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Teaching chemistry, biology and physics with the help of food analytical experiments

1. Summary

Experiments are of particular importance in the school education of physics, biology and chemistry. Students welcome gladly if the subject of an experiment is some kind of food, well-known to them. In the current work, ten simple experiments of physical, chemical and biological nature are described. The foods analyzed or used in the experiments are apples, apple juice, potatoes, lemons, lemon juice, vinegar, food coloring, table salt, vegetable oil, beet sugar, baking powder, baking soda and gelatin.

2. Introduction

In our previous article [1] we wrote that, in our opinion, presenting experiments has a particular importance in the teaching of natural science subjects. If chemistry, biology and physics experiments – and, of course, there is no sharp dividing line between these subjects – form a major part of the education then, in all likelihood, it will be easier to arouse the interest of the majority of students in these subjects with practical real-life examples. By presenting experiments, i.e., by demonstration, our teaching will hopefully be more effective and more efficient. We can be confident that the knowledge of the students will expand and their logical thinking will develop and improve by forming conclusions from the observations. What is certain is that students participate more eagerly in lectures demonstrating experiments and so they might be more inclined to study the given subject [2], [3], [4], [5].

To quote the thoughts of György Marx on the relationship between natural science subjects [6] it should be noted that although teaching of the traditional boundaries of physics, chemistry and biology could serve as suitable information in the centuries of scholastic thinking, but this is the past. One hundred years ago nature was viewed as separate plots, and this division is maintained today by the cells of the school timetable. However, today the expression natural science is mainly used in the singular, and it was especially in science that the special areas of, for example, biophysics, biomechanics, agrophysics, food phys-

ics, food chemistry, biochemistry, agrochemistry, radioecology and ecochemistry were established by the synthesis of the two directions characterizing development, differentiation and integration, demonstrating and proving clearly the substantial concentration and the material unity of the world [7], [8], [9], [10].

In our paper published in the 2nd issue of 2015 of the Journal of Food Investigations, we already described ten experiments, 5 of which were more physics in nature, 4 were chemistry and 1 biology. In the following, another ten simple experiments related to food analysis are presented (described) which can be carried out without much difficulty in a moderately equipped school laboratory suitable for performing physical, biological and chemical experiments. 4 each of the ten can be considered physical and chemical in nature, while two can be classified as biological. We emphasize that attention should be called to observing occupational safety and accident prevention regulations before performing each experiment, and also to the application of the most important scientific laws and their validity during the evaluation of the experiments.

3. Description of the recommended physical, biological and chemical experiments

3.1. Creation of a galvanic cell using agricultural products

Thanks to the Italian natural scientists Luigi Galvani (1737-1798) and Alessandro Volta (1745-1827), the so-called galvanic cell, a source of electricity, has

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been known for over 200 years. The important finding was the realization of the principle that if two different metals are immersed in acidic or alkaline solution, or in solutions containing salts/ions, then there will be a difference in potential between them. Just how big this potential difference will be can be calculated from the electrode potentials which are related to the Volta electrochemical series. Here we are talking about voltages of roughly 1 V.

Preparation of our experimental equipment – i.e., the galvanic cell – is very simple, a copper and a zinc plate (these are the two electrodes) are inserted into an apple, a lemon or a potato on opposite sides, and then the circuit is closed. The resulting potential can be measured using a voltmeter, the current with an ammeter or, by inserting a small flashlight bulb into the circuit we can “prepare” an operating light source from a fruit or vegetable, thus gaining the enthusiastic appreciation of the students. When performing the experiment, one should draw the students’ attention to the following:

- The potato, lemon or apple here serves as an electrolyte, i.e., a solution containing ions (cations and anions). Ask the students what are the ions expected to be present in these foods (the better ones will surely mention, for example, potassium and calcium as cations and chloride, citrate and phosphate as anions).
- The water content of these raw food electrolytes is roughly as follows: potato – 76%, apple – 90%, lemon – 89%. The mineral content (essentially the ash content) is this: potato – 1.1%, apple – 0.4%, lemon – 0.6%.
- Let us ask the question: is the resulting voltage value influenced by the identity of the product (food) the electrodes were inserted into, i.e., would the voltage be different in the case of pears or oranges?
- If there is time, we can perform the experiment using other metals (e.g., iron, silver, aluminum) as well, pointing out the differences in electrode potential and hence the differences in the voltage values obtained.
- Be sure to mention that the voltage obtained can be increased by connecting several galvanic cells in series.

