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**Faraday Effect as a New Technique for Testing  
Vegetable Oils**

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# Chapter One

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## *Introduction*

### 1.1 Background

Magneto-optics is an important field of research; it deals with phenomena arising from the interaction between light and matter when the latter is subjected to a magnetic field. For magnetically ordered matter (ferromagnets, ferrimagnets, etc), magneto-optical effects may appear in the absence of an external magnetic field as well (Moraru *et al.*, 2006; Palik, 1967). The presence of a magnetic field changes the dispersion curves of the absorption coefficient and leads to the appearance or variation of optical anisotropy (Ivanov and Nikolaev, 1999).

It is possible to divide magneto-optical phenomena into two distinct classes. The first class comprises those in which the source of light is acted upon by a magnetic field resulting in a change of wavelength accompanied by polarization (Zeeman Effect). The second class is the one in which the velocity of light and its state of polarization are modified when it passes through a magnetized medium i.e. Faraday effect (Jenkins and White, 1976). Both effects are very closely related (Sommerfeld, 1978; Van Vleck, 1932; Tan and Arndt, 1997) and are best studied simultaneously. The theoretical treatment of the Faraday effect involves the use of theorems developed for the explanation of the Zeeman effect, while the presence of the Faraday effect in some instances shows the

existence of a Zeeman Effect too small to be detected spectroscopically. A great number of magneto-optical phenomena are the direct or indirect outcome of the splitting of system energy levels in an external magnetic field, i.e. the Zeeman Effect. Essentially, all other magneto-optical effects are consequences of the Zeeman Effect (Kessler, 1967).

Michael Faraday in 1845 was the first to observe the effect of a magnetic field on optical phenomena (Nussbaum and Phillips, 1976). After many unsuccessful efforts to find a relation between magnetism and light, a successful trial was achieved by placing a block of heavy lead glass between the poles of an electromagnet, and passing plane polarized light through the block in a direction parallel to the lines of field (Yen *et al.*, 1999). The main observation was that the plane of polarization was rotated by the magnetized medium.

The early investigations focused on solid and liquid substances. Recently, because of the importance of the study of the effect, investigations were extended to gases, especially the gases having narrow absorption bands. From a theoretical point of view a new phenomenon is best studied with matter in its simplest state, a condition best met by a monoatomic gas such as the vapors of the alkali metals and mercury, the rare gases or atomic hydrogen (Jenkins and White, 1976).

This thesis is concerned mainly with the study of the Faraday effect in some vegetable oils; therefore it would be right to talk briefly about oils.

## **1.2 Oils**

Oils constitute an important part of the human diet. Formo *et al.*, (1979) mentioned that more than 90% of the world oils production from vegetable, animal and marine sources is

used as food or as an ingredient in food products. Sunflower oil is widely used for deep frying. In developing countries palm oil is a major tropical product of great economic importance. It has considerable versatility within the edible oil industry (Clegg, 1973). It is used extensively in the manufacture of the cooking fats and high quality confectionary fats.

The most widely used oil in the countries bordering on the Mediterranean sea is the olive oil, which is one of the world's most important and ancient oils. It is used almost entirely for edible purposes as a cooking and salad oil (Formo *et al.*, 1979).

A large variety of packaged oils and fats is available in the retail trade. Vegetable oils are packaged in glass, metals and different kinds of plastic films. Nutritionists, food processors, government regulators and consumers are paying great attention to storage stability and shelf life for fats and oils (Kaya *et al.*, 1993). The barrier properties of the package against moisture, oxygen and the interaction of food constituents with the packaging materials determine the quality and shelf-life of the packaged food (Sharma *et al.*, 1990). Hence, the major function of packaging is to minimize reactions that affect the stability of the contained products (Karel and Heidelburgh, 1975; Gilbert and Mannheim, 1982). The environmentally omnipresent gaseous reactants, water vapour and oxygen can seriously affect stability under normal food storage and distribution conditions. However, when certain reactions occur spontaneously packaging does not affect stability in most cases (Gilbert, 1985).

Food products usually lose their quality through rancidity which is the development of an off flavour by oxidation and hydrolysis which makes the food unacceptable (Labuza, 1971; Frankel, 1983; Paquette *et al.*, 1985; Robards *et al.*, 1988).

Most plastic films are inert towards food constituents. However, a small amount of unconverted monomers and oligomers migrate into foods. These substances are used in the manufacture of plastic films to provide stability, plasticity and other desirable functional characteristics. Crompton (1979) and Shepherd (1982) found that this migration becomes extensive through direct contact with fatty food surfaces and at high temperature.

Plasticizers, antioxidants, antistatic agents, lubricants and other additives are compounded into the basic polymer before being molded into the respective plastic materials (Jayaraman and Vasundhara, 1976). Leached-out substances of various plastic materials used for food packaging applications influence the quality and stability of foods.

It is believed that fat soluble phenolic antioxidants added to the polymer migrate at an appreciable rate into the stored fat. Mahadeviah, (1975) and Crosby, (1981) have studied butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) as representatives of these additives. Other studies of antioxidants including Niebergall and Hartmann, (1983); Freytag *et al.*, (1984); Baner *et al.*, (1992); Miltz *et al.*, (1988), reported on extension of the shelf life of the products as a result of added antioxidants.

Vitamin D, which is found at high concentrations in vegetable oils, is a fat soluble vitamin. Tocopherols, especially the  $\alpha$ -isomer, have a great influence on shelf-life, preserving oils from rancidity by interrupting the chain reactions involved in the formation of hydroperoxides (Shahidi and Wanasundara, 1992).

After studying the oxidative stability of olive oil stored in glass and polyethylene (PE) plastic bottles (Kiritsakis, 1984), Kiritsakis has concluded that glass bottles provide better protection from oxidation than polyethylene plastic bottles do. The effect of plastic film contact on the storage stability of refined sunflower oil and groundnut oil at 37 °C was studied by Sharma *et al.*, (1990). This included polyethylene (PE), polypropylene (PP) and butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) incorporated in polyethylene. These authors concluded that changes in peroxide value and thiobarbituric acid were significantly less in the presence of plastic films than in control samples. Both BHA and BHT were found to leach out from plastic films into vegetable oils during storage. It has been shown that crude palm oil, packaged in clear plastic bottles, sealed polyethylene film and clear glass bottles, recorded higher total oxidation values than oils packed in either lacquered metal or amber and green glass bottles (Nkpa *et al.*, 1990; 1992). Lacquered metal cans gave the greatest protection against oxidation. The effect of permeability and transparency of the packages (PET and glass bottles) on the shelf-life of sunflower and olive oils was studied by Kaya *et al.*, (1993).

The oxidative stability of olive oils was determined by measuring their peroxide values.

The increase of storage stability with respect to packaging materials was as follows:

PET < Clear glass < Coloured glass. Sirokhman (1983) used peroxide, thiobarbituric acid values and acid number to determine oils' quality. Statue *et al.*, (1995) mentioned that measuring the peroxide value (PV) is frequently used to determine oxidation in oils. This index is related to the hydroperoxides, the primary oxidation products. Mixtures of volatile aldehyde compounds are formed from decomposition of hydroperoxides which are unstable. These aldehyde compounds are considered important markers of oxidative rancidity because they are directly responsible for rancid flavour (Frankel, 1983).



Olive oil has a characteristic aroma, taste and colour which distinguish it from all other edible vegetable oils. Consumers tending to choose the least-processed foods have enhanced the presence of olive oil in their diets because of its excellent organoleptic and nutrient properties.

The main olive oil constituents are: triacylglycerols and small quantities of free fatty acids, glycerol, pigments, aroma compounds, sterols, tocopherols, phenols, unidentified resinous components and others (Kiritsakis, 1998). Among these constituents the unsaponifiable fraction which covers a small percentage (0.5 - 15%) plays a significant role on human health.

Vegetable oils have numerous components, therefore many analytical techniques have been employed to identify and quantify them. Among these techniques are: chromatographic analysis, stable carbon isotope ratio analysis (SCIRA) (Antolovich *et al.*, 2001; Andrikopoulos, 2002). Mass Spectrometry (MS), Nuclear magnetic resonance spectroscopy (NMR) (Vigli and Philippidis, 2003), Near-infrared spectroscopy (NIR) (Bartlet, 1957), Fourier Transform Infrared Spectroscopy (FT-IR) and FT-Raman spectroscopy (Guillén and Cabo, 1999).

Most of these chromatographic or spectroscopic techniques are laborious. So a more simple technique to test vegetable oils is welcomed. We believe that Faraday effect could provide such valuable technique for this purpose.

One of the factors affecting oil quality is storage conditions. A review of the effect of the container on oil quality can be found in (Tsimis and Karakasides, 2002). Kanavouras *et al.* (2004) made shelf-life predictions for packaged olive oil using flavour compounds as markers. The influence of light on the shelf-life of packaged olive oil was studied by

Kanavouras and Coutelieris (2005) and by Caponio *et al.*, (2005); Mousa *et al.*, (1996) studied the effect of altitude of fruit growth on fruit and oil quality characteristics of ‘Mastoides’ olives. EL-Sarahneh (1995) used the photopyroelectric effect to monitor olive oil quality and olive fruit oil content during the ripening period.

However, the quality of virgin olive oils decreases over the course of time as a consequence of oxidative and hydrolytic degradations which also cause the partial loss of other minor constituents having health-promoting effects (Visoli and Galli, 1998).

It is a matter of great concern for the olive oil industry to preserve the positive attributes of oil during the time elapsing from production to bottling, and up to purchasing. Oil producers need to pay a great deal of attention to the type of containers they place the oils in after production and to the storage conditions they are kept in before sale.

### **1.3 Statement of the Problem**

Food authentication is an important subject and it has evolved continually being governed by a global market trend. Devious adulterations are made by fraudsters. So there is a need to develop new techniques to check the authenticity of food products. This is what we address our selves to in this study.

One of the major food products are oils and fats. Today consumers are demanding food products that combine a pleasant flavour with nutritional benefits. Therefore, there is an expanding market for vegetable oils. Thus there authenticity is important from both commercial and health perspectives. For example, large amounts of money can made by adding cheaper oils to virgin olive oil. Authenticity covers many aspects including adulteration, mislabeling, characterization and misleading origin.

In this work the Faraday effect in some vegetable oils was studied. The aim is to use the Verdet constant as a new technique to determine the stability of some vegetable oils as follows:

1. Study the effect of the container material (e.g. glass, plastic) on the Verdet constant.
2. Study the effect of exposure to light on the Verdet constant.
3. Study the variation of the Verdet constant with the region of cultivation in different parts of Palestine (north, center and south).
4. Study olive oil adulteration with some vegetable oil (wheat oil) depending on the value of the Verdet constant of the mixture.

#### **1.4 Thesis Organization**

Following this introduction, chapter two presents the Faraday effect theory from different perspectives and gives some applications of the Faraday effect. In Chapter three, is the experimental system in which the techniques and the explanation of apparatus were presented. Chapter four shows the experimental results for test samples and original results. In Chapter five the results were discussed and finally Chapter six presents the conclusions and further work.

## **Chapter Two**

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### *Theoretical Background*

#### **2.1 Introduction**

This research is concerned with the measurement and interpretation of the Faraday effect in some vegetable oils. The Faraday effect (magnetically induced circular birefringence) reveals a fundamental connection between optics and magnetism (Barth, 2000).

Transparent substances in which the molecules are not mirror symmetric are “optically active” to some extent (Stone, 1963). Dextrose which is also known as d-glucose and d-tartaric acid used in soft drinks are nutritious optically active substances. Whether pure, or in solution form these substances rotate the plane of polarization counterclockwise relative to the direction of propagation. The opposite is done by the mirror images of these substances which are incidentally not nutritious.

In 1845 Faraday discovered circular birefringence in connection with magnetic fields. He established for the first time a direct connection between optics and magnetism. However, it took half a century to formulate the Faraday effect in terms of Maxwell’s electromagnetic theory of light and the concept of the atomicity of charge which had evolved during the 19<sup>th</sup> century under the influence of electrochemistry and had been confirmed by Thomson’s discovery of the electron in 1897 (Wayman, 1997).

Most of the work in this thesis is based on the empirical formula  $\theta=VLB$  (Surma and Ciszek, 1996), where:  $\theta$  is the Faraday rotation angle,  $V$  is a proportionality factor called that Verdet constant,  $L$  is the length of the sample,  $B$  is the applied magnetic field.

It remained, however, to calculate the value of  $V$  from the fundamental physics of light, magnetism and matter. As will be seen in the following sections the Faraday effect is due to the difference in the indices of refraction for right and left-circularly polarized light. This difference is a result of the presence of the magnetic field.

Becquerel, in 1897 took the first step towards understanding the Faraday effect in terms of electromagnetic theory and the atomic structure of matter (Shen, 1984). His theory included the concept of the newly discovered electron (Lorentz, 1952), but was not based on the idea of quantized energy states or the concept of light quanta. Even though the Becquerel theory does not make use of quantum principles, it is a useful framework for a preliminary understanding of the phenomenon and gives quantitative predictions for the Verdet constant that are noticeably close to the measured values. It was not until the early 1930's that substantial steps beyond Becquerel's theory were taken. At that time the effect was studied in gases (Serber, 1932; Van Vleck, 1932). A large amount of theoretical and experimental work has been done on the Faraday effect in solids since 1960, (Hayakawa *et al.*, 1997; Takeuchi *et al.*, 2001; Adachi *et al.*, 1995; Holm *et al.*, 1995).

