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Article

Near-Null Geomagnetic Field as an Innovative Method of Fruit Storage

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Abstract: The article presents the findings of a study investigating the effects of storing Jonagold apples for six weeks in a condition in which the vertical component of the geomagnetic field has been eliminated (near null GMF) and in control conditions representing those applied in traditional storage (i.e., in the local geomagnetic field (local GMF)). Analyses of the fruit were performed before the start of and three times during the experiment (i.e., following four, five and six weeks in storage). The contents of simple sugars were measured using the HPLC (high performance liquid chromatography) method; refractometry was applied to identify total extract; thermogravimetry was used to measure the water content, volatile substances and total ash; calorific value and intensity of respiration were examined by measuring CO₂ emissions. Significant differences were found between the apples stored in the experimental and under control conditions, showing an advantage of storage in a condition with the vertical component of the geomagnetic field removed. Statistically significant differences were mainly identified in the speed of starch conversion into simple sugars, as well as the intensity of respiration and the appearance of the two groups of apples. Storage of fruit in a compensated geomagnetic field proved to be an effective method permitting an extended duration of storage without significant deterioration of the physicochemical and organoleptic properties of apples.

Keywords: geomagnetic field; compensation; apples storage; chemical profile; sugars

1. Introduction

The geomagnetic field is a natural component of the environment experienced by living organisms inhabiting the Earth [1]. Some studies have investigated directional orientation in birds and other migratory animals based on the magnetic poles and the geomagnetic field [2]. A number of hypotheses have been suggested to account for this phenomenon. In particular, research has focused on optical orientation and navigation based on “maps” of the terrestrial surface and the stars in the sky. Other researchers have investigated navigation along the lines of force of the geomagnetic field, which are known to be rigidly bound to the geophysical coordinates of the Earth [3]. There is a large body of experimental evidence in favour of the latter hypothesis, related to abilities observed in certain biological species of microorganisms [4–6], insects [7,8], fish [9,10], birds [11–14], and mammals [15,16].

The structure of the geomagnetic field comprises an important type of geomagnetic variability, such as geomagnetic pulsations (or short-term oscillations) which are not reflected by standard planetary indicators. We know; however, that short-term oscillations in the geomagnetic field may play an important role for biological subjects, including the human brain and its functional activity. The stability of brain function requires an optimal level of geomagnetic activity expressed as periodic oscillations at a certain range of amplitudes and frequencies, with geomagnetic pulsation playing an important role. A significant decrease in geomagnetic activity, as well as the occurrence of aperiodic disturbances, may lead to unstable states of the brain [17].

The apple tree (*Malus domestica*) has been cultivated for centuries. Due to the short storage life of most varieties, apples are mainly available on the market from August to November [18]. Therefore it is necessary to increase the availability of apples by improving their storability. Numerous changes occurring in apples during storage affect such parameters as water content, concentration of soluble solids, contents of glucose, fructose and sucrose, mainly resulting from enzymatic activity and cellular respiration [19,20].

Solutions designed to increase fruit storability include a controlled atmosphere (CA) and a modified atmosphere (MA). CA is a system designed for storing products in an atmosphere differing considerably from normal air as regards the levels of CO₂ and O₂. The purpose of this method is to ensure ongoing monitoring and regulation of the basic gases in gas-tight chambers or containers. The mixture of gases constantly changes due to the metabolic activity and respiration of the fruit and because of potential gas leaks penetrating container doors and walls [21].

MA is one of the methods designed to preserve food and maintain the natural quality of products, and to improve their storability. The storage life of food products is significantly extended due to their decreased respiration and as a result of the reduced activity of microorganisms in food. In this case, the composition of gas is initially modified and is subject to dynamic changes depending on the respiration rate of the food product and on the permeability of the membrane or the storage structure surrounding the food product [22].

In order to investigate the effects of near null magnetic field applied during the storage of apples, and to identify its influence on the contents of sugars and soluble solids and on respiration by measuring CO₂ emissions, we stored Jonagold apples at 4 °C, in near null magnetic field, and, as a comparison, at 4 °C in the Earth's magnetic field.

2. Materials and Methods

2.1. Plant Material

Jonagold apples at the stage of harvest maturity were collected on 11 October 2017 at the Experimental plant garden in Albigowa. After the fruit were brought to a laboratory at the University of Rzeszow, a number of analytical tests were run to determine the initial contents of water, total ash, volatile compounds, as well as calorific value, total soluble solids and contents of simple sugars.

