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Advanced Mass Spectrometry for Food Safety and Quality

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Series Editor’s Preface

I am delighted to introduce this new volume on Food Safety and Quality in the *Comprehensive Analytical Chemistry* Series edited by my friend and colleague, Professor Yolanda Picó. Professor Picó previously edited Volume 58 on a similar topic, Food Contaminants and Residue Analysis, published in 2008. Then, the first lines of my Preface already indicated that food safety has become a key issue in our society, due to globalization where food is traveling around the world. Under these circumstances quality issues are always on the agenda and their importance has steadily increased since then.

In the series we have devoted much attention to Food Quality. We published a volume on pesticide residues in food in Volume 43, edited by my old friend and colleague Professor Amadeo R Fernández-Alba, already 10 years ago, back in 2004. Amadeo was also the editor of Volume 58, in 2012, on Pesticides and other Food Contaminants. Volumes 63 and 64 on the Fundamentals and Applications of Advanced Omic Technologies, edited by Carolina Simó, Alejandro Cifuentes, and Virginia García Cañas, reported on the applications of these technologies to food science and food safety among other related applications to cancer and clinical research.

The volume that you have now in your hands is an excellent addition to the series, reinforcing our interest in keeping you updated on this essential research topic. The book includes chapters on the most advanced mass spectrometric techniques, such as different types of ionization forms and analyzers, like isotopic, ambient ionization, and ion mobility as well as novel applications in the broad field of food safety. There is a comprehensive, state-of-the-art list of emerging contaminants and materials in the application chapters that include food allergen, lipidomics, food forensics, engineered nanomaterials, food pathogens, and foodomics. In total the book comprises 13 chapters with a good balance between the description of the advanced mass spectrometric techniques and new applications.

Finally I would like to thank Yolanda for the amount of work, time, and expertise she has devoted as editor of and contributor to this book. I would like to acknowledge as well the other well-known authors for their contributions in compiling such a world-class and timely book that will be of help to newcomers, PhD students, and senior researchers. The book should serve as a tool to improve food quality in our globalized market of goods exchange.

D. Barceló

IDAEA-CSIC, Barcelona and ICRA, Girona, February 5, 2015
Editor in Chief of the *Comprehensive Analytical Chemistry* Series, Elsevier
The scope, relevance, and degree of food safety and quality have never been higher than in today’s global world. Confidence in the safety and integrity of the food supply is an important requirement for consumers. Recent advances in mass spectrometry technologies provide tremendous opportunities for a range of food-related applications. However, the distinctive characteristics of food, such as the wide range of different components and their extreme complexity, give rise to enormous difficulties. In this book, recent advances in mass spectrometry-based techniques and their applications in food safety and quality, as well as the major challenges associated with implementing these technologies for more effective identification of unknown compounds, food profiling or candidate biomarker discovery are summarized and discussed. Recent developments in sample preparation, matrix treatment, and traditional biochemical techniques, in combination with substantial improvements in MS platforms, have enabled the study of new areas within food quality and safety, such as food pathogens, biopolymers (lipids or proteins), components produced by genetically modified organisms, naturally occurring antibiotics or allergens, food authenticity and adulteration, emerging contaminants and nanomaterials. Despite these significant advances and efforts, major challenges associated with the dynamic range of measurements and extent of food coverage, confidence of compound identifications, quantitation accuracy, analysis throughput, and the robustness of present instrumentation must be addressed before mass spectrometry platforms that are suitable for efficient food quality and safety applications can be routinely implemented.