Recent theoretical treatments are very complex as a perusal of reviews will show (Mavroides, 1972). Indeed the quantum treatment of the problem in even the simplest of materials is complicated and the results depend critically on the nature of the medium i.e.

whether it is dielectric, semiconducting, diamagnetic, paramagnetic ferromagnetic etc. Incidentally, in ionized gases where the active agents are free electrons the theory of the Faraday effect is not so complicated.

Recently, there are studies of Faraday effect in glasses (Hayakawa *et al.*, 1997; MacFarlane *et al.*, 1997; Tan and Arndt, 1997), magnetic garnets (Takeuchi *et al.*, 2001; Adachi *et al.*, 1995; Kucera *et al.*, 1996) and Faraday sensors (Holm *et al.*, 1995; Villaverde *et al.*, 1998).

## 2.2 The Classical Theory of Faraday Effect

When optically inactive substances are placed in a magnetic field parallel to the direction of propagation of a light wave they become active. For the sake of simplicity, it is assumed that all electronic oscillators have the same angular frequency  $\omega_0$ . Consider a circularly polarized monochromatic wave of angular frequency  $\omega$  traveling in the direction of the x-axis of a cartesian frame of reference. In the absence of a magnetic field, the forces acting upon a given electron are the restoring force and the force  $-e\vec{E}$  due to the electric field  $\vec{E}$  of the wave (Francon, 1963). Since  $\vec{E}$  remains constant in magnitude and rotates with the constant angular velocity  $\omega$ , the electron in the steady state condition will be forced to describe a circular orbit with the same angular velocity  $\omega$ . The radius  $r$  of this orbit is determined by the condition that the resultant force should equal the product of the mass times the centripetal acceleration. If  $\vec{r}$  is the vector from the center of the circle to the instantaneous position of the electron, the restoring force is  $-k\vec{r}$  and the centripetal acceleration is  $-\omega^2\vec{r}$ , then the following equation is obtained:

$$-e\vec{E} - k\vec{r} = -m\omega^2\vec{r}. \quad (2.1)$$

Or, recalling the expression,  $\omega_0 = \sqrt{\frac{k}{m}}$  and solving equation (2.1) for  $\vec{r}$  to get:

$$\vec{r} = -\frac{e/m}{\omega_0^2 - \omega^2} \vec{E} \quad (2.2)$$

Thus, by making use of equation (2.2), the electric dipole moment of each oscillator has the expression (Nussbaum and Phillips, 1976).

$$\vec{p} = -e \vec{r} = \frac{e^2/m}{\omega_0^2 - \omega^2} \vec{E} \quad (2.3)$$

If N is the number of oscillators per unit volume, the polarization vector is given by

$$\vec{P} = N\vec{p} = \frac{Ne^2/m}{\omega_0^2 - \omega^2} \vec{E} \quad (2.4)$$

This equation is identical to expressing the relation between  $\vec{P}$  and  $\vec{E}$  for a linearly polarized wave.

Let us suppose now that the substance is placed in a magnetic field  $\vec{B}$  parallel to the x-axis and pointing, for example, in the positive direction. Upon each moving electron the magnetic field will exert a force directed along the radius of the circular orbit, and equal  $+eB\omega\vec{r}$  if the electron rotates counterclockwise (i.e. if the light wave has left-handed circular polarization) or to  $-eB\omega\vec{r}$  if the rotation is clockwise. Therefore, equation (2.1) becomes:

$$-e\vec{E} \pm eB\omega\vec{r} - k\vec{r} = -m\omega^2\vec{r} \quad (2.5)$$

Which yields,

$$\vec{r} = -\frac{e/m}{\omega_0^2 - \omega^2 \pm eB\omega/m} \vec{E} \quad (2.6)$$

and therefore

$$\vec{P} = \frac{Ne^2/m}{\omega_0^2 - \omega^2 \pm eB\omega/m} \vec{E} \quad (2.7)$$

The electric displacement is followed according to

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} = \varepsilon_0 \vec{E} + \frac{Ne^2 / m}{\omega_0^2 - \omega^2 \pm eB\omega / m} \vec{E} \quad (2.8)$$

In equations (2.7) and (2.8) the - sign refers to left handed polarization, the + sign refers to right handed polarization. In both cases, the light wave is assumed to travel in the direction of the magnetic field. For light waves traveling in the opposite sense, the signs would be inverted (Didosyan and Barash, 1995).

Equation (2.8) is fulfilled in the presence as well as in the absence of the magnetic field.

$\vec{D}$  is proportional and parallel to  $\vec{E}$  in general. The permittivity  $\varepsilon$  can be defined by means of the constitutive relation  $\vec{D} = \varepsilon \vec{E}$ . Thus the following equation is obtained for  $\varepsilon$ :

$$\varepsilon = \varepsilon_0 + \frac{Ne^2 / m}{\omega_0^2 - \omega^2 \pm eB\omega / m} \quad (2.9)$$

From this equation, the refractive indices  $n_L$  and  $n_r$  corresponding to the left-handed and right-handed polarization, can be written as:

$$n_L^2 = 1 + \frac{Ne^2 / \varepsilon_0 m}{\omega_0^2 - \omega^2 - eB\omega / m} \quad (2.10 a)$$

$$n_r^2 = 1 + \frac{Ne^2 / \varepsilon_0 m}{\omega_0^2 - \omega^2 + eB\omega / m} \quad (2.10 b)$$

Where the index of refraction  $n$  of the medium in the absence of the magnetic field is given by:

$$n^2 = 1 + \frac{Ne^2 / \varepsilon_0 m}{\omega_0^2 - \omega^2} \quad (2.11)$$

Combining equations (2.10 a) to (2.11), to get:

$$\frac{1}{n_r^2 - 1} - \frac{1}{n^2 - 1} = \frac{1}{n^2 - 1} - \frac{1}{n_L^2 - 1} = \frac{\varepsilon_0 B \omega}{Ne} \quad (2.12)$$



Since  $n - n_r \ll n$  and  $n_L - n \ll n$ , then to a good approximation, equation (2.12) can be written as:

$$\frac{1}{n_r^2 - 1} - \frac{1}{n^2 - 1} = \frac{n^2 - n_r^2}{(n^2 - 1)^2} = \frac{2n}{(n^2 - 1)^2} (n - n_r) \quad (2.13)$$

Similarly,

$$\frac{1}{n^2 - 1} - \frac{1}{n_L^2 - 1} = \frac{2n}{(n^2 - 1)^2} (n_L - n) \quad (2.14)$$

Hence,

$$n - n_r = n_L - n = \frac{(n^2 - 1)^2}{2n} \frac{\varepsilon_0 B \omega}{Ne} \quad (2.15)$$

From these results it is recognized that left-handed and right-handed circularly polarized waves travel in the direction of the magnetic field with different velocities. This is the characteristic property of optically active substances (Nussbaum and Phillips, 1976). Equation (2.15) shows that the index of refraction of the left-handed circularly polarized wave is larger than that of the right-handed wave if, as it is assumed, light travels in the direction of the magnetic field. For the opposite direction of propagation, the index of refraction of the left-handed wave becomes smaller than that of the right-handed wave.

It is then concluded that the substance behaves as a dextrorotary medium for a wave that travels in the direction of the magnetic field, and as a levorotary medium for a wave that travels in the direction opposite to the field. This is confirmed by experiment. It should be noted that naturally active substances do not change from levorotary to dextrorotary, or vice versa, when the direction of propagation of the wave is inverted.

### 2.3 Becquerel's Theory of the Faraday Effect

Following Becquerel and subsequent presentations of his theory (e.g. Rossi, 1957) it is assumed that a transparent material contains particles of mass  $m$  and charge  $q$  embedded in a continuum of opposite charge and restrained by elastic force to vibrate about fixed sites (Le Grand, 1968).

Consider the situation in which there is a steady magnetic field  $\vec{B}$  of magnitude  $B$  in the +x direction and a plane right circularly polarized electromagnetic wave which, at a given point, produces a rapidly varying electric field  $\vec{E}$  of constant magnitude  $E$ , rotating clockwise with respect to  $\vec{B}$  in a plane perpendicular to  $\vec{B}$ . In the steady state the charged particles move in a circle of radius  $r$  governed by the following equation:

$$-m\omega^2 r = -kr + Eq + Bq\omega r \quad (2.16)$$

Where  $k$  is the "spring constant" of the restoring force. For left circularly polarized light the sign of the magnetic term is reversed. When equation (2.16) is solved for  $r$ , the following expression is obtained:

$$r = (Eq/m) / (\omega_0^2 - \omega^2 - Bq\omega/m) \quad (2.17)$$

where  $\omega_0 = (k/m)^{\frac{1}{2}}$  is a defined earlier

Displacement of a charge  $q$  from its oppositely charged equilibrium site by the distance  $r$  creates an electric dipole of magnitude  $qr$  (Garbuny, 1965). If there are  $N$  such dipoles per unit volume, then the polarization  $\vec{P}$  has the magnitude  $Nqr$ , and the electric displacement is  $\vec{D} = \epsilon_0 \vec{E} + \vec{P}$ . Therefore,

$$\vec{D} = \epsilon_0 \vec{E} + (Nq^2 \vec{E}/m) / (\omega_0^2 - \omega^2 - Bq\omega/m) \quad (2.18)$$

Using the constitutive relation  $\vec{D} = \epsilon \vec{E}$ , the following equation is obtained for  $\epsilon$ :

$$\varepsilon = \varepsilon_0 + (Nq^2 / m) / (\omega_0^2 - \omega^2 - B\omega q / m) \quad (2.19)$$

So, in the presence of a magnetic field the index of refraction for right circularly polarized light can be given as:

$$n_r^2(\omega) = \varepsilon / \varepsilon_0 = 1 + (Nq^2 / m) / (\omega_0^2 - \omega^2 - B\omega q / m) \quad (2.20a)$$

And for left circularly polarized light

$$n_L^2(\omega) = \varepsilon / \varepsilon_0 = 1 + (Nq^2 / m) / (\omega_0^2 - \omega^2 + B\omega q / m) \quad (2.20b)$$

Equations (2.20) show that the indices “blow up” as the frequency of the light approaches a value such that  $\omega_0^2 - \omega^2 \pm B\omega q / m = 0$  (one can avoid this physical catastrophe of our simple assumptions by adding to the equation of motion a damping term representing a drag force proportional to the velocity of the charged particle (Garbuny, 1965). Such a term can give a classical account of the phenomenon of absorption. Both the indices of refraction and the absorption coefficient have maxima near  $\omega_0$ . Fortunately, omission of a damping term has very little effect on the accuracy of the theory at frequencies far from  $\omega_0$  as in the present case. The sign of the effect of the magnetic field on the indices of refraction for circularly polarized light depends on the sign of the product  $B\omega q$ . In particular, for right circular polarization with  $\vec{B}$  in the direction of propagation ( $B_x > 0$ ) and negatively charged particles,  $B\omega q < 0$ , which implies a decrease in  $n_r$  and a corresponding increase in  $n_L$ . Therefore, under these assumptions  $(n_L - n_r) > 0$ . The change of  $n_r$  caused by turning on a magnetic field  $B$  is equal to the change of  $n_r$  when the frequency of light is changed from  $\omega$  to  $\omega + \Delta\omega_r$ , where  $\Delta\omega_r$  is defined by the quadratic equation:

$$\omega^2 + B\omega q / m = (\omega + \Delta\omega_r)^2 \quad (2.21 a)$$

The solution of this equation is

$$\Delta\omega_r = Bq / 2m \quad (2.21 \text{ b})$$

$$\text{Similarly, } \omega^2 - B\omega q / m = (\omega + \Delta\omega_L)^2 \quad (2.22 \text{ a})$$

$$\text{And } \Delta\omega_L = -Bq / 2m \quad (2.22 \text{ b})$$

These  $\Delta\omega$ 's are very small compared to  $\omega$ . Thus the difference in the indices of refraction can be written with high accuracy as

$$n_L - n_r = (dn/d\omega)(\Delta\omega_l - \Delta\omega_r) = (dn/d\lambda)(\lambda^2 / 2\pi c)(Bq / m) \quad (2.23)$$

Where  $\lambda = 2\pi c / \omega$  is the vacuum wavelength of the light. Introducing the angle of Faraday rotation  $\theta$  as:-

$$\theta = \tan^{-1}\left(\frac{E_z}{E_y}\right) = \frac{\omega(n_L - n_r)L}{2c} = \frac{\pi(n_L - n_r)L}{\lambda} \quad (2.24)$$

then using equation (2.24), to express  $\theta$  in terms of other parameters as:

$$\theta = \frac{dn}{d\lambda} \frac{\lambda}{2c} \frac{q}{m} LB \quad (2.25)$$

Thus, using the equation  $\theta = VLB$ , the Verdet constant is related to the constants of the interacting particles Bequerel formula. Thus,

$$V = \frac{dn}{d\lambda} \frac{\lambda}{2c} \frac{q}{m} \quad (2.26)$$

The complication can be buried by defining a constant  $C$  such that equation (2.26) is written as:

$$V = \frac{-dn}{d\lambda} \frac{\lambda}{2c} C \frac{e}{m_e} \quad (2.27)$$

Where  $-e$  and  $m_e$  are the charge and mass of the free electron. It is reassuring that for visible light in ordinary molecular hydrogen gas  $H_2$ , the value of  $C$  is 0.99. For other substances and other spectral bands the values of  $C$  can be substantially different from unity and in some cases, even negative.