Subsequently, the fruit were divided into two groups, and were placed in storage (4 °C, 55% RH). The first group was stored in the traditional way at the local geomagnetic field (GMF) (in Central Europe the value of the vertical component of the Earth's magnetic field being 49 µT (Figure 1).

The second group of fruit was kept in storage facilities in which the vertical component of the geomagnetic field was compensated for by an induced vector opposing the natural vector of the geomagnetic vertical component (Figure 2)—near null GMF.

The apples were stored in a cold room for one month. Subsequently, a series of tests were run to measure the analytic parameters; these were performed at the start and during the following three weeks. Each time three apples were retrieved from each group in storage (local magnetic field, near null field).

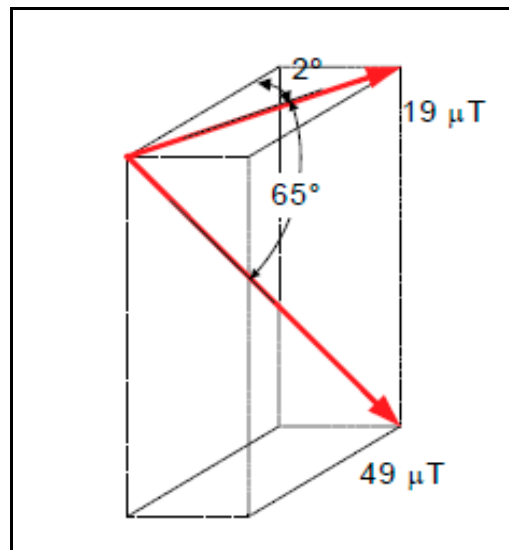


Figure 1. Schematic distribution of the Earth's magnetic field in Central Europe.



Figure 2. Coil designed for fruit storage at near null GMF (geomagnetic field).

At the subsequent stage, another batch of apples was divided into two groups, 1 kg each; these were closed in tight containers, with a volume of 10 dm^3 , for 72 h, at a room temperature of $20 \text{ }^\circ\text{C}$, and relative air humidity of 55%. The following tests were replicated three times. After 72 h, the measuring sensors of an ULTRAMAT 23 apparatus (Siemens, London, England) from Siemens were connected to each container in order to measure the level of oxides (intensity of respiration). After the sensor was connected to the container with the fruit, the stopper at the bottom of the container was released and the apparatus was able to detect CO_2 and CO as well as SO_2 and NO discharged during the 72 h process of respiration occurring in the apples (Krebs cycle) at the cellular level. The apparatus collects a sample via a heated gas probe at the rate of $1 \text{ dm}^3/\text{minute}$, and then conveys it via a heated hose to

the metering cabinet. There the sample is forwarded to the cooler, where moisture is removed from the material, which is then conveyed to the analysers. The gas analyser may measure three gases sensitive to infrared light simultaneously. The system is designed to perform the measurement of CO₂ (range of 0%–50%), CO (range of 0%–5%) as well as NO (range of 0–2000 mg/m³) and SO₂ (0–750 vpm). In the two groups of apples the gas concentrations were measured for 10 min to make sure that the containers were completely emptied.

The results recorded by the apparatus were transferred to an Excel worksheet with a specially designed algorithm which analysed measurements of the concentration of each gas every 6 s, taking into account the concentration of the gas in the total volume of the air drawn by the apparatus, the gas flow rate in the measuring detectors as well as the density of the gas at the temperature observed during the measurement. The algorithm designed in this way was used to determine the amounts of gases (mg) detected in the weighed fruit sample (kg). The result was presented as a percentage concentration of the discharged gas in the total mass of the fruit (mg/kg). The results were significant only in the case of CO₂ concentrations. The concentrations of the remaining gases did not differ significantly.