The book is structured in two parts; the first describes the basic and essential topic—the current status of mass spectrometry within food safety and quality—and will identify those issues that are promising but not fully resolved yet. The chapters of this part introduce a number of hot topics, including high-resolution mass spectrometry, imaging mass spectrometry, isotope ratio-mass spectrometry, ambient ionization techniques, and high-performance ion-mobility spectrometry. The second part describes the main and most innovative applications in food safety and quality that are current in mass spectrometry, and the difficulties in porting them to this technique. These applications include proteomics, lipidomics, and emerging contaminants with special detail to nanomaterials, food forensics and foodomics. The upcoming developments of mass spectrometry in food quality and safety are presented and the future of this line of work is discussed.
The proposed book has some idiosyncratic features that make it more interesting to read, such as new topics in food quality and safety and descriptions of the latest advances in mass spectrometry. This book aims to serve as a general reference for postgraduate students, who are not expert in many of the emerging mass spectrometry platforms and their applications, as well as a practical reference for a wide range of specialists: biologists, biochemists, microbiologists, food chemists, toxicologists, chemists, agronomists, food hygienists, and everybody who need to use mass spectrometry for evaluating food quality and safety. The different advances and applications described here are not only emerging now but will also be critical in the future for assuring an affordable, safe, and available food supply.

I thank all the authors who have contributed to the successful completion of this book for their labor and dedication in producing high quality work. Time is a precious resource and all of us are beyond our capacity, and writing a chapter is not usually high on the priority list. Therefore, the remarkable effort of the contributors, all of them specialists in their fields, is greatly appreciated. I also acknowledge the Elsevier staff for their helpful assistance through the development of this project, especially to Derek Coleman for his incredible patience when I missed nearly every deadline—it has been a pleasure to work with all of you. Prof. Dr Damià Barceló of CSIC-Spain and editor of this Elsevier series deserves special mention for the opportunity to publish this work and his encouragement. Many, many thanks!

Last but not least, I hope that you find reading and studying the chapters as exciting as I found the writing and editing process. I trust that you will find this book an invaluable source of information.

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February 2015
Chapter 1

Mass Spectrometry in Food Quality and Safety: An Overview of the Current Status

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1. INTRODUCTION

According to the World Health Organization (WHO) [1], the terms food safety and food quality can sometimes be confusing. Food safety refers to all those hazards, whether chronic or acute, that may make food injurious to the health of the consumer. It is not negotiable. Quality includes all other attributes that influence a product’s value to the consumer. This comprises negative attributes such as spoilage, contamination with filth, discoloration, off-odors and positive attributes such as the origin, color, flavor, texture, processing method of the food.
The importance of food safety and quality today is clear considering the food and drink industry is a fundamental pillar of the European Union (EU) economy with 500 million of consumers. The sector is among the top three manufacturing industries in terms of turnover (1016 € millions in 2011–2012) and employment (4 million people in approximately 280,000 companies in 2011–2012) in several Member States. It ranks first in France, Spain, the UK, Denmark and Belgium [2]. Transforming today’s challenges and demands within the sector (e.g., higher quality and safety standards at affordable prices to the consumer, sustainable crop management, environmental compatibility, etc.) into opportunities is required to increase the competitiveness of the EU food and drink industry.

Quality and safety testing of food is an area of growing importance, where accurate analytical results are critical, be that for exporters, importers, or government bodies [3]. As a result of the rising globalization levels, food suppliers, producers, manufacturers, and regulatory agencies are all facing greater pressure than ever before to test more food products for more contaminants and attributes and quantify their presence at lower levels with greater accuracy—and in less time [4–6]. The utilization of mass spectrometry has grown rapidly within the sector because it is now recognized as an extremely specific and exceptionally sensitive technique for testing food products with superior accuracy and higher throughput [7,8]. The ability to simultaneously monitor a range of contaminants and/or natural components greatly improves throughput, and new levels of sensitivity allow more simplified sample preparation protocols [9,10].

Several reviews give an idea of the complexity of some aspects of the applications of mass spectrometry (MS) in food. Some of them presented the most recent applications of MS-based metabolomic approaches for food quality, safety, and traceability assays [11,12]. Ibañez et al. [13] reported an overview of the current developments and applications of capillary electrophoresis–mass spectrometry (CE-MS) as an analytical platform for Foodomics. The highest number of reviews covers the field of liquid chromatography–mass spectrometry (LC-MS) in food analysis [14] and food safety [3]. Mohamed et al. [15] evaluated the contribution and the potentialities of MS-based techniques to ensure the absence of chemical contaminants in food-based products. Recently, the state of the art of MS within food quality and safety was already reviewed, including matrix-assisted laser desorption ionization coupled to time-of-flight mass spectrometry (MALDI-TOF-MS) and ambient ionization MS for direct food analysis [16]. The revolution of “omic” sciences introduced within MS integrated high-throughput approaches to address the understanding of the biochemical systems and their dynamic evolution as well [17]. Applications of modern MS-based techniques in proteomics, all ergonomics, glycomics, metabolomics, lipidomics, food safety and traceability were also surveyed [18]. These advances in MS provide the capacity to screen for more analytes at lower levels, with greater accuracy, and in less time.