In the case of the interstellar medium where the effect is due to the presence of free electrons one has  $\omega_0 = 0$  and  $C = 1$ . For convenience rewrite equations (2.20) to express the dependence of the index of refraction on wavelength ( $B = 0$ ), the result can be rewritten as:

$$n = \left\{ 1 + \frac{K}{1 - (\lambda_0 / \lambda)^2} \right\}^{\frac{1}{2}} \quad (2.28)$$

where  $\lambda_0 = 2\pi c / \omega_0$ , and  $K = Nq^2 / \varepsilon_0 m\omega_0^2$ .

It is possible to see that the classical theory of Faraday effect retains many of the elements of Becquerel's theory. Both derivations are based on the classical electromagnetic theory. However, in Becquerel's derivation he arrived at an explicit formula for the Verdet constant, while the classical derivation of the Faraday effect is mainly interested in proving that the indices of refraction for left and right circularly polarized light become different in a magnetized medium and give a value of the Faraday rotation angle in terms of the difference in indices of refraction.

Becquerel's theory gives a fairly accurate account of the phenomenon of the Faraday effect, such that the calculated values of the Verdet constant agree with experimental results.

#### **2.4 Applications of Faraday Effect**

Faraday effect has many applications in optical recording and optical communication. The increased number of optical and laser based devices require either rapid switching or protection against back-reflected beams. Faraday effect has sensor applications and is used in astronomy to probe the ionosphere ( Kravtsov and Naida, 2001).

The Faraday effect has been used for the construction of a linear displacement sensor (Villaverde *et al.*, 1998), current sensors (Maystre and Berthholds, 1989; Muto *et al.*, 1992) and magnetic field sensors (Deeter *et al.*, 1990).

The basic magneto-optical materials used in near infrared region are garnets (Didosyan and Barash, 1995). A great number of investigations of these crystals performed in the past decades resulted in increasing compositions with substantially improved characteristics (Belt *et al.*, 1994).

Other perspective magneto-optical materials are orthoferrites which comprise a whole number of unique features. Therefore, they can find wide applications in various practical devices, especially as optical isolator. Because of their rectangular hysteresis loop they can work without external magnets, thus substantially reducing dimensions of the element and improving its characteristics.

Among many other applications Faraday effect is used in the determination of optical anisotropy of molecules, to infer the susceptibility of materials and measure carrier densities in semiconductors if the effective mass of the carrier is known.

## **Chapter Three**

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### *Experimental*

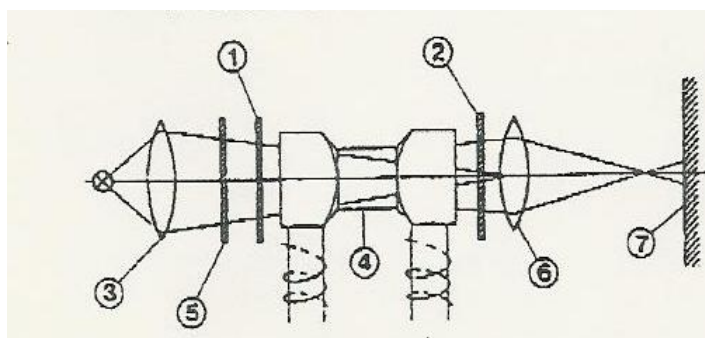
#### **3.1 Introduction**

This chapter presents the experimental techniques used in this work. Faraday effect experiment will be carried out in its conventional form, but with slight modifications specially in the angle of rotation measurement. The methodology used to perform this study was experimental and quantitative. A phase sensitive method (a lock-in amplifier) was used to monitor the Faraday effect for different olive oil samples from different parts of Palestine and with different production years and different storage conditions. The same method was also used to measure the Faraday effect for some other vegetable oils. The measurements were taken in the year 2005.

In section 3.2 a description of the apparatus is presented while in section 3.3 the detection scheme is explained. Angle measurements and magnetic field measurements are described in section 3.4 and 3.5, respectively, while the samples are described in section 3.6.

### 3.2 Description of Apparatus

The basic setup of the Faraday effect is as shown in Figure 3.1. It consists of a light source, a polarizer, an analyzer, a condenser, a test specimen, coloured glass (filter), a lens, an electromagnet and a translucent screen (Phywe, 1995).



- |                   |             |                       |                  |
|-------------------|-------------|-----------------------|------------------|
| 1. Polarizer      | 2. Analyzer | 3. Condenser          | 4. Test specimen |
| 5. Coloured glass | 6. Lens     | 7. Translucent screen |                  |

**Figure 3.1** The basic setup of the Faraday effect.

The description of these elements is as follows:

#### 3.2.1 The Light Source

The experiment lamp is a universal standard lamp which can be fitted with three different lamp sockets according to requirement. This allows to use it as:

- Point light source 30 W.
- Halogen lamp 50W or 100 W.
- Spectral lamp.

In this work the 50 W lamp was used. The lamp consists of the following parts:

- Casing for experiment lamp which is a plastic casing with metallic interior cladding, stem articulation for inclination  $\pm 90^\circ$ . Sliding mount which can be shifted externally about 13 cm in the direction of the optical axis and which can



take different lamp sockets. There are also adjustment knobs for height and lateral adjustment of the lamp sockets. At the back there is an adjustment disk with looking window to identify the used type of lamp. In addition, there is a light emission tube which can take standard components (condenser, diaphragm holder, etc.). Provided also is a fixed connecting cable 140 cm with 4 mm plug pins.

- b. Halogen lamp 12 V/50 W.

### **3.2.2 Polarizer and Analyzer**

High quality filter to generate and analyze linearly polarized light. The glass filter is mounted on a screen with a stem and can be rotated. The angular graduated scale range is 0 – 95°.

### **3.2.3 Framed Coloured Glass**

This is used to obtain monochromatic light.

Colour filter	440 nm
Colour filter	525 nm
Colour filter	580 nm

### **3.2.4 Electromagnet**

It is used to generate strong magnetic fields together with pole pieces (drilled). It consists of a U-shaped iron core with coils which can be used either in parallel or in series. It has also coil flanges of electrically conducting material for practically total annihilation of field energy when the coil current is switched off, thus assuring only small overvoltages. It is also equipped with a clamping device for sensitive air gap adjustment with pole pieces. Smoothed direct current is not required to operate the

electromagnet. As a suitable transformer is used e.g. adjustable transformer with rectifier, 25 VAC /20 VDC, 12 A.

Number of turns per coil		842 turns
Resistance per coil		2.66 $\Omega$
Maximum current		5 A (short term operation 20 min.)
Admissible permanent Current		4 A
Dimensions	width	350 mm
	depth	140 mm
	height	180 mm
Mass		~ 17 kg

### 3.2.5 Variable Transformer 25 VAC / 20 VDC, 12 A

It supplies 25 VAC / 20 VDC, 12 A, a continuously adjustable DC and alternating voltage and also two frequently used fixed voltages, e.g. used by filament lamps.

The output is galvanically isolated from the mains grid and non-grounded; it is also protected with an overcurrent circuit breaker.

### 3.2.6 Digital Teslameter:

It is used for accurate measurement and displays of direct and alternating magnetic field. Its characteristics are:

- Large  $3\frac{1}{2}$  digits, luminous display.
- Indication of field direction (sign) in the case of direct fields.
- Display from  $10^{-5}$  till 2 T in 3 measurement ranges which can be selected.
- Zero adjustment.
- Possibility to compensate disturbing fields (e.g. terrestrial field).

- f. Calibrated, so that no calibrating magnets or coils are required.
- g. 2 probes with particularly large, temperature independent Hall effect.
- h. Flexible, very flat tangential probe for measurements in air gaps.
- i. Long axial probe to measure fields in the vicinity of conductors and inside coils.
- j. Analogue output to connect a recorder.

### **3.3 Detection Scheme**

Since judgment about complete extinction by the translucent screen or by eye inspection is not very accurate a more advanced detection scheme was applied. The light signal was detected by a photocell and the signal was fed to a lock- in amplifier. Several options were tried for light signal detection for example using a photometer, a phototransistor and a photodiode. However the best results were obtained with the phase sensitive detector in conjunction with a photocell. Therefore, this technique was used in the present work.

Using lock-in amplifiers it is possible to detect very small AC signals, all the way down to a few nanovolts. It is possible to make accurate measurements even when the small signal is obscured by noise sources many thousands of times larger. The technique used in lock-in amplifiers is called phase-sensitive detection. It is used to single out the component of the signal at a specific reference frequency and phase. Noise signals at frequencies other than the reference frequency do not affect the measurement because they are rejected.

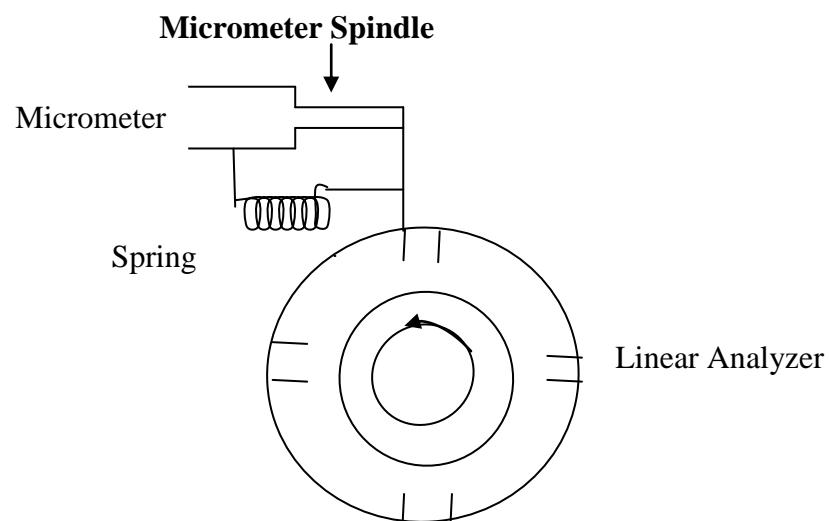
To get an AC signal the light beam was chopped at a frequency of 12 Hz. The signal from the chopper was fed into the lock in reference to be compared to the signal from the photocell. Only the component of the signal at the reference frequency and phase will be considered by the phase sensitive detector. All noise at other frequencies will be rejected.

The output of the lock-in amplifier (DC Voltage) was used as a reference. First, a rotation of the polarization plane was achieved by an input current to the electromagnet, then the same deflection was brought about manually by turning the micrometer attached to the pointer of the analyzer. Thus, only the proportionality between the Faraday rotation angle and the reading of the lock-in amplifier was used. The explicit dependence of the lock-in amplifier reading on the Faraday rotation angle was not worked out since the deflection angle was measured manually.

The sensitivity of the lock-in amplifier was  $300 \mu V$  and the time constants for the internal oscillators were 1 second, 1 second respectively.

### 3.4 Angle Measurement

Another improvement on the Faraday effect experiment was introduced. This was done through angle calibration. Instead of measuring the angle directly from the scale on the analyzer, which is not a very accurate process, a micrometer was used. This was attached to the pointer of the polarization filter using a spring and the reading of the micrometer was converted into angle measure, as shown in Figure 3.2.



**Figure 3.2** Apparatus for calibrating Faraday rotation angle.

The micrometer spindle was rotated to compensate for the increase in the photo-current, as a result of polarization rotation of the light beam.

### **3.5 Magnetic Flux Density Measurement**

Using the axial Hall probe of the teslameter the magnetic flux density between the pole pieces was measured for different coil currents. The mean flux density was calculated by numerical integration and the ratio maximum flux-density over mean flux density established. The maximum flux density is at the center of the gap, while the mean flux density is the average over the length of the sample.

### **3.6 Samples**

Different olive oil samples from different parts of Palestine were collected from various production years. These samples were stored under different conditions e.g. in room light or in the dark, plastic or glass container, totally filled or partially filled container.

In addition to the olive oil samples different other vegetable oil samples were bought from a local store to be analyzed. The oil was placed in a cuvette cell of BK-7 glass ( $\sim \text{SiO}_2$ ), of the length 12 mm. After the cuvette cell was accidentally broken, the oils were placed in Ordinary glass of length 20 mm. The cell or the Ordinary glass was placed between the poles of an electromagnet to measure the Verdet constant.

In simple terms, the Faraday effect setup consists of passing a linearly polarized beam of light through a sample subjected to a magnetic field, and measuring the resulting rotation of the plane of polarization depending on light extinction as determined by the naked eye.