2.2. Analytic procedures

The analytical procedures were replicated in each case, with the use of the following equipment and standards:

- A LECO TGA 701 thermogravimetric analyser (Leco, St. Joseph, MI, USA) was used to determine the contents of water (according to PN-A-75101-03:1990P), total ash (PN-90/A-75101.08), volatile compounds (PN-EN 15148:2010(U)),

- A LECO AC 500 calorimeter (Leco, St. Joseph, MI, USA) was used to determine the calorific value of the dry matter, according to PN-EN 14918:2010(U),

- An automatic hand-held ATAGO PAL-1 refractometer (Artisan, Champaign, IL, USA) with temperature compensation was used to determine total soluble solids,

- A high-performance liquid chromatography system from YoungLin (Gyeonggi-do, Republic of Korea) was used to determine the contents of simple sugars (i.e., glucose, fructose and sucrose). The system consists of a YL9110 quaternary pump with an eluent mixer at low pressure, a reagent vial coupled with a YL9101 vacuum phase degasser, a YL9131 thermostatted column and RI YL9170 detector. Chromatography separation was performed with the use of a COSMOSIL Sugar-D chromatography column as well as reagents and reference material (glucose, fructose, sucrose, HPLC purity). The yield in the case of the three sugars was not lower than 98.7%.

- An ULTRAMAT 23 manufactured (Siemens, London, England) by Siemens was used for CO₂ analysis.

2.3. Statistical Analysis

The results are expressed as mean values \pm standard errors. The data acquired during three independent measurements of Jonagold apples stored in the local geomagnetic field and in near null magnetic field were subjected to a one way analysis of variance (ANOVA) to detect differences between the mean parameters, using Statistica 10, with Tukey's post-hoc test, at $\alpha = 0.05$ and the number of repetitions $n = 3$.

3. Results

The following findings show the differences identified in two groups of apples stored either in the local geomagnetic field (local GMF) or in a condition with a compensated vertical component of the geomagnetic field (near null GMF).

Table 1 shows the contents of the basic simple sugars and soluble solids in Jonagold apples measured directly after the fruit were transported from the orchard to the storage place (initial analysis), and then following four, five and six weeks in storage.

Table 1. Soluble solids and simple sugars in apples stored in the local GMF and in near null GMF.

Timing of the Analysis	Initial Analysis	After Four Weeks		After Five Weeks		After Six Weeks	
		Local GMF	Near Null GMF	Local GMF	Near Null GMF	Local GMF	Near Null GMF
Magnetic Field Modification							
Soluble solids (%)	11.98 ± 0.12	13.53 ± 0.06	12.63 * ± 0.06	13.77 ± 0.06	13.17 ± 0.06	13.81 ± 0.05	13.28 ± 0.07
Glucose (%)	2.04 ± 0.08	2.17 ± 0.06	2.13 ± 0.05	2.36 ± 0.06	2.07 ± 0.05	2.42 ± 0.05	2.24 ± 0.09
Fructose (%)	6.40 ± 0.11	6.72 ± 0.15	6.05 ± 0.12	7.05 ± 0.06	6.54 ± 0.04	7.84 ± 0.06	6.70 ± 0.05
Sucrose (%)	0.99 ± 0.03	0.74 ± 0.05	0.78 ± 0.03	0.79 ± 0.01	0.78 ± 0.02	0.77 ± 0.02	0.79 ± 0.08

* Mean ±SD values in bold print show statistical differences in the results after four, five and six weeks, observed between apples stored in near null GMF and apples stored in local GMF, $\alpha = 0.05$ (Tukey's test), $n = 3$.

Analysis of the above results shows significant differences in the speed of starch conversion in the apples stored in a compensated geomagnetic field, compared to the apples stored in traditional conditions (in the local geomagnetic field). The findings suggest a decreased rate of enzymatic processes leading to conversion of starch into monosaccharides. This is particularly reflected by the level of fructose in the cell sap of the fruit stored without a geomagnetic field. The contents of sucrose (i.e., a disaccharide functioning as a transporting medium) are varied and show no clear-cut tendencies. The results related to simple sugars are also confirmed by the differences in the concentrations of solids dissolved in the cell sap, reflected by the analysis of the refractive index.

The following Table 2 presents the contents of water, total ash and volatile compounds as well as the calorific value of the dry matter.

Table 2. Contents of water, total ash and volatile compounds as well as the calorific value of dry matter in apples stored in the local GMF and in near null GMF.