3.2. Determination of sugar content by density measurement

Prepare 10, 20 and 30 weight percent beet sugar (sucrose) solutions – or possibly 10 g/100 ml, 20 g/100 ml and 30 g/100 ml sugar solutions – and measure the density of these solutions in an easy to perform, but quite accurate way, using a pycnometer. We will see that the measured density will be about 1.04 g/cm³ for the 10% solution, 1.08 g/cm³ for the 20% solution and 1.12 g/cm³ for the 30% solution. So there

is a strong correlation between the concentration and the density, and the change in sugar concentration can be followed by a simple physical measurement, without resorting to chemical analysis. Point out the following:

- An unknown sugar concentration can be determined knowing tabular data (e.g., Chemists’ pocketbook or the internet), or by recording a calibration curve.
- In theory, density measurement as the method of determination can only be used in the case of binary (two-component) systems, but there are many foods where, in addition to water, there really is just one dominant component present, so the procedure can be used routinely with acceptable accuracy, for example, in the case of measuring the sugar content of must or the alcohol content of dry wines based on density measurement.
- In the case of components other than beet sugar, naturally the density values will be different in the case of the same concentration so, for example, in the case of table salt (NaCl) the density will be roughly 1.07 g/cm³ for the 10% solution and 1.15 g/cm³ for the 20% solution.
- Of course, to a very small degree, the densities of the solutions tested are influenced by the temperature – tabulated data are usually for 20 °C – , but the difference in density of a 20% sugar solution at 15 and 20 °C is negligible – 1.08233 and 1.08094 g/cm³ – , the values are within the measurement error.
- There are other physical and chemical techniques for the measurement of sugar content, such as the polarimetric analysis that can be used in the case of optically active substances (such as sugar), in which case the rotation of the vibration plane of polarized light is measured, and the concentration is calculated from this. Another well-known and simple procedure is the refractometric method, in which the refractive index is measured.

3.3. Measurement of pH with a hand-held pH meter, using an electroanalytical procedure

pH measurement was already discussed in our previous article mentioned above, but then it was not performed using an electroanalytical procedure, but a fine-scale universal pH paper. The basis for the electrometric measurement is the Nernst equation, describing the relation, in the case of dilute solutions, between the potential of the electrode immersed in the solution and the hydrogen ion concentration [11]. The glass electrode measurement technique (hand-held pH meter with a glass electrode) can basically be considered direct potentiometry [12].

Data are provided by a digital pH meter with an accuracy of ± 0.1 pH value, and the measurement can be performed relatively easily, after washing the glass electrode with distilled water and calibration using a pH 7 buffer solution. Since the measurement range of the instrument covers 14 orders of magnitude – it can be used between the pH values of 0 and 14 –, it is suitable for the testing of very different substances and beverages, possessing very different pH values, such as fruit juices, fruit syrups, mineral waters, or even the aqueous solutions of baking powder or baking soda. Let's perform two measurement series. In the first, measure the pH value of the same sample, taken from a fruit juice, ten times, and check if there is a difference between the data provided by the membrane electrode instrument with an accuracy of 0.1 pH value. Second, prepare multiple dilutions of the test solution, using the same degree of dilution, and check to what extent the pH value changes. Try to have the students solve the problem of why the change in pH will be smaller and smaller after successive dilutions of the same degree (in this case, the change meaning an increase).

Regarding the above, students' attention should be drawn to the following aspects: When evaluating measurement data, point out the relationship and the difference between accuracy and reproducibility!

- Mention that there is a correlation between the titratable acid content of foods and beverages (very often a qualifying factor!) and the measurable pH value [13], and in the case of a given sample group, the titratable acid content can be estimated with good approximation, based on the pH value.
- Discuss with the students if it makes any sense to report pH values with an accuracy of more than 0.1 pH value, and if not, why not.