For the purpose of the current work the basic setup of the Faraday effect was not sufficient because high accuracy was needed. Therefore, several improvements of the

basic set up were introduced. These included calibrating the Faraday rotation angle, and chopping the light signal to be able to use a phase-sensitive detection scheme. Upon introducing the previous improvements the complete experimental system looks as in Figure 3.3 below.

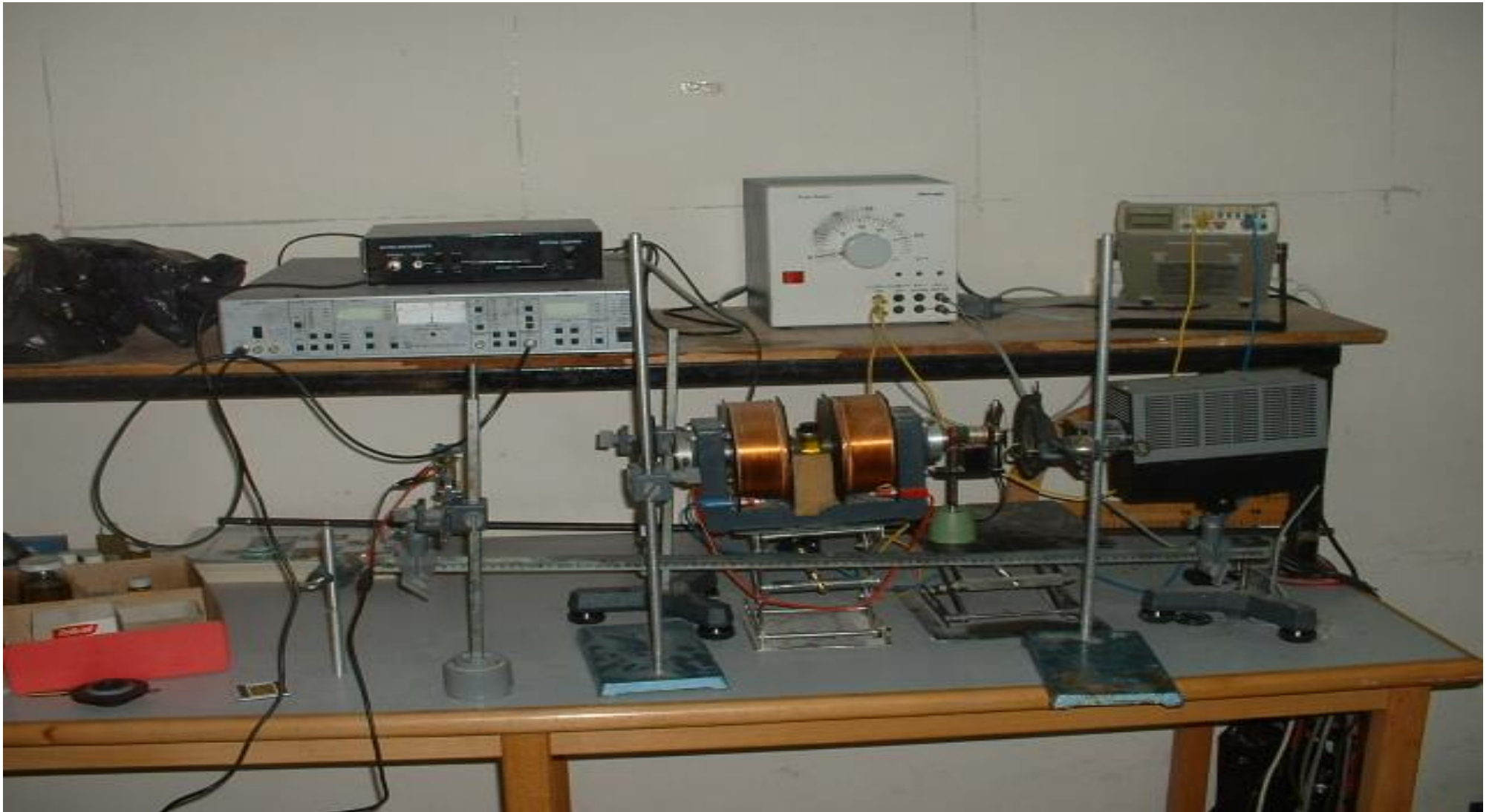


Figure 3.3 Photo of the complete system used to study Faraday effect of some vegetable oils.

## **Chapter Four**

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### ***Experimental Results***

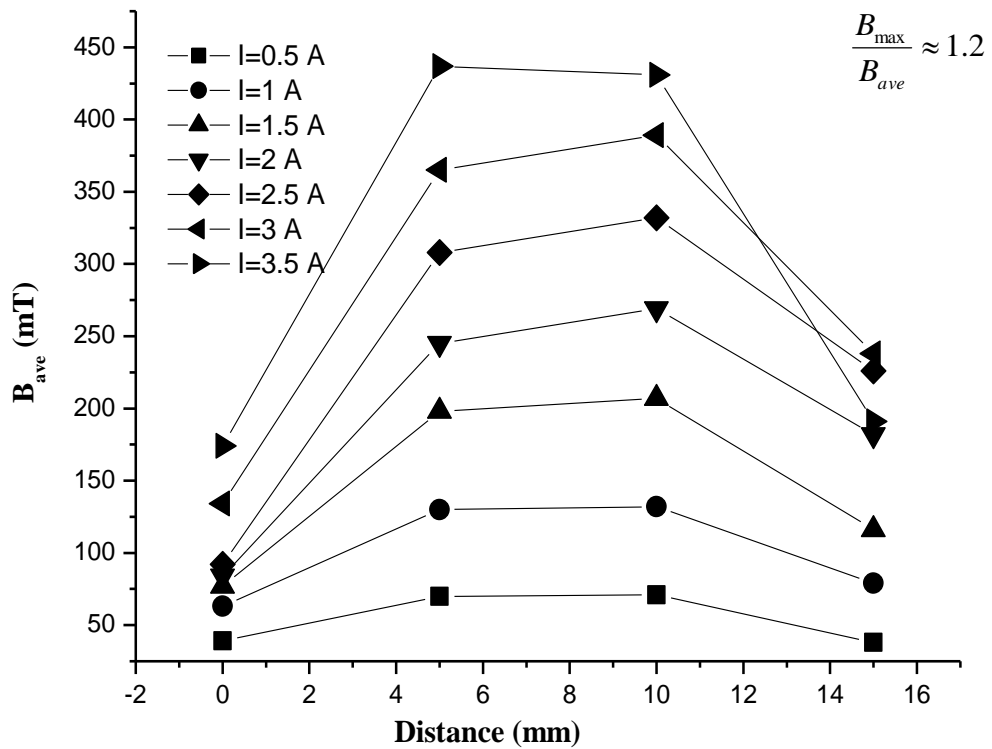
#### **4.1 Introduction**

This chapter deals with the experimental results of measuring the Verdet constant for some vegetable oils. The first part is related with the system itself. The Verdet constants of known samples were measured to gain the knowledge and experience required to perform accurate measurements with samples that have never been tested before. Therefore results concerned with system authentication are presented first followed by the original results.

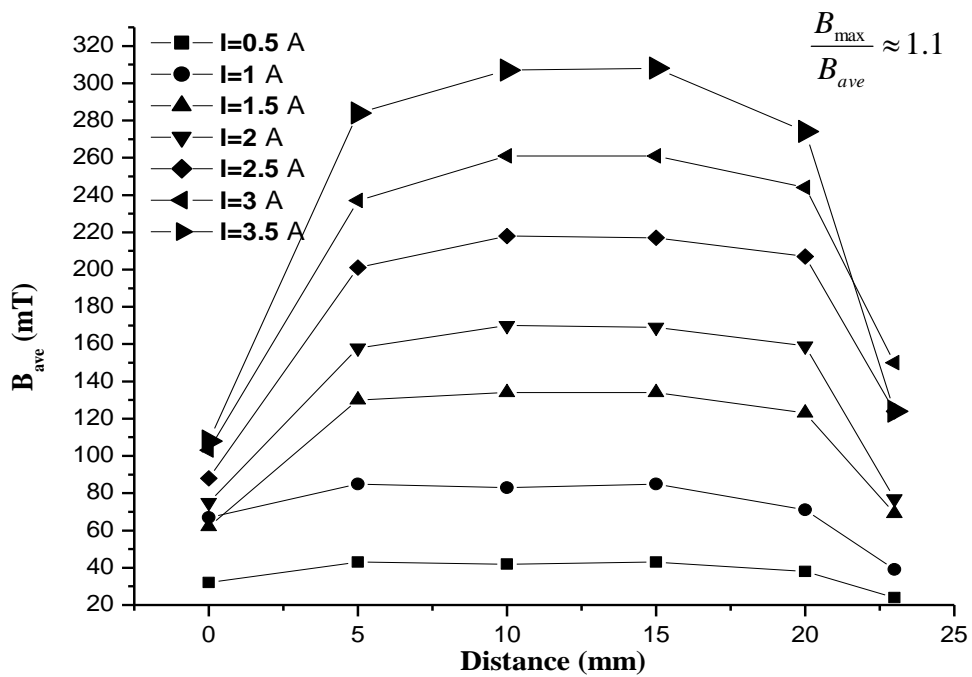
#### **4.2 Magnetic Flux Between Poles**

It is necessary to understand the magnetic flux distribution since it is going to vary along the sample. Hence, in the absence of the sample, the distribution of the magnetic flux-density was determined in the space between the pole pieces. The axial probe of the teslameter, which can be easily moved through one of the holes of the pole pieces when fixed in a universal clamp on a slide mount, was used to measure the flux density along the whole gap in steps of 5 mm. The procedure was repeated for different current intensities. The results are shown in Figure 4.1 (for a 16 mm gap) and Figure 4.2 (for a 23 mm gap).





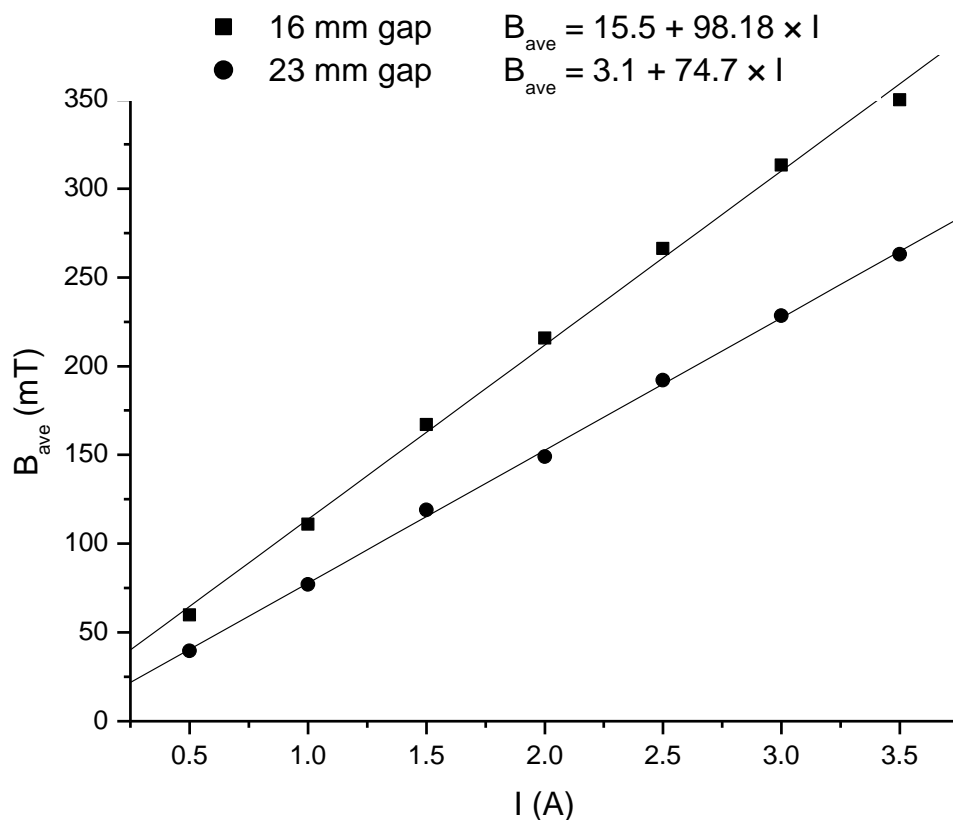
**Figure 4.1** Flux density distribution between the pole pieces for different coil currents for a 16 mm gap.



**Figure 4.2** Flux density distribution between the pole pieces for different coil currents for a 23 mm gap.

The flux density increases strongly to the center of the gap and decreases to either side. No matter what the coil current may be, the ratio maximum flux density over mean flux density (determined by numerical integration) was in each case approximately equal to 1.2 for a 16 mm gap and 1.1 for a 23 mm gap.

