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EFFECTS OF ELECTROMAGNETIC FIELDS AND PACKAGING SHAPE ON PHYSICOCHEMICAL AND MICROBIOLOGICAL CHARACTERISTICS OF WATER

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By

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MAHER ABDELALEEM ABDELRAZIK ABDELSAMIE

October 2015

Chair: Prof. Russly B Abdul Rahman, PhD
Institute: Halal Product Research Institute

The production of Halal food is an integrated process that produces not only food that is ritually blessed, but must be safe, innocuous and healthy (Tayyib). The widespread use of electromagnetic (EM) waves and its ability to induce non-thermal effects in water solutions calls for a study of the relationship between environmentally abundant electromagnetic fields (EMFs) and packaging shape, to determine its effects on the physicochemical and microbiological characteristics of water during storage. The study was accomplished through developing computer simulation models of four water containers and then performing EM simulation. The validation of the computer simulation was done by studying the exposure of the containers to 2.4GHz EM waves and environmentally abundant EMFs. Two high and low ionic content solutions representing natural mineral drinking water and H2O-NaCl was used as a samples, respectively.

The EM simulation results showed that the absorption of EM energy was changed by changing the shape of the container. After exposure to free space 1.3V/m plane waves, the total specific absorption rate (SAR) values of EM energy absorbed by water at 2400MHz for vertical polarization were 0.0292, 0.0203, 0.0201 and 0.01723 mW/kg, for pyramidal, rectangular, square and cylindrical container models, respectively. The maximum values of the electric field induced in water in the reverberation chamber after exposure to 1 W EM radiation were 111.7, 22.9, 33.6 and 60.3 V/m for pyramidal, rectangular, square and cylindrical container models respectively. Although there were variations in the physicochemical and microbiological parameters between water stored in shielded and unshielded container groups, as well as between water in the same group of containers, the water remained within the permissible guidelines of the WHO. There were significant variations in the values of zeta potential and cluster size of water of H2O-NaCl and natural mineral drinking water stored in the unshielded containers exposed to EM waves, as shown in the results of the 17O Nuclear Magnetic Resonance NMR and Raman spectroscopy techniques, respectively.

It can be concluded that the variations in the electric and magnetic fields and SAR values induced in water affected the cluster size of water molecules, which were reflected in the results of particle size and the crystallization mode of water's mineral content in both high and low ionic content solutions. This might indirectly affect the physicochemical and microbiological characteristics of the natural mineral drinking water. The results of the study are significantly useful in obtaining parameters for water solutions storage and packaging process optimization.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah.

HUBUNGAN DI ANTARA MEDAN ELEKTROMAGNETIK YANG BANYAK DI PERSEKITARAN DAN BENTUK PEMBUNGKUSAN SERTA KESANNYA KE ATAS CIRI-CIRI FIZIKOKIMIA DAN MIKROBIOLOGI AIR

Oleh

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Penghasilan produk makanan halal adalah proses integrasi yang bukan sahaja meliputi makanan yang bertepatan panduan ritual, tetapi juga selamat, tidak merbahaya dan sihat (Tayyib). Penggunaan dan kebolehan gelombang elektromagnet (EM) untuk memberi kesan dalam larutan tanpa dorongan haba; pendedahan larutan kepada persekitaran yang tinggi gelombang medan EM semasa tempoh penyimpanan jangka masa pendek dan jangka masa panjang; kebolehan bentuk geometri produk makanan untuk mempengaruhi penyebaran dan penyerapan tenaga EM serta peranan air sebagai pelarut universal, metabolit dan persekitaran tempat tinggal mikroorganisma, telah melahirkan kajian mengenai hubungan di antara medan elektromagnetik yang banyak di persekitaran dan rekabentuk pembungkusan untuk menentukan kesannya ke atas ciri-ciri fizikokimia dan mikrobiologi air semasa penyimpanan serta mendapatkan parameter bagi penyimpanan air dan proses pembungkusan yang optimum.

Kajian telah dijalankan dengan membangunkan model simulasi berkomputer bagi model bekas piramidal, segiempat tepat kubik, kubik dan silinder kemudian simulasi EM dijalankan. Validasi simulasi komputer dijalankan dengan mengkaji pendedahan kepada 2.4 GHz gelombang EM dengan menghasilkan ruang gema, di samping menggunakan pelindung Faraday untuk menutupi satu kumpulan bekas bagi mengkaji pendedahan kepada medan elektromagnetik yang banyak di persekitaran. Dua larutan, iaitu larutan yang tinggi ion dan larutan rendah ion, yang diwakili air mineral semulajadi dan H_20-NaCl telah digunakan digunakan sebagai sampel. Kualiti parameter air ditentukan melalui kaedah piawai. Struktur molekul air, keupayaan zeta dan mod penghabluran kandungan mineral air masing-masing ditentukan menggunakan ^{17}O Spektroskopi Resonans Magnetik Nukleus (^{17}O NMR), Teknik

Spektroskopi Raman, Penyerakan Cahaya Dinamik dan Mikroskop Pengimbas Elektron.