3.4. Removal of food coloring with activated carbon

Activated carbon is a microporous material with high specific surface area. The surface area of 1 gram of activated carbon can be as high as 500 m². The high specific surface area of activated carbon can bind (adsorb) many compounds, giving it several application areas. It is used, among other things, for purifying gases and gas mixtures (e.g., in air filters, respirators), for water treatment and in medicine, but it is of great importance in the food industry as well. It can be used, for example, for the preparation of decaffeinated coffee or to improve the color of wines. The surface binding capacity of activated carbon can be demonstrated clearly by the following experiment.

Place activated carbon (it can be powdered or a tablet) in a beaker and add a small amount of food coloring solution, e.g., the dilute aqueous solution of red food coloring containing azorubine (E122). Stir the

mixture briefly, then pour it into a funnel fitted with filter paper and placed above a test tube. Comparing the color of the filtrate and that of the original dye solution, the difference between the two solutions will be clearly visible, because the filtrate will be colorless. The colorless nature of the filtrate can be explained by the fact that the organic dye substances of the food coloring are bound or absorbed by the large surface area of the activated carbon.

During the experiment, one should draw the students' attention to the fact that adsorption on activated carbon is a weak, secondary interaction. One evidence of this is that the coloring substance can be dissolved from the surface of the adsorbent using a properly selected organic solvent.

It is also worth mentioning that adsorption (binding) should not be confused with the phenomenon of absorption.

Of course, instead of food coloring, one can also try to bind the dyes in red wine, fruit syrup or fruit tea, however, before presenting the experiment, it is recommended to optimize the amounts of activated carbon and colored solution beforehand in all cases.

3.5. Separation of the dye components of green food coloring

In chemistry, the separation of mixtures is a part of the curriculum, so students could learn about the most important characteristics of sedimentation, filtration, evaporation, crystallization and distillation, among other things. Although chromatographic separation techniques play a key role among modern chemical separation methods, very little is said about them even in the high school curriculum. The principle and the importance of the method can be demonstrated by a very simple experiment. Students can easily answer the question how, for example, sugar and sand or salt and iron can be separated, but who would be brave enough to separate the blue and yellow components of green food coloring? In fact, this "trick" is not hard at all, it is just a simple paper chromatography separation.

Place a few drops of blue and yellow food coloring on a watch glass, and then mix them. This is how the green colored solution is obtained. Draw a faint horizontal line on a piece of filter paper with the help of a ruler. Place the drops of the two-component solution on this line (the starting line). Place the paper in a glass jar containing water, then put a lid on the jar. Care must be taken that the water level does not reach the starting line drawn on the filter paper. The water flowing upward on the filter paper (the so-called eluent or mobile phase) carries with it the colored substances to be separated, which will gradually separate from each other while moving upward on the filter paper or the stationary phase (the experiment takes time).

The explanation for the phenomenon is that different dye substances are bound to the surface of the filter paper with different intensities. Thus, the water flowing upwards on the filter paper carries them to different distances. For comparison's sake, blue and yellow food colorings can also be applied to strips of filter paper. The experiment can be made even more spectacular by using a thin layer chromatographic stationary phase.

You can remind students that the thin layer chromatography technique is also referred to in the English terminology as the abbreviation TLC.

3.6. Chemical "yo-yo"

The chemical "yo-yo" is a spectacular, real "kitchen experiment" related to the topics of dissolution and acid-base reactions that can be performed both easily and quickly [14].

The experiment is performed by placing baking powder (or baking soda) in a beaker, and then carefully pouring oil on top of it. Following this, a few drops of red food coloring is added to vinegar in a small beaker, and small drops of the resulting red colored solution are transferred to the beaker with the oil, with the help of a dropper.

During the experiment, red colored vinegar drops first sink to the bottom of the beaker where they get into contact with the baking powder, and then rise to the surface of the oil. The repeated sinking and rising of the vinegar drops is in fact similar to the movement of a yo-yo.

The experiences of the experiment are explained by the fact that vinegar is insoluble in oil and, therefore, the vinegar remains as small drops. At the same time, the density of vinegar is higher than that of oil, so the small globules sink to the bottom of the beaker. When they get into contact with the baking powder, the vinegar reacts with the sodium hydrogen carbonate of the baking powder. During the reaction, carbon dioxide evolves, propelling the drops to the top of the oil. At the surface of the oil the carbon dioxide leaves the vinegar drop, which starts to sink again.