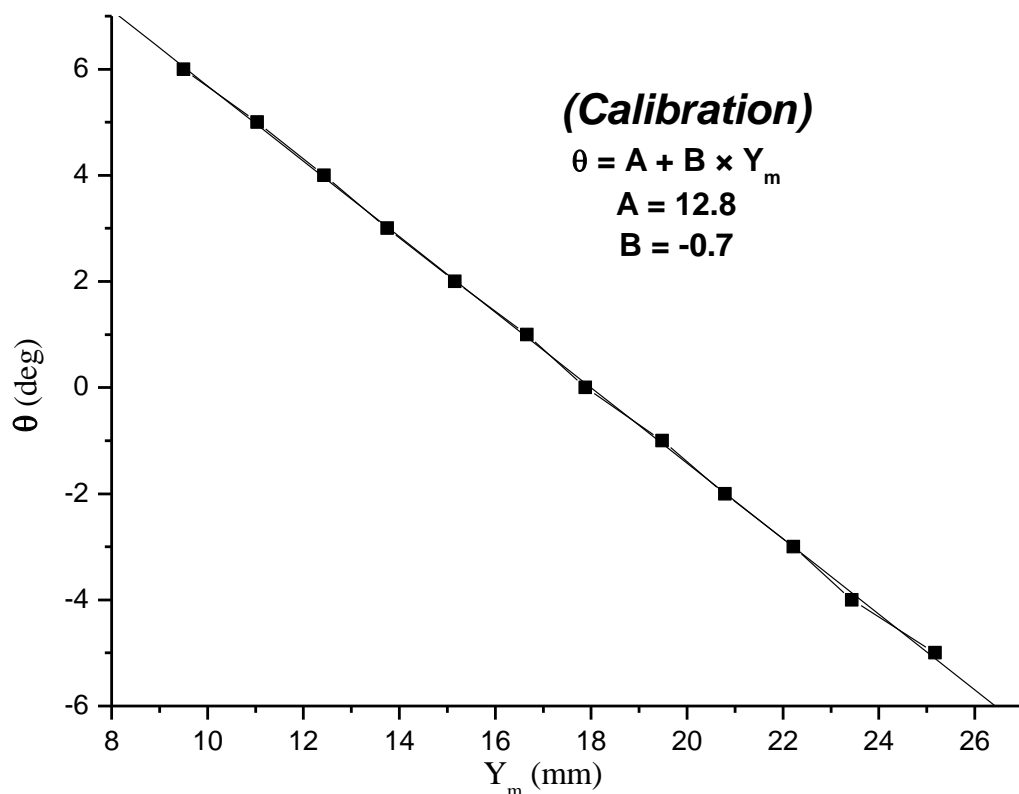
Starting from the maximum flux-density in the gap it was possible to attribute a mean-flux density to the test specimen for any coil current given. The corresponding graphs have been plotted in Figure 4.3 (for a 16 mm gap), and (for 23 mm gap). It is anticipated that the test specimen is subjected to this mean flux density for all further considerations.



**Figure 4.3** Magnetic mean flux density between the pole pieces as a function of the coil current for a 16 mm gap (■) and for a 23 mm gap (●).

### 4.3 Improvement of the Measuring Technique

The ordinary technique of Faraday effect leading to the measurement of Verdet constant involves measuring the rotation angle depending on the extinction of light when the polarizer is slowly rotated to counteract the passage of light upon the introduction of the magnetic field. This technique is not quite sensitive. In the present work, with a phase sensitive detector and the intensity as a reference, it was possible to measure the rotation angle of polarization when light was passed through the test specimen. As already mentioned in chapter three to measure the angle of rotation, a micrometer was used and a calibration procedure was devised to convert the reading of the micrometer into an angle measure. The calibration is shown in Figure 4.4



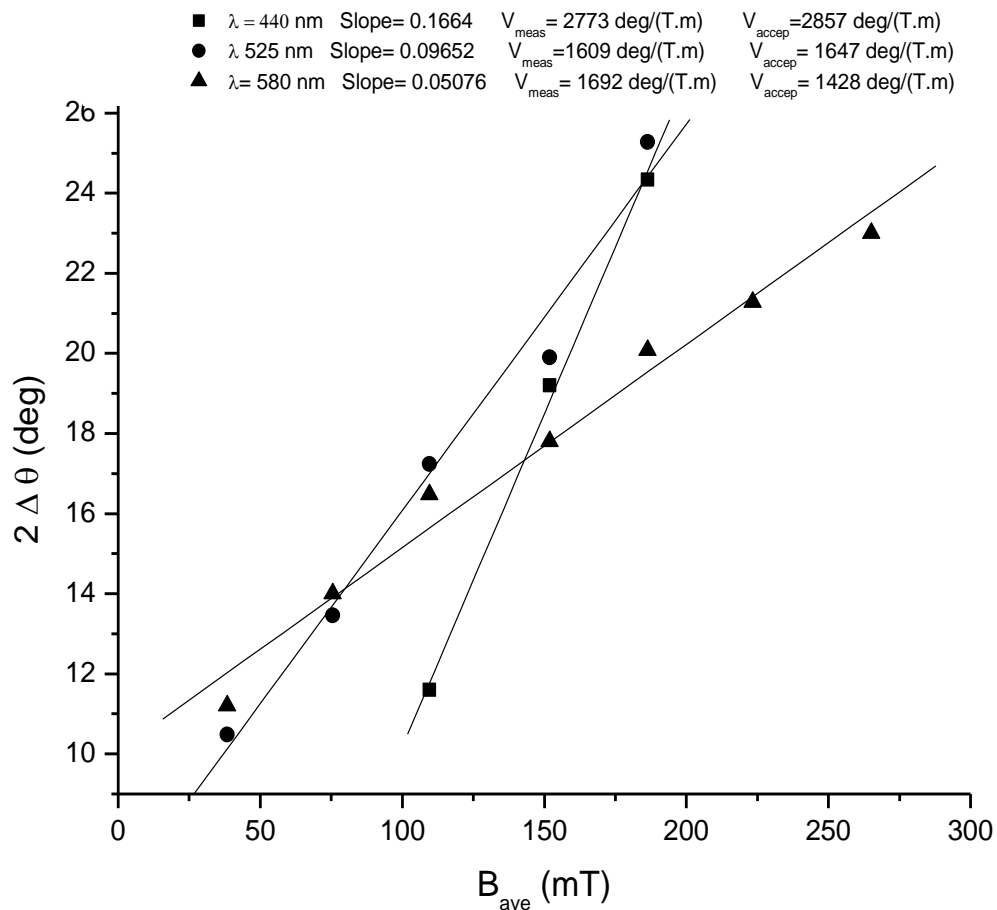
**Figure 4.4** Calibration curve for rotation angle ( $\theta$  in deg.) and micrometer reading ( $Y_m$  in mm).

#### 4.4 Results Using Test Samples

As an authentication of the system samples of known Verdet constant were employed prior to testing of unknown samples. These were:

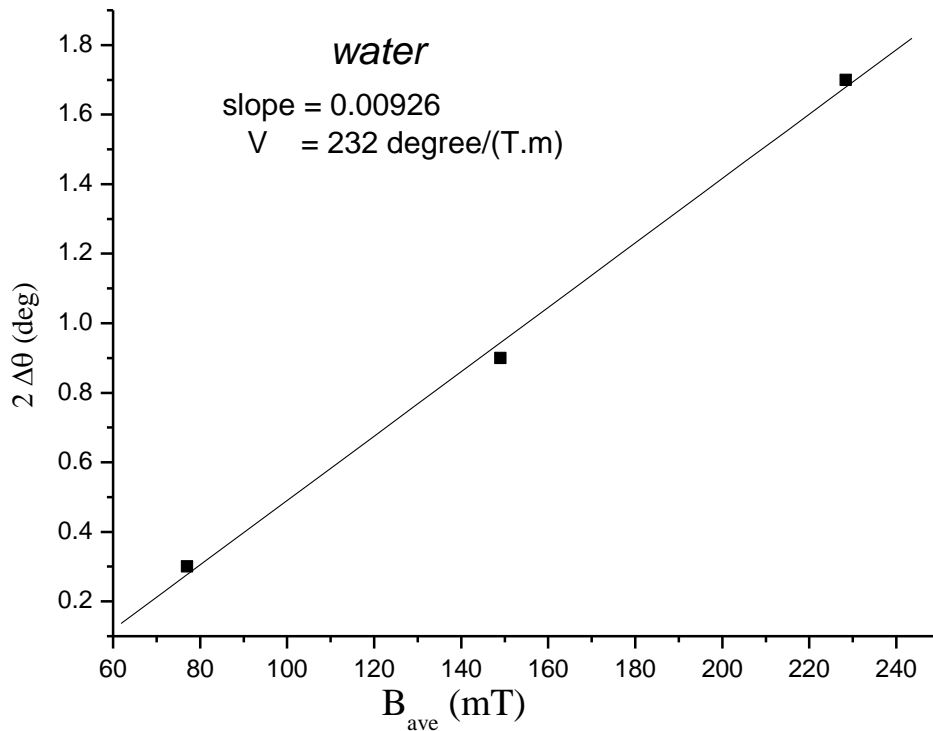
- a. A flint glass rod.
- b. Water sample.

For flint glass the Verdet constant was evaluated at three different wavelengths 440 nm, 525 nm and 580 nm the results are shown in Figure 4.5.



**Figure 4.5** Angle of rotation of the polarization plane as a function of the mean flux density for a flint glass rod for (■)  $\lambda = 440 \text{ nm}$  (●)  $\lambda = 525 \text{ nm}$  and (▲)  $\lambda = 580 \text{ nm}$ .

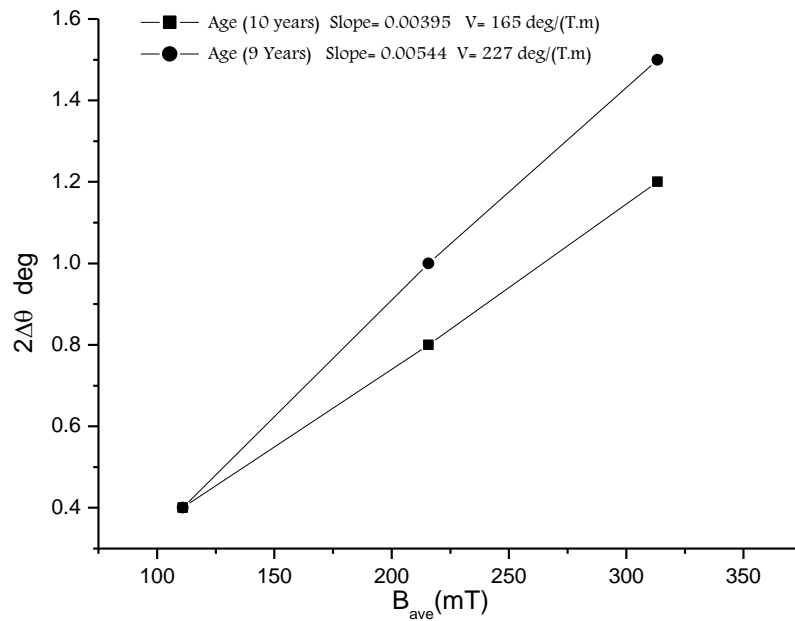
The Verdet constant for water was evaluated at 525 nm and the result is shown in Figure 4.6



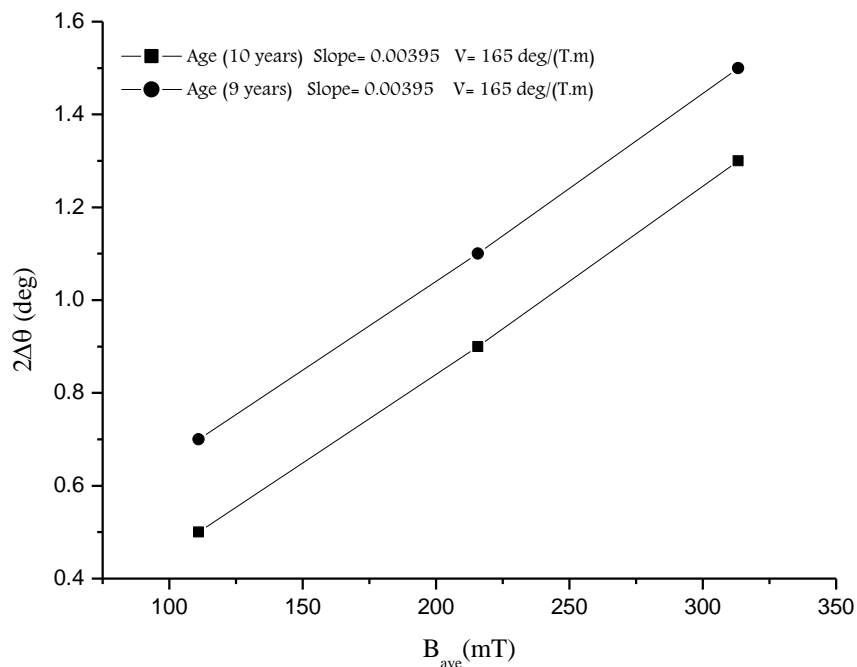
**Figure 4.6:** Angle of rotation of the plane of polarization as a function of the mean flux density for water sample for  $\lambda = 525 \text{ nm}$ .