Keputusan simulasi medan elektromagnetik menunjukkan penyerapan tenaga medan elektromagnet berubah dengan perubahan bentuk bekas. Selepas didedahkan kepada gelombang 1.3V/m planar, nilai kadar jumlah penyerapan spesifik tenaga elektromagnet yang diserap oleh air pada 2400MHz untuk polarisasi vertikal adalah 0.0292, 0.0203, 0.0201 dan 0.01723 mW/kg, masing-masing bagi model bekas piramidal, segiempat tepat kubik, kubik dan silinder. Nilai maksimum medan elektrik yang terhasil di dalam air di dalam ruang gema selepas didedahkan kepada 1 W radiasi elektromagnet adalah 111.7, 22.9, 33.6 dan 60.3 V/m masing-masing bagi model bekas piramidal, segiempat tepat kubik, kubik dan silinder. Walaupun terdapat variasi dalam parameter fizikokimia dan mikrobiologi di antara air yang disimpan di dalam kumpulan bekas terlindung dan tidak terlindung, serta di antara air di dalam kumpulan bekas yang sama, air masih berada di dalam garis panduan WHO. Terdapat perbezaan signifikan [$p < 0.05$] di dalam kiraan plat heterotropik dan nilai pH di antara air yang disimpan di dalam bekas piramid tidak tertutup dan air tersimpan di dalam bekas piramidal, segiempat tepat kubik, kubik dan silinder tidak tertutup di dalam tiga fasa jangka masa kajian.

Secara kesimpulannya variasi dalam nilai jumlah penyerapan spesifik disebabkan air mempengaruhi saiz kluster molekul air dan nilai keupayaan zeta, yang ditunjukkan di dalam keputusan saiz partikel dan mod penghabluran kandungan mineral air di dalam larutan ion yang tinggi dan rendah. Ini secara tidak langsung mungkin mempengaruhi ciri-ciri fizikokimia dan mikrobiologi air mineral semulajadi. Keputusan kajian adalah sangat signifikan dalam mendapatkan parameter untuk penyimpanan air dan proses pembungkusan optimum.

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I certify that a Thesis Examination Committee has met on 22 October 2015 to conduct the final examination of Maher Abdelaleem Abdelrazik Abdelsamie on his thesis entitled "Effects of Electromagnetic Fields and Packaging Shape on Physicochemical and Microbiological Characteristics of Water" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

^{17}O NMR	Oxygen-17 nuclear magnetic resonance
APHA	American public health association
BDE	Bond dissociation energy
CNC	Computerized numerical control
DLS	Dynamic light scattering
DO	Dissolved oxygen
EM	Electromagnetic
EMF	Electromagnetic fields
EPA	Environmental protection agency
FDTD	Finite-difference time-domain
FEM	Finite element method
HDPE	High-density polyethylene
HPC	Heterotrophic plate count
IARC	International Agency for Research on Cancer expert panel report
MCL	Maximum contaminant level
MOE	Ontario Ministry of the Environment
PC	Personal computer
PD	Power density
PEC	Perfect electric conductor
PET	Polyethylene terephthalate
PLD	Power loss density
PML	Perfectly matched layer
PML	Perfectly matched layer
PMMA	Polymethyl methacrylate
R&S	Rohde and Schwarz
RF	Radiofrequency
SAR	Specific absorption rate
SEM	Scanning electron microscopy
SF	Spectrometer frequency
TDS	Total dissolved solids
VNA	Vector network analyzer
VP-SEM	Variable pressure scanning electron microscopy
WHO	World health organization

WLAN	Wireless local area networks

CHAPTER 1

INTRODUCTION

The production of halal food is an integrated process, starting from the farm (which represents the source of the food) to the consumer's fork or mouth. The process produces food that is not only ritually blessed but must also be safe, innocuous, and healthy which means (Tayyib). The halal standard for foods, MS1500:2009, was developed by Malaysia's Department of Standards and covers the production, preparation, handling, and storage of halal foods (Malaysian Standard). The Malaysian standard stated that Halal food must be non-intoxicating, or non-hazardous to health, safe for consumption and non-poisonous. It was also stated that drinks, microorganisms, natural minerals and chemicals are all Halal except those that are poisonous, intoxicating or hazardous to health (Malaysian Standard). The proper storage and packaging are important as they protect the food from deterioration. Such deterioration results from inappropriate environmental conditions during storage that could promote harmful chemical reactions and encourage the growth of microorganisms. The exposure of water-based liquid food products to environmentally abundant EMFs that has thermal and non-thermal effects during short or long-term storage could promote harmful chemical reactions and encourage the growth of microorganisms, which in turn will affect the Tayyiban aspect of water-based liquid food products.