Timing of the Analysis	Initial Analysis	After Four Weeks		After Five Weeks		After Six Weeks	
		Local GMF	Near Null GMF	Local GMF	Near Null GMF	Local GMF	Near Null GMF
Water (%)	85.51 ± 0.09	84.35 ± 0.25	85.38 * ± 0.10	84.20 ± 0.18	85.23 ± 0.24	84.12 ± 0.09	85.21 ± 0.12
Total ash (%)	0.19 ± 0.01	0.46 ± 0.03	0.27 ± 0.05	0.45 ± 0.04	0.33 ± 0.16	0.55 ± 0.03	0.38 ± 0.11
Volatile compounds (%)	5.52 ± 0.14	4.79 ± 0.11	5.05 ± 0.06	3.64 ± 0.09	5.02 ± 0.17	2.27 ± 0.07	4.31 ± 0.09
Calorific value (cal g ⁻¹ d.m.)	3947 ± 21	3805 ± 22	3900 ± 12	3762 ± 22	3872 ± 12	3720 ± 15	3850 ± 11

* Mean ±SD values in bold print show statistical differences in the results after four, five and six weeks, observed between apples stored in near null GMF and apples stored in the local GMF, $\alpha = 0.05$ (Tukey's test), $n = 3$.

The analyses show that the different storage conditions influenced each of the parameters in question. Partial loss of water accumulated during vegetation growth was lower in the fruit which were not exposed to the vertical component of the geomagnetic field while in storage. This corresponds with a lower value of total ash resulting from the process of natural mineralisation in the case of the apples stored in the compensated field. Furthermore, the increased calorific value of dry matter in the fruit stored in the experimental conditions is consistent with the changes in sugars illustrated in Table 1. Slower conversion of starch (a polysaccharide with a calorific value of 4200 cal g⁻¹ d.m.) into simple sugars (i.e., glucose and fructose; with a calorific value of 3800 cal g⁻¹ d.m.) resulted in a lower rate of decrease in the calorific value of the fruit dry matter.

Another series of results shows measurements of respiration rates in apples stored in the local geomagnetic field and in a condition with the vertical component of the geomagnetic field eliminated. The following results in Figure 3 present the distribution of CO₂ accumulation during 10 min tests (i.e., the mean results from three test samples).

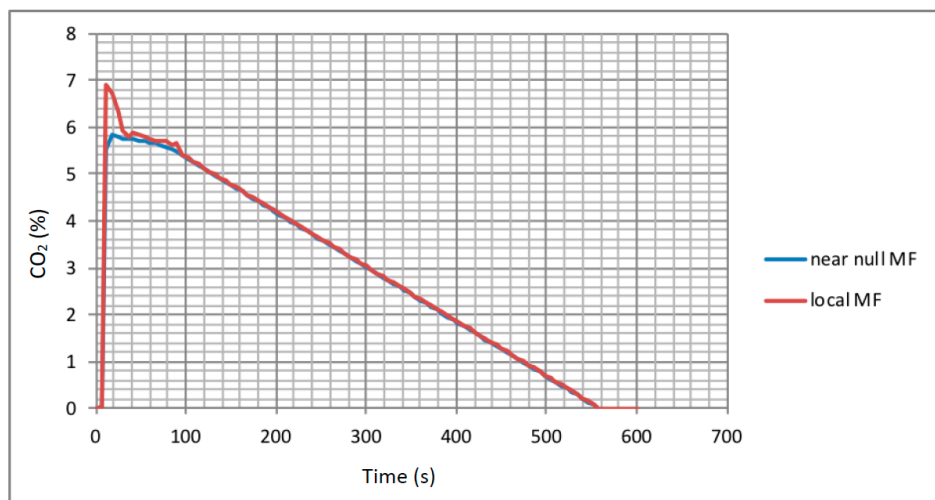


Figure 3. The absolute values of CO₂ during the examination of the respiration process in fruit, after 72 h storage at near null GMF and at the local GMF.

The results subjected to analysis using an integrating algorithm showed a tendency for more intense respiration processes in apples stored in the geomagnetic field. Compensation of the vertical component of the geomagnetic field resulted in a reduced respiration rate in the fruit, on average by 20 mg of the released CO₂ per kilogram of the apples subjected to the tests.

This difference is reflected in the intensity of the saccharometabolism occurring within the cells. A decreased rate of starch conversion into simple sugars corresponded with an inhibition of the aging process in the apples, which was also confirmed during organoleptic examination of the apples following six weeks storage in varied geomagnetic conditions (Figure 4).