#### 4.5 Results Using Vegetable Oils

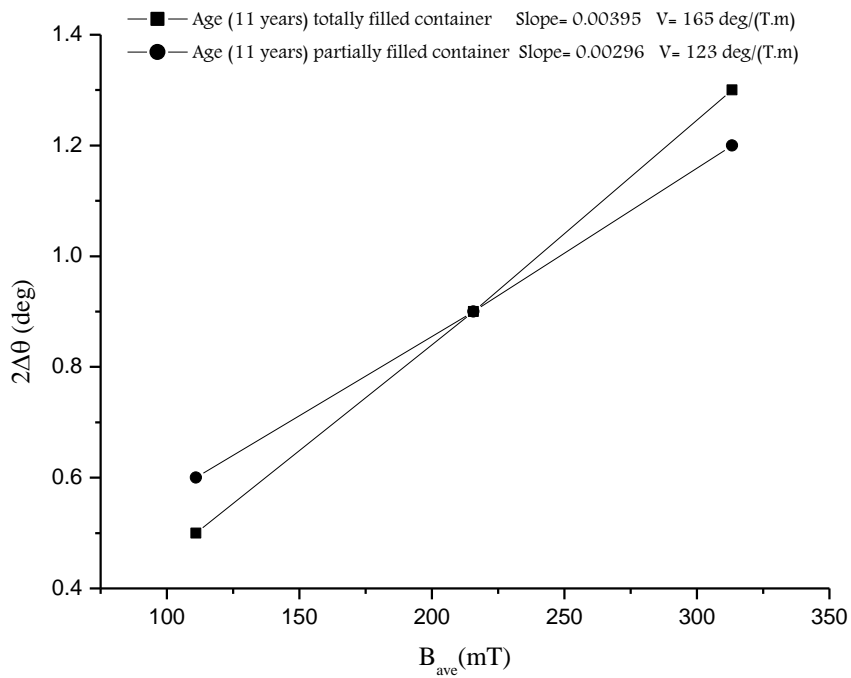
Olive oils samples from different regions and different years of production were analyzed to evaluate the Verdet constant for each sample. The samples were stored under different conditions: glass or plastic containers, in the dark or in the room light, containers totally or partially filled with oil. The results are shown in Figures 4.7 – 4.15.



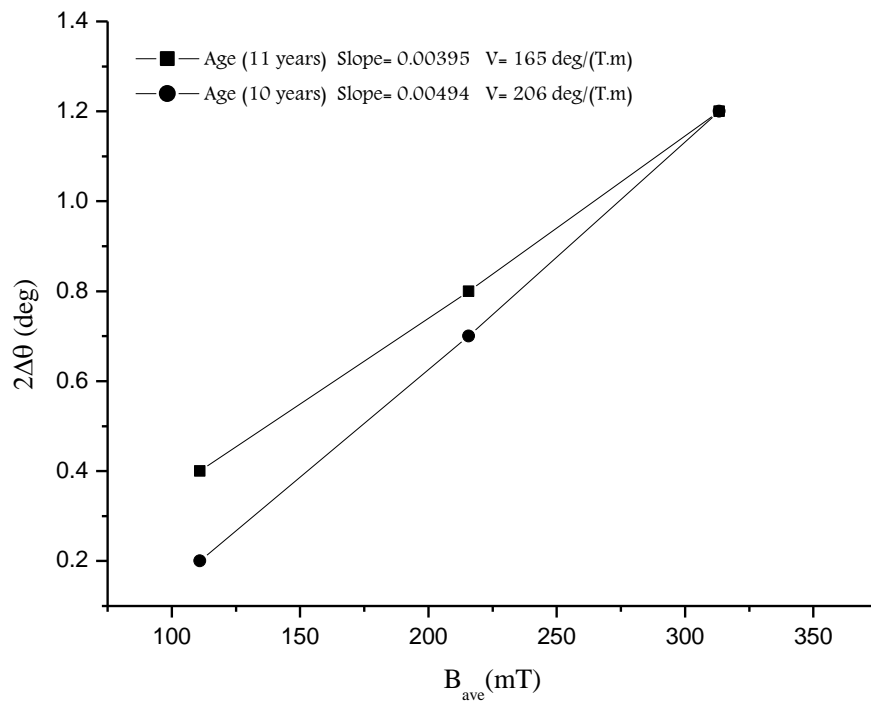
**Figure 4.7** Angle of rotation of the polarization plane as a function of the mean flux density for Yatta olive oil, aging 10 and 9 years respectively, from a valley stored in plastic container in room light for  $\lambda = 525 \text{ nm}$ .



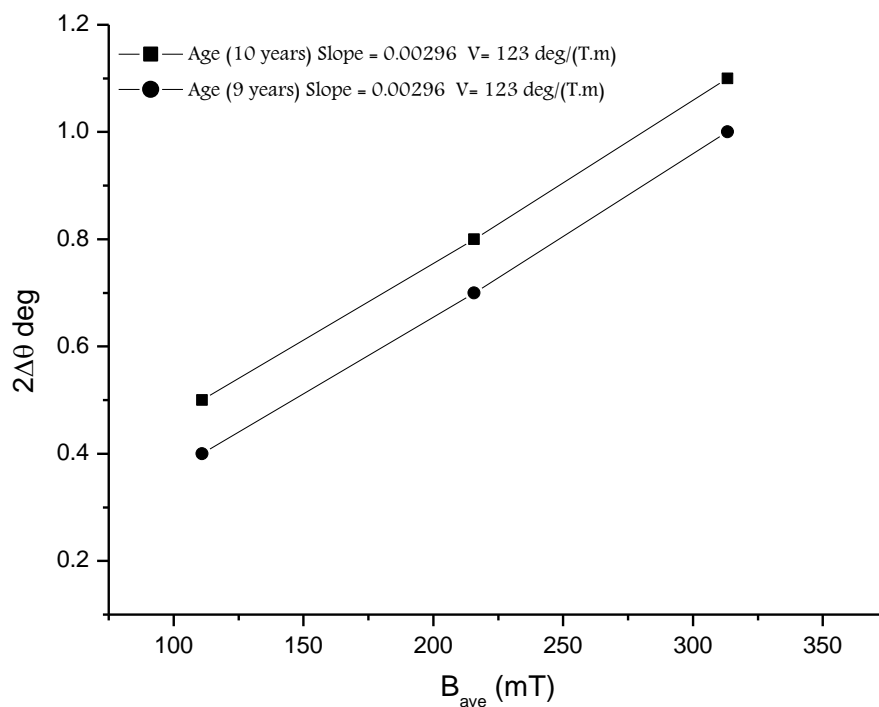
**Figure 4.8** Angle of rotation of the polarization plane as a function of the mean flux density for Yatta olive oil, aging 10 and 9 years respectively, from a valley stored in glass container in the dark for  $\lambda = 525 \text{ nm}$ .



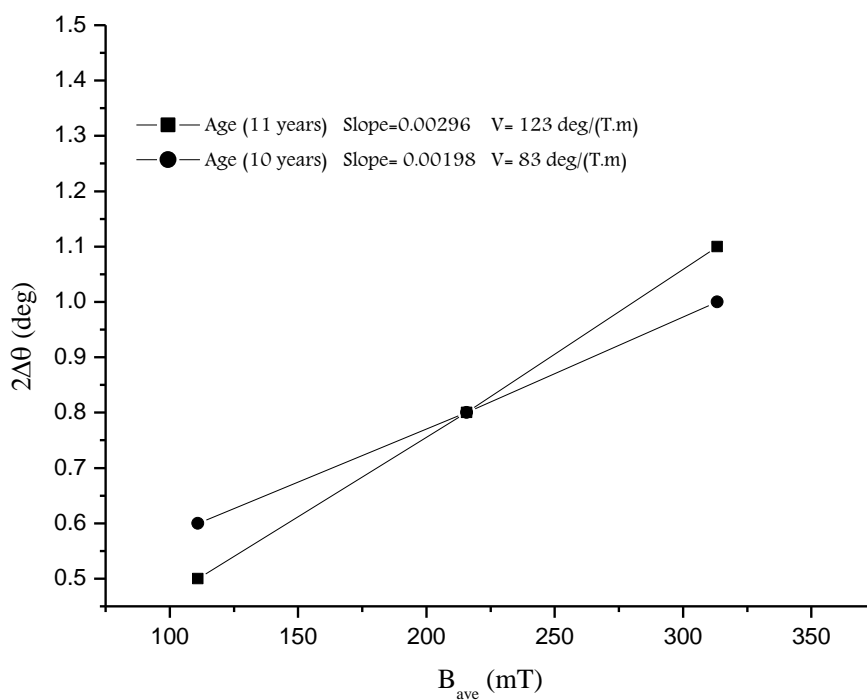
**Figure 4.9** Angle of rotation of the polarization plane as a function of the mean flux density for Yatta olive oil, aging 11 years, from a mountain, stored in plastic totally filled container (■) and partially filled container(●), for  $\lambda = 525 \text{ nm}$ .



**Figure 4.10** Angle of rotation of the polarization plane as a function of the mean flux density for Sho'afat olive oil, aging 11 and 10 years respectively, stored in plastic container in room light for  $\lambda = 525 \text{ nm}$ .

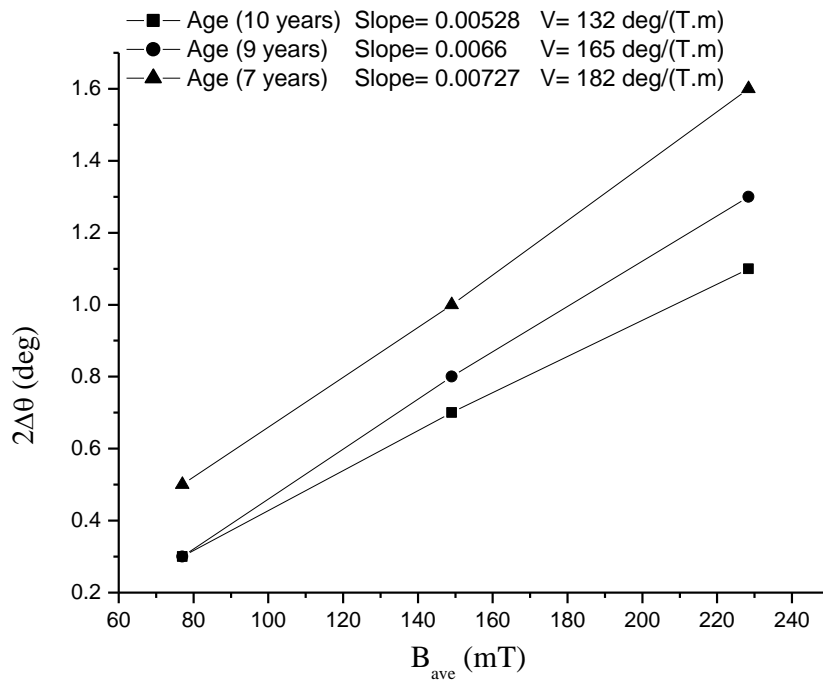


**Figure 4.11** Angle of rotation of the polarization plane as a function of the mean flux density for Sho'afat olive oil, aging 10 and 9 years respectively, stored in glass container in the dark for  $\lambda = 525 \text{ nm}$ .

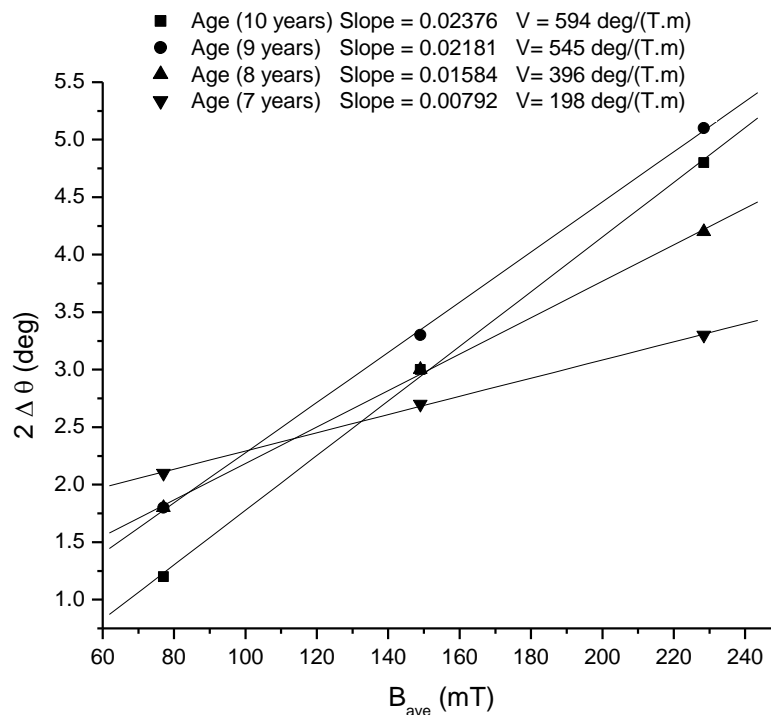


**Figure 4.12** Angle of rotation of the polarization plane as a function of the mean flux density for Aboud olive oil, aging 11 and 10 years respectively, stored in plastic container in the dark for  $\lambda = 525 \text{ nm}$ .