The advances in wireless communication technologies (such as Wi-Fi, WiMAX, and GSM) have made the exposure of biological and non-biological materials to electromagnetic waves emitted from various sources (such as mobile phone base stations, Wi-Fi antennas, and broadcasting stations) a universal phenomenon. In the last few years, the number of studies on the biological implications of low-intensity electromagnetic radiation within the radiofrequency/microwave range emitted from wireless communication sources have increased tremendously. The studies on the non-thermal biological effects of low-intensity electromagnetic radiation reported in *The Bioinitiative Report 2012* were backed by considerable scientific evidence. The report summarized the findings of more than 1,800 studies that highlighted the biological effects of non-thermal low-intensity radiation (Group *et al.*, 2012a).

Water plays a major role in absorbing electromagnetic radiation that has thermal and non- thermal biological effects. Water is a polar molecule. The polarization of liquid water increases with the rise in the number of clustered molecules (Lorence *et al.*, 2009). The electromagnetic waves within the microwave range interact with individual molecules to a lesser extent than they do with clustered molecules. The clusters and individual molecules try to align with the applied electromagnetic field (Lorence *et al.*, 2009). This phenomenon is called dipole relaxation, and it is the dominant electromagnetic energy absorption mechanism in liquid water (Lorence *et al.*, 2009). Another dominant electromagnetic absorption mechanism is called ionic conduction. It involves the ions in water-electrolyte solutions moving in the direction of the applied electric field. The exposure of water or any biological material to electromagnetic

waves induces electric and magnetic fields in the exposed materials. These fields can be simulated by applying numerical techniques such as the finite-difference time-domain (FDTD) method or the finite element method (FEM) to solve Maxwell's equations for given boundary conditions. Many studies were conducted using the FDTD and FEM techniques to determine the distribution and the absorption rate of electromagnetic energy in food (Chen *et al.*, 2008; Geedipalli *et al.*, 2007; Liu *et al.*, 2013; Pitchai *et al.*, 2014).

Polarity is the reason behind the ability of molecules and ions to dissolve in water. Water is a universal solvent. A wide range of polar molecules, such as amino acids, sugars, small nucleic acids, and proteins dissolve in water (Hanslmeier, 2010; Hopkins *et al.*, 1995). Water plays a role as a metabolite in chemical reactions such as aerobic respiration (Hosler *et al.*, 2003) and photosynthesis (Reece *et al.*, 2013): It may be a product of a reaction or a reactant. Water also plays a role as a living environment for microorganisms and a vehicle for pathogens such as *Cryptosporidium, Giardia lamblia, Legionella,* viruses (enteric) (Cabral, 2010; Hanslmeier, 2010), and indicators such as faecal coliform and *Escherichia coli (E. coli)* (Edberg *et al.*, 2000). Moreover, water is used to manufacture a wide range of liquid pharmaceuticals whose quality and stability are of prime concern. Water is also the main constituent of liquid food products.

1.1. Problem Statement

It has been reported that the geometrical shape of human head models (which are flat, spherical, and ellipsoidal) significantly affect the absorption of EM energy at 900 MHz (Ruo, 1999). Furthermore, it is well known that the geometrical shapes of food products affect the absorption and distribution of electromagnetic energy in the microwave oven (Lorence *et al.*, 2009). For example, the edge overheating phenomenon that occurs during the microwave heating process is due to the concentration of the amplitudes of the electromagnetic fields at the edges and corners of the food product (Lorence *et al.*, 2009). Although the geometrical shape of biological materials affects the absorption of EM energy, the manufacturers of food products compete to develop innovative and attractive packaging shapes due to their role in the marketing process and influencing consumer purchasing decisions (Becker *et al.*, 2011; Silayoi *et al.*, 2004). No attempts have been made to explore the effects of the packaging shape of food products on the absorption of environmentally abundant electromagnetic radiation during storage. This absorption process could impact the physicochemical and microbiological characteristics of stored water-based food products in turn.

It appears from the aforementioned investigations that numerous investigations have been conducted on the impact of low-intensity electromagnetic radiation (within the radiofrequency/microwave range) on biological materials and water. However, no attempt has been made to investigate the relationship between environmentally abundant electromagnetic fields and packaging shapes or to study their effects on the physicochemical and microbiological characteristics of water-based food products during short-term or long-term storage.