This chapter presents an overview of the current status of MS techniques applied in food safety and quality, as well as their future prospects that will be
developed in other chapters of the book. The general characteristic steps of MS-based techniques and the main chemical analytical procedures applied in the field are introduced. Furthermore, applications of the different techniques and ionization sources are discussed.

2. CURRENT INSTRUMENTATION AND OPERATION IN MASS SPECTROMETRY

MS appeared at the beginning of the twentieth century but current advances in this technique are the result to face the inherent challenge in it—interfacing atmospheric pressure ionization sources (760 torr) to analyzers maintained at $10^{-6}$ to $10^{-11}$ torr, a remarkable pressure differential of more than nine orders of magnitude [19,20]. Nowadays most common methods of sample introduction are direct insertion with a probe or plate commonly used with MALDI, direct infusion or injection into the ionization source such as electrospray ionization (ESI) or electron impact (EI) ionization [21]. These ionization sources are schematized in Figure 1.

Prior to the 1980s, EI was the primary ionization source for MS analysis. EI energetic electrons interact with gas phase atoms or molecules to produce ions. The ionization process often follows predictable cleavage reactions that give rise to fragment ions which, following detection and signal processing, convey structural information about the analyte [22,23]. However, EI limited analyst to small molecules well below the mass range of common food components, such as proteins, lipids and polysaccharides. This limitation motivated scientists during 1980s such as John B. Fenn, Koichi Tanaka, Franz Hillenkamp, Michael Karas, Graham Cooks, and Michael Barber to develop ionization techniques, including fast atom/ion bombardment (FAB), particle beam (PB), MALDI, and ESI [23–25]. Although FAB and PB have already fallen into disuse, these techniques have revolutionized food analyses, especially for large molecules such as protein. Among them, ESI and MALDI have clearly evolved to be the methods of choice for food analysis and they are still evolving to the ambient ionization and imaging techniques [25]. In ESI, high voltage is applied to a liquid supplied through an emitter (usually a glass or metallic capillary). The charged droplets, generated at the exit of the electrospray tip, pass down a pressure gradient and a potential gradient toward the analyzer region of the mass spectrometer. MALDI is a soft ionization technique in which a short laser pulse, instead of continuous laser, of nitrogen gas usually around 237 nm is used to ionize molecules. ESI is also a soft ionization technique that is typically used to determine the molecular weights of either small molecules or biological macromolecules [25,26].

During the 1990s, research moved from the ionization source to the mass analyzer. Quadrupoles (single and triple), three-dimensional ion traps ($^3$DIT), linear ion traps (LTQ), time of flight (TOF), quadrupole time of flight (QqTOF), and different types of orbitrap mass analyzers have been developed and/or undergone numerous modifications/improvements [4,26].
These mass analyzers can be distinguished into (1) quadrupole-base, (2) ion traps, and (3) TOF. The fundamentals of the different mass spectrometers is beyond the scope of this chapter, and the reader is referred for a good description of the theory behind them [8,11,14,16,27]. However, schemes of the most used ones are outlined in Figure 2: Quadrupoles consist of four cylindrical rods, set parallel to each other. In a quadrupole mass spectrometer the quadrupole is the component of the instrument responsible for filtering sample ions, based on their mass-to-charge ratio (m/z). Ions are separated in a quadrupole based on the stability of their trajectories in the oscillating electric fields that are applied to the rods. Only ions of a certain m/z will reach the detector for a given ratio of voltages: other ions have unstable trajectories and will collide with the rods [14]. These mass analyzers are little sensitive in scan mode (MS is obtained for a full range of m/z) and