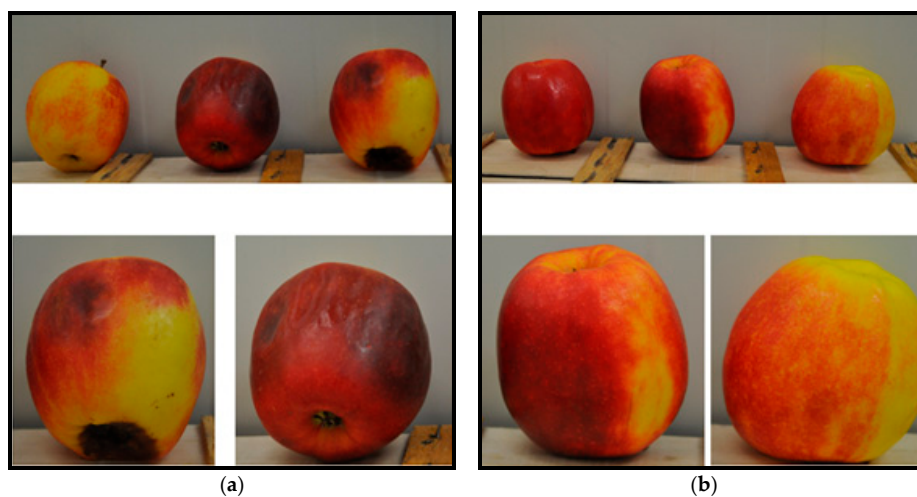


Figure 4. Difference in the appearance of apples stored in the local geomagnetic field (a) and in a condition with a compensated vertical component of the geomagnetic field (b).

4. Discussion

The numerous studies investigating the influence of geomagnetic field compensation on living organisms mainly focus on such effects in animals and in humans. Few authors report the effects of such conditions on the growth and development of plants, as well as the storage of fruit and vegetables. The rare studies describing changes in the vital parameters of plants exposed to fluctuations in the Earth's magnetic field include those reported by Dubrov [23], who found significantly altered respiration parameters (reflected by CO₂ concentration) in tobacco leaves due to fluctuations in the

geomagnetic field. These observations are supported by the present findings which show a decrease in CO₂ discharged in the process of respiration by Jonagold apples, the difference amounting to approximately 20 mg per 1 kg of the fruit in storage.

Chunxiao Xu [1] reports decreased yield of *Arabidopsis* plants grown in near null magnetic field. The author suggests that this decrease in yield in near null magnetic field is linked with interactions between the geomagnetic field and cryptochrome, a flavoprotein responsible for the regulation of anthocyanin synthesis [24].

The procedure applied by these authors, which was designed to prolong the duration of fruit storage by means of magnetic field compensation, resulted in an inhibition of the process of starch conversion into simple sugars by slowing down the mechanism of enzymatic decomposition of starch. The enzymes promoting the decomposition of starch in this case are amylases [25]. The interactions between a magnetic field and α - as well as β -amylase and glutathione S-transferase (GST) in wheat plants are described by Rochalska and Grabowska [26].

A decrease in enzymatic activity was particularly reflected by fructose contents. Following six weeks storage, the apples stored in the compensated magnetic field were found to have an over 1% lower content of fructose, compared to the control apples stored in the geomagnetic field. Such an effect may only be achieved if fruit are stored in specially designed conditions, with a controlled atmosphere. Significant differences were also identified in such parameters as contents of water, total ash, and volatile compounds.

Furthermore, the findings obtained following six weeks storage suggest a higher market value of fruit stored in a condition with a near null magnetic field because of their higher water contents, and consequently their greater firmness and cell turgor pressure. The lower contents of simple sugars, ash producing substances and greater turgor pressure resulted in the fact that, following the six-week testing procedure, the fruit looked healthier and were not infected by diseases, fungi or parasites.

All these changes may be associated with decreased enzymatic activity, lower intensity of respiration and slowing down of all physiological processes in apples stored in a condition with a compensated vertical component of the geomagnetic field.

5. Conclusions

As a result of the experiment involving storage of Jonagold apples in a condition with a compensated vertical component of the geomagnetic field and in control conditions, the findings showed statistically relevant improvement in the qualitative characteristics of the apples. Elimination of the component of the Earth's magnetic field led to slower decomposition of the sugar reserve (i.e., starch). It seems we can justifiably conclude that elimination of the Earth's magnetic field contributes to a decreased activity of the enzymes promoting conversion of starch into simple sugars, which considerably improves the storability of such fruit as apples.

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Conflicts of Interest: The authors declare no conflicts of interest.

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