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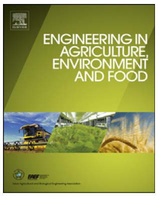

Microwave dielectric spectroscopy – A versatile methodology for online, non-destructive food analysis, monitoring and process control

R.T. Blakey [a], [*], A.M. Morales-Partera [b]

[a] *CICAP Food Research Centre, Polígono Dehesa Boyal, Parcela 10-13, 14400, Pozoblanco, Spain*
[b] *AMP Laboratorios, Rabanales21, Edificio Aldebarán, M2.15, Parque Científico Tecnológico de Córdoba, 14014, Córdoba, Spain*

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ABSTRACT

Microwave dielectric spectroscopy (MDS) is an online, compact, non-destructive/invasive, low power analytical methodology based upon the rotation of molecules and their functional groups in the presence of an electromagnetic field in the frequency range of 0.3–300 GHz which may then be used to differentiate materials of different composition. Recent technological developments have increased the availability of the equipment needed to investigate the application of MDS within the food industry. This article gives an overview of the fundamentals of the technology and a review of potential applications in the food industry. Challenges and the future potential of this technology are also considered.

Contents

1. Introduction

The microwave region of the electromagnetic spectrum extends from 300 MHz to 300 GHz and is more widely known for communication, radar and heating applications. However, the application of the fundamental concept of these technologies can

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[*] Corresponding author.
E-mail addresses: rtblakey@gmail.com (R.T. Blakey), amorales@amplab.es (A.M. Morales-Partera).

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be used to analyse and differentiate electrochemical samples as a function of frequency in a methodology called microwave dielectric spectroscopy (MDS), alternatively known as impedance spectroscopy. Research in the food industry within this specific field has largely derived from the desire to understand and optimise how materials can be heated and processed using high power microwaves. Until quite recently interest in using microwave MDS has been limited due to the expense and limited frequency range of equipment. Developments in component fabrication and computational power have reduced the size and increased the efficiency of the equipment needed for MDS, so that now handheld, broadband devices are commercially available. As a result the interest and research has been able to gain momentum with the aim of developing online, compact, non-destructive/invasive, low power analytical and monitoring sensing equipment.

The quality, and more importantly the safety of food products are highly reliant on the effective control of microbial, bio-toxic and chemical contaminants that are inherently present or extrinsically introduced throughout production and processing of food (Fischer et al., 2011; Nag, 2010). A number of control and detection methodologies exist that are implemented to ensure that stringent safety and quality parameters set by national and intergovernmental organisations are met. However, these are often implemented offline and/or off-site in specialised laboratories using specialised equipment. This leads to some analysis being extremely time consuming and expensive, leading to bottlenecks in the production processes. On-site, online, non-destructive analysis and monitoring of food has the possibility to introduce significant economic benefit to both producers and processing plants by reducing analytical costs and reducing inefficient practices. Therefore there is a need for versatile, rapid, economic, quantitative analysis methodologies that can continuously, directly and non-destructively analyse specific characteristics of food throughout the production and processing stages. Technologies such as infrared spectroscopy, Raman spectroscopy and ultraviolet spectroscopy are all currently being investigated for their applicability to this task. However, they do not have the penetration depth, cost-effectiveness or simplicity of MDS.

Microwave MDS technology can be designed to operate in reflection or transmission mode depending on the sample's characteristics. Electromagnetic radiation in the microwave frequency range has sufficient energy to induce the rotation of molecules and their functional groups which may then be used to differentiate samples. Microwaves are non-ionising as they propagate insufficient energy to ionise atoms or molecules while sensing applications of microwaves utilise sufficiently low power so as not to induce dielectric heating, making them safe to use within the food industry. The number of reported applications of MDS for the food industry research has steadily been increasing since the early 1990s. However, since the late 2000s, publications of applied research have increased significantly. It therefore seems appropriate to provide an up to date review of the technology, existing applications of MDS while exploring factors that may expedite the development and commercial availability of a viable analytical product. The article is structured as follows: the next section provides an overview of the theory of MDS. The following section describes the instrumentation and methodology for determining dielectric characteristics of materials. The body of the article compiles reported applications of MDS (summarised in Table 1). This is followed by a discussion of the future of MDS in the food industry including the most promising applications together with limitations and obstacles that must be overcome before the technology becomes a useful and viable analytical tool.

2. Dielectrics and permittivity

MDS characterises the dielectric properties of a material as a function of frequency. It is based upon the interaction of an externally applied alternating electric field with the electric dipole relaxation moment of the material. A material that can be polarised by an applied electric field is known as a dielectric. An external electric field applied to a material causes an amount of the electrical energy to be stored through an interaction with the molecular and structural properties of the material. The ability of the material to store energy in this way is described as the permittivity (ε), usually expressed as a product relative to the permittivity of free space (ε_0) (Barthel and Buchner, 2003).

MDS quantifies permittivity of the material in the complex form. The complex permittivity is composed of the real and imaginary permittivity represented by the equation

$$\boldsymbol{\varepsilon}^*(\omega) = \varepsilon' + \frac{\boldsymbol{\sigma}^*}{j\omega} \tag{1}$$

Table 1
Summary of MDS application for food analysis.

Food analysed	Author, year	Application	Measurement methodology	GHz range
Alfalfa	(Bijay et al., 2005)	Moisture content	Probe	0.3–18
Vinegar	(Bohigas and Tejada, 2009)	Acetic acid content	Probe	1–20
Alcoholic beverages	(Bohigas and Tejada, 2010)	Ethanol content	Probe	1–20
Meat (pork)	(Castro-Giráldez et al., 2010b)	Salting process	Probe	0.5–20
Pomegranate	(Castro-Giráldez et al., 2013)	Ripening (citric acid content)	Probe	0.5–20
Olive Oil	(Cataldo et al., 2012)	Adulterant oils	Probe	- 15
Cheese (Parmigiano–Reggiano)	(Cevoli et al., 2012)	Ripening (rind percentage and moisture content)	Cavity	2–20
Meat (Ham)	(Fulladosa et al., 2013)	Salt, water and fat content	Probe	0.02–5
Grape juice and wine	(García et al., 2004)	Brewing Process	Probe	0.2–3
Olive Oil	(Korostynska et al., 2013)	Olive oil quality	Coplanar	6.62–7.81
Vidalia onions	(McKeown et al., 2012)	Moisture content	Probe	0.2–20
Meat paste (beef)	(Ng et al., 2008)	Fat content	Probe	−40
	"	"	Cavity	8–10
Milk	(Nunes et al., 2006)	Fat content, dilution and freshness	Probe	1–20
Egg (thick and thin albumin)	(Ragni et al., 2007)	Storage time	Probe	0.02–1.8
Cheese	(Smith et al., 2011)	Texture (calcium content)	Probe	0.2–1.3
Peanut hull	(Trabelsi et al., 2013)	Moisture content	Free space	5–15
Beer (lager)	(Velázquez-Varela et al., 2013)	Sugar & ethanol content during brewing process	Probe	0.5–20
Chickpea flour	(Guo et al., 2008)	Moisture content	Probe	0.01–1.8
Honey	(Guo et al., 2011)	Sucrose adulteration	Probe	0.01–4.5
Milk	(Guo et al., 2010)	Dilution and freshness	Probe	0.01–4.5

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