. Chemat and G. Cravotto, Springer, New York, 2013.

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Kinetics of microwave-assisted *D*-limonene extraction demonstrates a five-fold increase in yield over conventional extraction in a two stage process.