The following factors have contributed to the rising significance of research on the relationship between the packaging shape of water-based food products and environmentally abundant electromagnetic fields: 1) the role of water as a universal solvent, metabolite, and living environment for microorganisms, 2) the increasing and widespread use of electromagnetic waves, 3) the ability of low-intensity electromagnetic radiation to induce non-thermal effects in biological materials and water solutions, 4) the exposure of water solutions such as water-based liquid-food products and liquid pharmaceuticals to low-intensity environmentally abundant electromagnetic radiation during short-term or long-term storage, and 5) the effect of the geometrical shape of food products on the absorption and distribution of electromagnetic energy. There is great demand for the study of the relationship between environmentally abundant electromagnetic fields and the packaging shape of food products and their effects on the physicochemical and microbiological characteristics of water during storage. Such efforts would help to obtain suitable parameters for storage and for packaging process optimization.

1.2. Scope of the Study

The prime and foremost goal of this research was to determine whether the packaging shape of water containers was capable of affecting the distribution and absorption of low- intensity electromagnetic radiation in stored water. Moreover, the research sought to determine whether that effect, in turn, would cause variations in the microbiological and physicochemical characteristics of water during storage. The study was accomplished through the following steps: 1) developing computer simulation models of rectangular, cylindrical, pyramidal, and square water containers of the same capacity, 2) manufacturing two identical groups of containers with the same dimensions and materials as those used to store water samples in the EM simulation, 3) determining the material properties of stored water and packaging material, 4) measuring the environmentally abundant EMF in the storage room during the storage period, 5) performing EM simulation by applying the finite-difference time-domain (FDTD) method to solve Maxwell's equations for given boundary conditions using the measured values of electric field strength and material properties, 6) validating the computer simulation models by applying three exposure scenarios: 1) exposing water containers to environmentally abundant EMFs, 2) conducting a sham-exposure experiment by storing the second group of four containers in an EMF- shielded room as a control, 3) exposing water containers to continuous EM waves (of 1 W at the microwave frequency of 2.45 GHz) as a single frequency emitted from a 1-W dipole antenna, and then determining the physicochemical and microbiological characteristics of water during storage and comparing them with the EM simulation results. The sixth steps were addressed in the third, fourth, fifth and sixth chapters of the thesis. The rectangular, cylindrical, and square packaging shapes were selected in this study because they are commonly used in the food packaging industry and they were compared with the selected pyramidal packaging shape, which was shown to induce biological effects in the stored biological materials as reported in the previous literature (Bhat *et al.*, 2007a; Bhat *et al.*, 2007b, 2009; Gopinath *et al.*, 2008; Murthy *et al.*, 2013; Narimanov, 2001; Nayak *et al.*, 2003).

1.3. Objectives

A high ionic content solution representing natural mineral drinking water was used as a sample. Standard methods were used to determine the water quality parameters (total dissolved solids (TDS), hardness, and total coliform count) in addition to the heterotrophic plate count (HPC). For the accurate study of the mechanisms by which EMFs affect water quality parameters, a low ionic content solution represented by H2O-NaCl was used. The water molecular structure, the zeta potential, and the crystallization mode of the water's mineral content for both natural mineral drinking water and H2O-NaCl solution were determined by Oxygen-17 Nuclear Magnetic Resonance (^{17}O NMR), Raman spectroscopy techniques, dynamic light scattering, and scanning electron microscopy, respectively. Therefore, this study was carried out with the main objective of studying the relationship between environmentally abundant low-intensity electromagnetic fields and packaging shapes, and their effects on the physicochemical and microbiological characteristics of water during storage. The specific objectives are:

1. To develop computer simulation models of rectangular, pyramidal, square, and cylindrical water containers, and to investigate the effects of packaging shape, polarization, irradiation geometry, and frequency on the computation of electric and magnetic fields and SAR in water containers and to study their relationship to the non-thermal biological effects of EMF;
2. To determine the relationship between the exposure to environmentally abundant EMFs, the 2.45-GHz EM waves, and packaging shape and their effects on the physicochemical and microbiological parameters of the natural mineral drinking water during storage;
3. To determine the relationship between the exposure to environmentally abundant EMFs, the 2.45-GHz EM waves, and packaging shape and their effects on ^{17}O NMR and Raman spectra of the H2O-NaCl solution and natural mineral drinking water during storage;
4. To determine the relationship between the exposure to environmentally abundant EMFs, the 2.45-GHz EM waves, and packaging shape and their effects on the zeta potential and the crystallization mode of the mineral content of the H2O-NaCl solution and natural mineral drinking water after seven days of exposure.

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