3.7. Studying osmosis with potatoes

During osmosis, diffusion of the solvent (usually water) happens through a semipermeable membrane, from the solution with the lower concentration towards the one with the higher concentration. Semipermeable membranes have small holes that only let particles through that are below a certain size limit. As a result of this, diffusion of the larger molecules is inhibited by the membrane, while that of the smaller ones (here, water) is not. Osmotic pressure is the pressure that has to be exerted on the solution in order to achieve a dynamic equilibrium (i.e., prevent osmosis) against the pure solvent. If the osmotic pressure of a solution is larger than that of another

solution, it also means that it has a higher concentration of dissolved particles.

During the experimental observation of the phenomenon of osmosis, a deep hole is carved into an unpeeled potato, which is then filled with table salt. The potato is placed in the mouth of a flask big enough to hold it, but not big enough for the potato to fall through. In our experience, the volume of the potato decreased after a few hours (or sometime a day) that it fell into the flask, and in the meantime salt solution flowed out of its cavity. The explanation for this phenomenon is that the cell membrane of the tissue cells of the potato is semipermeable. Due to the high concentration NaCl solution or NaCl crystals placed in the extracellular space, the water content of the cells starts to flow outward. Tissue cells start to shrink because of the loss of water, and so the volume of the potato decreases.

It is advisable to draw the students' attention to the fact that it is a similar phenomenon also based on osmosis when the skin of ripe cherries or sour cherries breaks as a result of rain, because water enters high the sugar content interior space (the cells) through the cell walls, and excess pressure ruptures the membrane. The inverse of the phenomenon of osmosis, called reverse osmosis (RO) is widely used in the food industry for the thickening of fruit and vegetable juices.

3.8. Studying the sol-gel states of protein colloids

To study the sol-gel states, gelatin is used. Gelatin (from the French *gélatine*) is a translucent, colorless, almost tasteless solid, prepared by the irreversible hydrolysis of collagen extracted from the connective tissues of animals. Its protein content is roughly 98%, and the biological value of the protein is low, containing mainly glycine, proline, hydroxyproline and glutamic acid, i.e., non-essential amino acids. It is widely used in the food industry, the pharmaceutical industry, and even in cosmetics. Materials containing gelatin or having similar consistency are usually also called gelatin. It is used in foods as E441 as emulsifier and also as a gelling agent.

Approximately 10 g of gelatin (protein) is warmed with about 60 ml of distilled water, and small amounts of the gelatin solution are added to several test tubes. By cooling it to room temperature, the material in the gel state can be observed, then warming it up in warm water, we can see how the gel turns into sol. After cooling, it becomes gel once again (it jellies).

The explanation of the phenomenon lies in the fact that the thermal movement of the water molecules accelerates due to the heat, and so the hydration shell around the gelatin particles becomes smaller. This means that the amount of free water increases, so the gelatin-water mixture reaches the sol (solution) state. As a result of cooling, the amount of water

arranged in the hydration shell increases, large hydration shells bind to each other, and the colloidal solution becomes a gel, i.e., a semisolid, form-stable state, a gelatinous consistency forms.

Incidentally, the development/change of sol-gel states forms the basis for the operation of biological systems, and often for different food industrial and food preparation technologies.

3.9. Examination of fruit firmness

It is our everyday experience that the quality and the shelf life of fruits correlates strongly to their firmness. Since one can now buy practically any fruit in any season, the measurement can be performed on a fruit of choice at any time during the school year. Of course, it is worth choosing a certain type of fruit and examine its versions of different firmness. With our students, we chose jonagold apples.

For the examination of firmness, a not too complicated measurement tool is assembled: a microphone is placed in a wooden box with a circular opening at the top, with a light, soft cover with a porous texture, ensuring free vibration of the fruit. The fruit to be examined is placed on this. The fruit is then simply hit by a stick – excitation – , generating a sound wave which is registered by the microphone. (By connecting the microphone to a computer, the characteristic frequency of the sound wave generated can be determined using a sound evaluation program.) It is important that the sound wave registered is the vibration in the fruit, and not the sound that can be heard in the air [15].