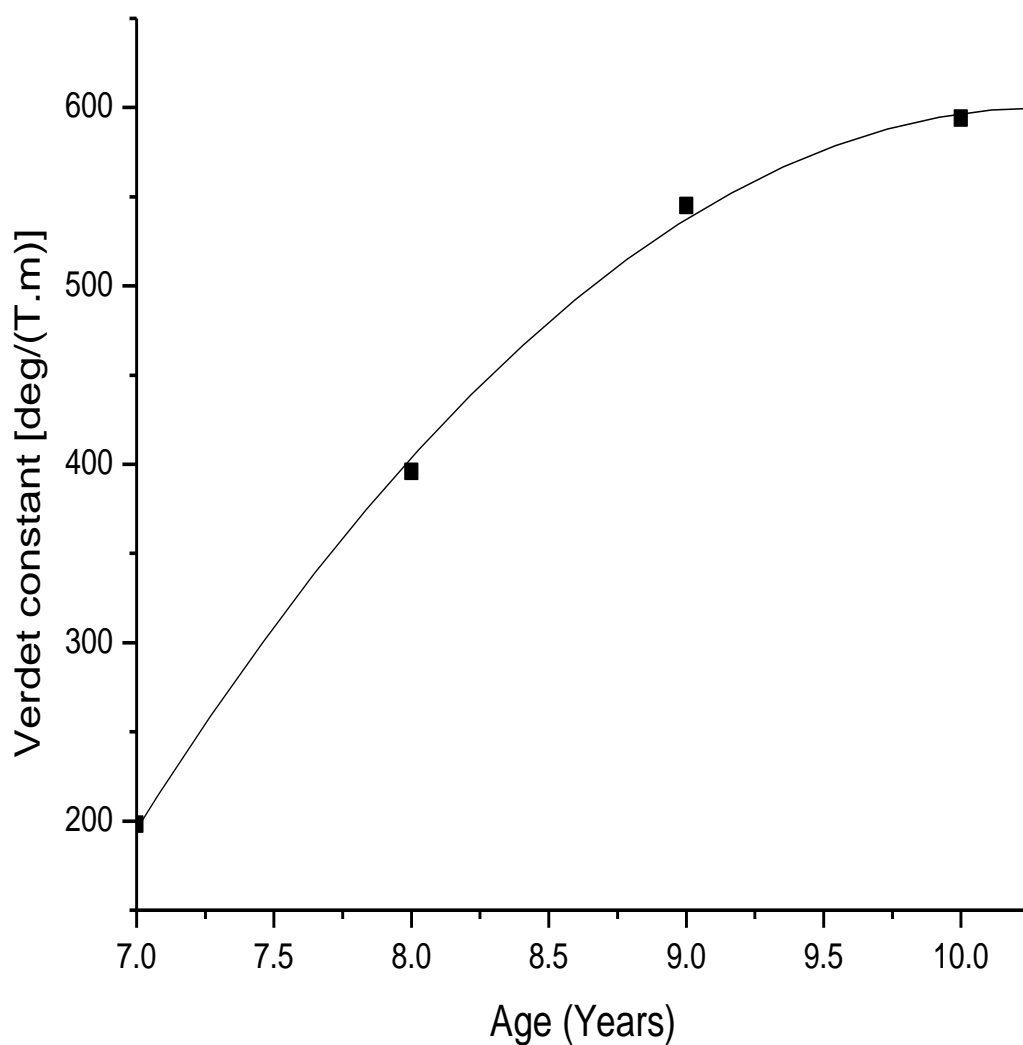




**Figure 4.13** Angle of rotation of the polarization plane as a function of the mean flux density for Asserah olive oil, aging 10, 9 and 7 years respectively, stored in glass container in the light for  $\lambda = 525 \text{ nm}$ .

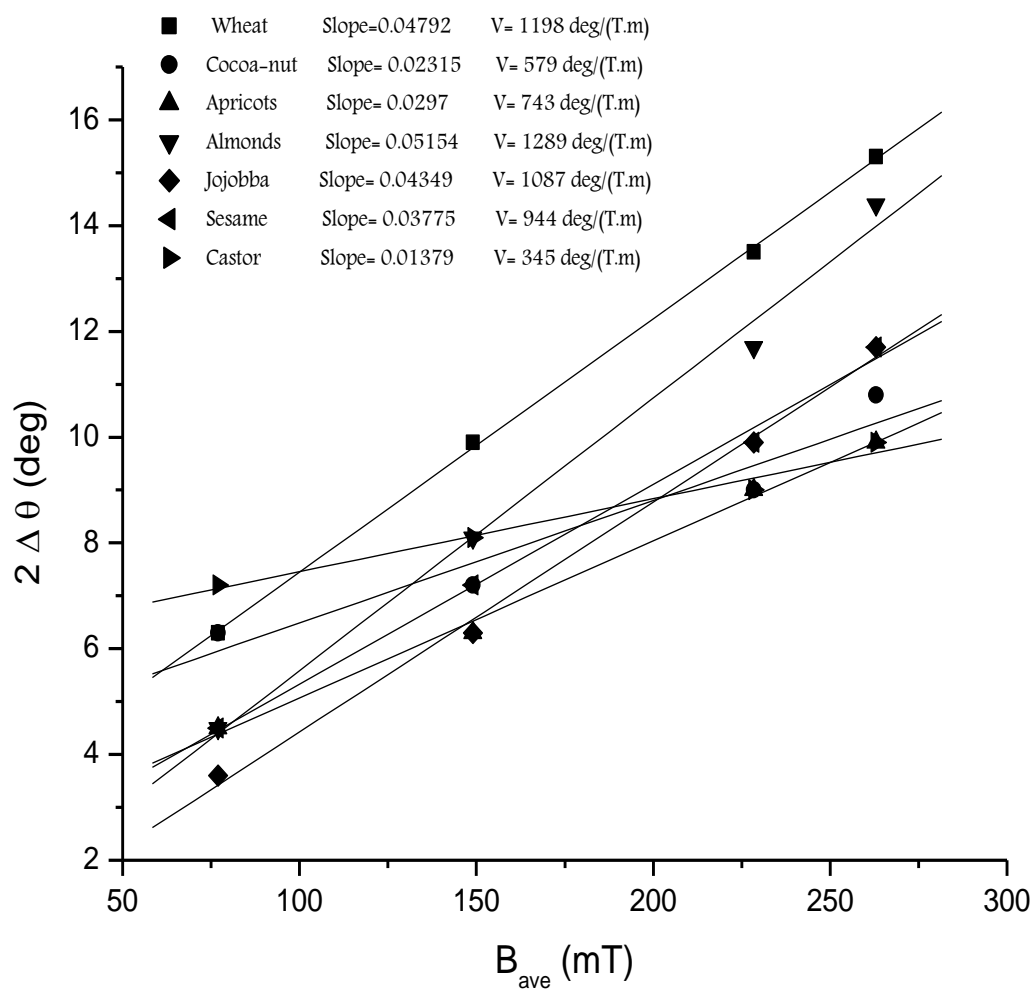


**Figure 4.14** Angle of rotation of the polarization plane as a function of the mean flux density for Asserah olive oil, aging 10, 9, 8 and 7 years respectively, stored in plastic container in the dark for  $\lambda = 525 \text{ nm}$ .



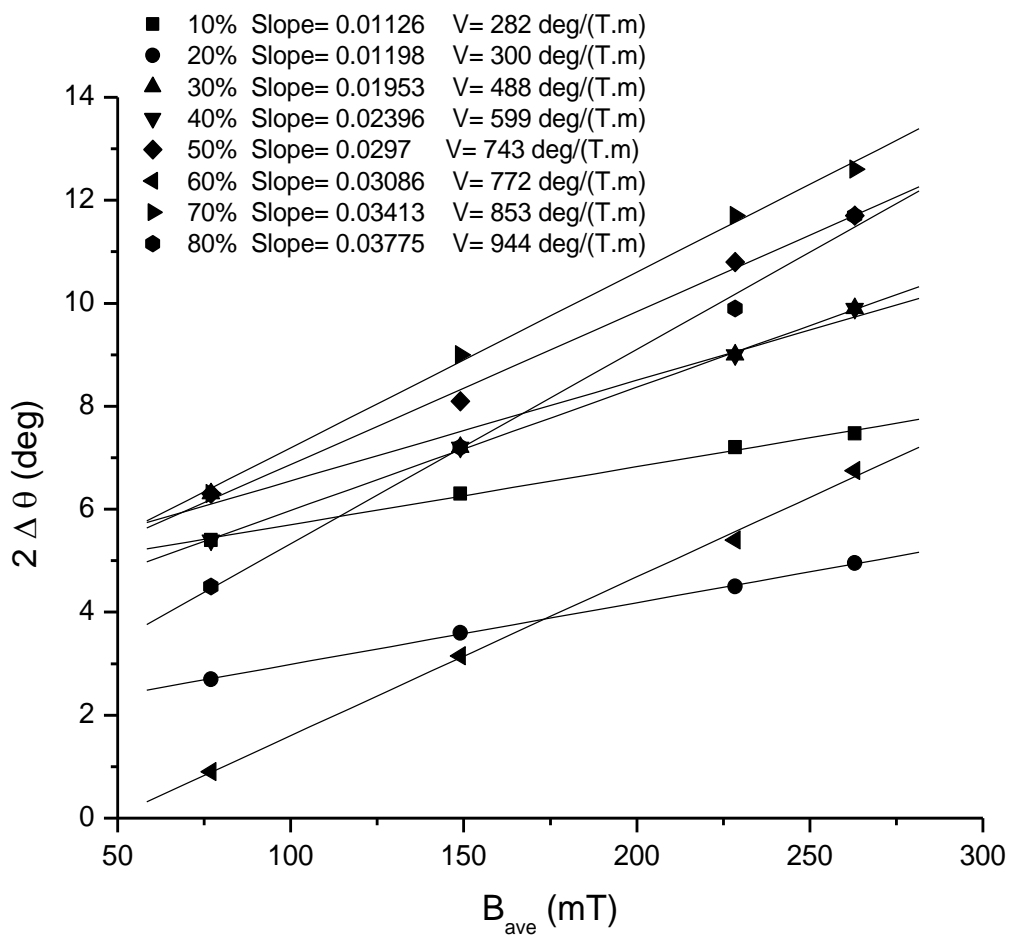
**Figure 4.15** Relation between the Verdet constant and age for olive oil samples from Aseerah stored in plastic containers in the dark.

Also, different other vegetable oil samples were analyzed and the Verdet constant was evaluated for each sample. The results are shown in figure 4.16.

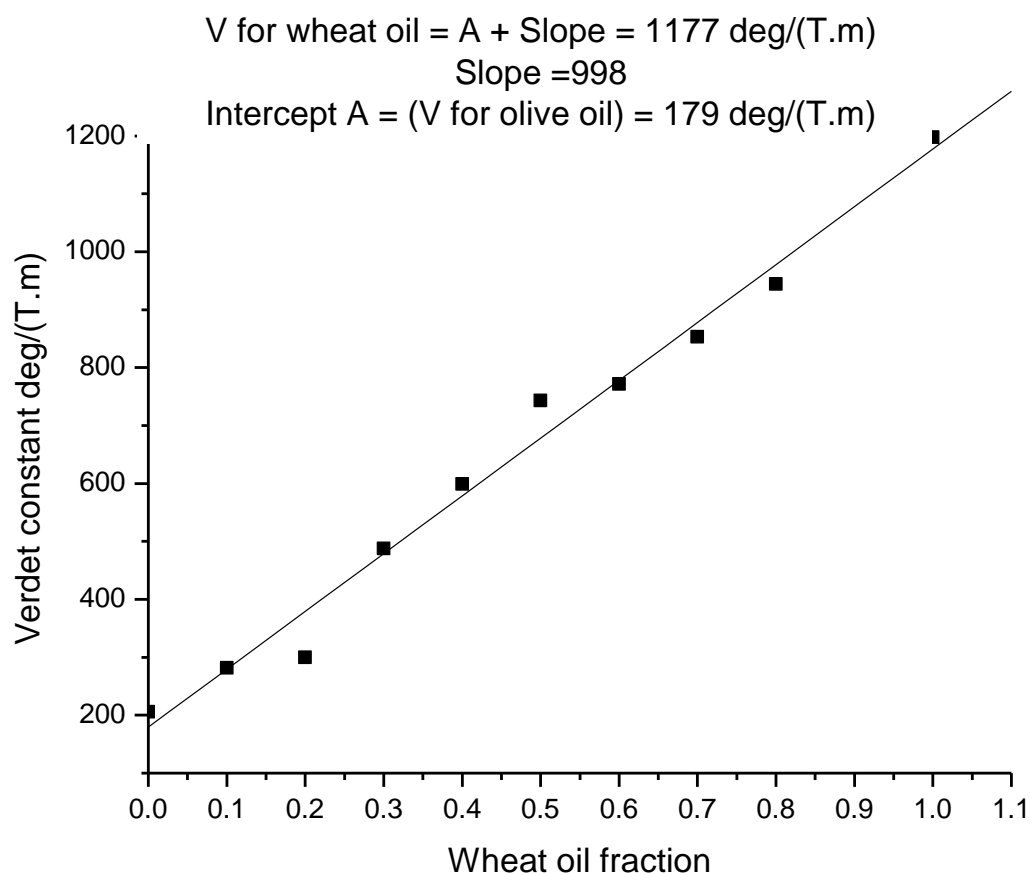


**Figure 4.16** Angle of rotation of the polarization plane as a function of the mean flux density for different vegetable oils, for  $\lambda = 525 \text{ nm}$ .

Oil adulteration was also studied. Olive oil was mixed with wheat oil in different proportions by weight from 10% - 80%. The Verdet constant was evaluated for each mixture. The results are displayed in Figures 4.17 and 4.18.



**Figure 4.17** Angle of rotation of the polarization plane as a function of the mean flux density for olive oil mixed with wheat oil in different proportions by weight for  $\lambda = 525 \text{ nm}$ .



**Figure 4.18** Relation between the Verdet constant of a mixture of wheat and Assawahreh olive oils ( $V = 206 \text{ deg}/(\text{T.m})$ ) and the concentration of wheat oil in the mixture.

The experimental results presented in this work, include authentication results and original results. The authentication results are based on flint glass and water while the original results come from vegetable oil samples. It is seen that there are differences in the Verdet constant depending on the type of material.

## **Chapter Five**

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### *Discussion*

#### **5.1 Introduction**

Many studies have been done on vegetable oils over the Past years. For example, the composition of these oils has been studied. Of particular interest is olive oil on which many studies have been done. However, these studies were made from a chemical point of view since chemical analysis was needed. In this work, the Faraday effect of some vegetable oils has been studied for the first time to the best of our knowledge.

To analyze the results of the current study reference is made to previous chemical studies since in this study no chemical analysis has been made.

#### **5.2 System Authentication Results**

The Verdet constant results for the test samples were compared with known results. This is done to understand the system and proves that our system is reliable and that the introduced improvements are beneficial.

The table below compares the values of the Verdet constant obtained in this work for flint glass with the accepted values (Phywe, 1995), at three different wavelengths, and for water (Jenkins and White, 1976) at  $\lambda = 525$  nm.

**Table 5.1** Measured and accepted values for the Verdet constant for flint glass at the wave lengths  $\lambda = 440$  nm,  $\lambda = 525$  nm, and  $\lambda = 580$  nm and for water at  $\lambda = 525$  nm

<b>Flint Glass</b>	<b>Wavelength</b>	<b>V(<math>\lambda</math>) measured in</b>	<b>V(<math>\lambda</math>) accepted in</b>	<b>% error</b>
	$\lambda$ (nm)	$\left[ \frac{\text{deg } ree}{T.m} \right]$	$\left[ \frac{\text{deg } ree}{T.m} \right]$	
	440	2773	2857	2.9%
	525	1609	1647	2.3%
	580	1692	1428	18.5%
<b>Water</b>	525	232	218.3	7%

It is seen from the table that the system is authenticated reasonably.

### 5.3 Original Results

The original results appear in Figures 4.7 - 4.18. Figure 4.7 has shown the angle of rotation of the polarization plane as a function of the mean flux density for Yatta olive oil stored in a plastic container in room light for ages 10 and 9 years respectively at  $\lambda = 525$  nm. It is seen that the Verdet constant decreases from 227 deg/(T.m) for 9 years aging to 165 deg/(T.m) for 10 years aging. Caponio *et al.*, 2005 found that oils stored in the light had significantly lower tocopherol, carotenoid and chlorophyll contents than did the same oils kept in the dark. Moreover, the oils stored in the dark mainly contained primary oxidation products while the oils kept in the light contained secondary oxidation products as confirmed by the  $K_{270}$  values which exceeded the legal limits even after purification by means of alumina (Muik *et al.*, 2005). Since photo-oxidation takes place faster than auto-oxidation, it is possible to conclude that the decrease of the Verdet constant in the samples exposed to light is due to the decrease in the concentration of tocopherol and carotenoid since chlorophylls disappear after 4 months of storage.

Figure 4.8 shows the angle of rotation of the polarization plane as a function of the mean flux density for Yatta olive oil stored in a glass container in the dark. This graph shows that the value of the Verdet constant does not change for at least one year. This can be attributed to the interruption of both photo-oxidation and auto-oxidation since glass is impermeable to oxygen. This agrees with the result obtained by Kanavouras and Coutelieris, 2006.

Figure 4.9 shows that the Verdet constant for Yatta olive oil aging 11 years and stored in a plastic container differed between a filled container ( $V = 165 \text{ deg}/(\text{T.m})$ ) and a partially filled container ( $V = 123 \text{ deg}/(\text{T.m})$ ). It is seen that the Verdet constant for the oil in the partially filled container is less than that for the oil in the totally filled container. This may be attributed to the oxidation of the oil in the partially filled container as a result of being exposed to oxygen layer on top of the oil in the container.

Figure 4.10 shows the results for Sho'afat olive oil stored in plastic container in room light for ages 11, 10 years respectively at ( $\lambda = 525 \text{ nm}$ ). It is seen that the value of the Verdet constant decreases with exposure to light. This can be explained as in the case of Yatta olive oil (Figure 4.7) i.e. the decrease in tocopherols and carotenoids as a result of photo-oxidation.

Figure 4.11 shows the angle of rotation of the polarization plane as a function of the mean flux density for Sho'afat olive oil stored in glass in the dark for ages 10 and 9 years respectively at  $\lambda = 525 \text{ nm}$ . This Figure is consistent with Figure 4.8 in which the value of the Verdet constant does not change for at least one year. As explained there, this is due to the interruption of both photo-oxidation and auto-oxidation.



Figure 4.12 shows the results for Aboud olive oil stored in a plastic container in the dark for ages 11 and 10 years respectively and  $\lambda = 525$  nm. This Figure shows that the value of the Verdet constant increases with storage in a plastic container in the dark. Caponio *et al.*, (2005) found that the samples stored in the dark showed a progressive increase in the peroxide value, which indicates greater primary oxidation, so the increase of the Verdet constant could be attributed to the increase in peroxide value for these samples.

Figure 4.13 shows the angle of rotation of the polarization plane as a function of the mean flux density for Aseerah olive oil stored in glass in the light for ages 10, 9 and 7 years respectively ( $\lambda = 525$  nm). The value of the Verdet constant decreased from  $V=182$  deg/(T.m) for the age 7 years to  $V=165$  deg/(T.m) for the age 9 years, to  $V=132$  deg/(T.m) for the age 10 years. This case has been discussed before and it is possible to say that photo-oxidation reduces the levels of tocopherols and carotenoids.

The results displayed in Figure 4.14 are similar to the results in Figure 4.12. The value of the Verdet constant increases progressively for Asserah olive oil stored in a plastic container in the dark for the ages 7, 8, 9 and 10 years respectively. The values of the Verdet constant are 198 deg/(T.m), 396 deg/(T.m), 545 deg/(T.m) and 594 deg/(T.m) respectively. The explanation is similar, namely, for olive oil stored in a plastic container in the dark the primary oxidation reaction is auto-oxidation for which the peroxide value increases progressively with aging.

The relation between the Verdet constant and age for olive oil samples from Asserah stored in plastic containers in the dark is shown in Figure 4.15. For these samples the Verdet constant increases with age.

Figure 4.16 displays the angle of rotation of the polarization plane as a function of mean flux density for different vegetable oils, ( $\lambda = 525 \text{ nm}$ ). For these vegetable oils the values of the Verdet constant range from  $345 \text{ deg}/(\text{T.m})$  for (Castor oil) to  $1289 \text{ deg}/(\text{T.m})$  for (Almonds oil).

Furthermore, the Verdet constant for olive oil from Assawahreh aging one year stored in a plastic container in room light was found to be  $V = 206 \text{ deg}/(\text{T.m})$ . Also, the Verdet constant for a very old oil sample (aging approximately 23 years) stored in a plastic container in the dark was found to be  $V = 1233 \text{ deg}/(\text{T.m})$ .

Moreover, in this work olive oil adulteration was studied. Olive oil [from Assawahreh aging one year, stored in a plastic container in room light,  $V = 206 \text{ deg}/(\text{T.m})$ ] was mixed with wheat oil [ $V = 1198 \text{ deg}/(\text{T.m})$ ] in different proportions by weight, from 10%-80%. As shown in Figure 4.17 the Verdet constant of the mixture increases with increasing the percentage of the wheat oil in the mixture. This is attributed to the high value of the Verdet constant of wheat oil i.e. the proportion of the adulterant oil is reflected in the result obtained. The Verdet constant increases from  $V = 282 \text{ deg}/(\text{T.m})$  for 10% wheat oil by weight to  $V = 944 \text{ deg}/(\text{T.m})$  for 80% wheat oil by weight.

Figure 4.18 shows the relation between the Verdet constant of the same mixture of wheat oil and Assawahreh (aging one year) olive oil and the concentration of wheat oil in the mixture. The Figure shows the increase of the Verdet constant with the increase of the concentration of wheat oil in the mixture.

## **Chapter Six**

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### *Conclusions and Further Work*

This study is concerned with the use of the Faraday effect as a new effective technique in the characterization of vegetable oils. The aim was to use the Verdet constant of the Faraday effect, as a probe to detect changes in these oils due to auto-and photo-oxidation during storage. To the best of our knowledge, this is the first time that the Faraday effect has been studied in vegetable oils. It was found that every vegetable oil has a unique Verdet constant such that it is possible to distinguish vegetable oils one from another by their Verdet constants.

In this work particular emphasis was placed on olive oil samples, collected from different parts of Palestine and from different production years. Different factors affecting the quality of olive oil are manifested in the value of Verdet constant. Among these are: the type of storage material (plastics, glass), the storage condition (light, dark) and the aging, i.e. shelf-life. The main part of this work was concerned with the effect of these factors, namely light, and the type of container on the quality of olive oil through the study of the Verdet constant.

The main findings were that two types of oxidation namely photo-oxidation and auto-oxidation exist and have reverse effects on the Verdet constant. For olive oil stored in the

light either in a plastic container or in a glass container the value of the Verdet constant decreases with time. This is possibly due to the decrease in the concentration of tocopherols and carotenoids associated with photo-oxidation and considering that photo-oxidation takes place faster than auto-oxidation.

However, for olive oil stored in a plastic container in the dark it was found that the value of the Verdet constant increases with time (sample age). This was explained by the fact that the samples stored in the dark showed a progressive increase in peroxide value which indicated greater primary oxidation.

This research also showed that by interrupting both auto-oxidation and photo-oxidation it was possible to keep the value of the Verdet constant unchanged for at least one year. This was done by storing the oil in a glass container in the dark. Since glass is impermeable to oxygen it was possible to stop both types of oxidation, and therefore maintain the value of the Verdet constant.

It is possible to conclude that it is desirable to preserve the value of the Verdet constant to keep the olive oil at its top quality. It is concluded that glass is the most protective material for oil storage when kept in the dark. For storage in the light however, it is favorable to slow down the fast reaction, therefore plastic containers have a particularly stronger protective role when the oil is stored in the light.

It is not clear, however, how the value of the Verdet constant can be taken as a measure of the quality of the oil when this value can be increased by auto-oxidation or decreased by photo-oxidation.

In the second part of this work Faraday effect of some vegetable oils, other than olive oil, has been studied. It was established that each vegetable oil has its own value for Verdet constant.

Finally oil adulteration was studied in this work. Olive oil was mixed with wheat oil in different proportions by weight and the effect on the Verdet constant was studied. It was found that the Verdet constant increased with the increase of concentration of wheat oil in the mixture, so in principle it is possible to detect oil adulteration using the Faraday effect.

In this work the signal / Noise ratio was found to be 26.1 which is quite good. To calculate this ratio the experiment was repeated 20 times to calculate the Faraday rotation angle when the current was changed from zero to 2 Amper. The mean value of the Faraday rotation angle for the 20 trials was calculated as well as the standard deviation of the data, the signal was considered to be the mean value of the Faraday rotation data while the noise was taken to be the standard deviation of the data. When the signal was divided by the noise the above value was obtained.

In conclusion, the Faraday Effect could be used as a sampling technique for vegetable oils. Calibration curves and standard Verdet constants can be prepared for comparison with those of samples under investigation.

As for further studies, it is possible to pursue the following:

- 1) Analyze the oil samples chemically to find out their composition. In this way it is possible to find out a relation between the oxidation products and the Verdet constant using chemical analysis it would be possible to discover if there is a relation between the substances dissolved into the oil from the polymer and the Verdet constant.

- 2) Study quantitatively the effect of oxygen concentration either in the container headspace or dissolved into the oil on the Verdet constant.
- 3) Study quantitatively, the effect of the permeability and transparency of the container on the Verdet constant.
- 4) Study the change of the Verdet constant as a function of wavelength for different oil samples.
- 5) Study the change of the Verdet constant with temperature.
- 6) Study the effect of altitude of fruit growth on the Verdet constant

Finally, I recommend that an alternating current (AC) measurement of the Faraday effect be used in future work for two reasons:

1. The currents in the solenoid are much smaller than the direct current case. This circumvents heating of the coils.
2. It allows for the use of lock-in amplifier with its high inherent signal to noise ratio capability.

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