Firmness determines what the size of the dent on the object examined will be as a function of the force used. So the unit of measurement is N/m. It is easy to see that the same unit is obtained when the mass of the sample examined is multiplied by the square of the frequency:

$$\frac{N}{m} = \frac{kg \frac{m}{s^2}}{m} = kg \cdot \frac{1}{s^2}.$$

So all we have to do during the measurement is to determine the mass of the fruit and the frequency of the sound wave generated.

It can already be important to students that, instead of dent size and force, mass and frequency can be measured, drawing attention to the importance of relationships between physical quantities. Furthermore, it is also good to emphasize how important it is to find preferably non-destructive methods when analyzing foods (in this case, fruits). Of course, the INSTRON instrument used for performing rheological and textural analyses or the fructometer are well-known in the profession, but it is quite unlikely that

high school laboratories will possess these. The measurement technique described above is applicable to vegetables and greens (e.g., tomatoes) as well.

Incidentally, if measurements on the given fruit samples are performed by students several days in a row, a “series” can be compiled, based on which it can be determined about a fruit type how old the product could be, and it can also be estimated how long it can be kept under certain storage conditions (temperature, relative air humidity).

3.10. Studying the conductivity of electrolyte solutions

During the studies on electric current – in the 8th and 10th grades – in physics classes it is worth dealing in more detail not only with the conductive properties of metals, but at the same time, also with the conductivity of electrolytes. With a few simple experiments it can be demonstrated that the resistance or the conductivity – which is the reciprocal of resistance – of electrolyte solutions (e.g., water, mineral water, tea, coffee, fruit juice, soft drink) depends:

- on the amount or concentration of ions present in the electrolyte solution
- similarly to metallic conductors, on the „geometry” of the solution
- on the temperature of the solution

The first, very simple experiment can be performed in order to prove that tap water is not, or only very slightly electrically conductive, however, in a solution of table salt, conductivity increases dramatically. For this, it is sufficient to pour tap water into a beaker, into which carbon electrodes are immersed. As a power source, a battery can be inserted into the circuit. The electrode-battery circuit can be completed with a light bulb connected in series. While there is pure tap water in the beaker, the bulb is not lit, but as soon as we start adding salt to the water, the bulb will glow brighter and brighter.

The same tools are needed for the second experiment. Here we show that if the carbon electrodes are immersed in the electrolyte solution deeper (let’s stick to the aqueous solution of table salt, but other liquids containing ions can also be used of course), then the bulb will glow brighter, and if we pull them out, the brightness is reduced.

The same assembly is used again in the third experiment, but two solutions of the same concentrations are measured simultaneously. One solution is warmed until there is a significant temperature difference between them. Then the carbon electrodes are immersed in the beakers. Experience now shows that warm aqueous salt solution conducts electricity better.

Experience that can be gleaned from the experiments:

- Electric conductivity increases with increasing electrolyte solution concentration, but it should be pointed out that it cannot be increased further beyond a certain concentration limit. At higher concentration, conductivity does not increase anymore, because with increasing ion density, the attraction between oppositely charged ions will be considerable as well.
- Similarly to primary conductors (metals), a greater cross-section means greater conductivity as well. (By performing a more complex experiment providing quantitative data, a linear relationship can be confirmed.)
- Conductivity in electrolytes increases with increasing temperatures. This is opposite to what is experienced in the case of metals. We can point out the cause also, since in the case of electrolytes conductivity depends not only on the concentrations of the ions, but also on their mobility, and the latter increases with increasing temperatures.

Finally, it can be emphasized that conductometry is a measurement technique used in several areas of food analysis, as well as quality control. For example, it is suitable for checking the quality of the coffee brewed, to determine whether the coffee served at a restaurant is prepared from the dregs. There is also a conductometric method for the determination of the ash content of sugar. Moreover, the CO₂ content of carbonated beverages can be determined by a conductometric titration [16] [17]. Incidentally, conductivity given in microsiemens units (μS) is also used for the characterization of waters used in food industry technologies, referring to the mineral content.

4. Conclusions

We believe that performing the above-described ten simple physical, biological and chemical experiments and measurements based on food analysis and the observation of phenomena on foods, and their presentation in classes helps to instill knowledge of these subjects in the students. By experimentally demonstrating causal relationships, they also improve their logical thinking. By performing the experiments on foods, i.e., substances known to everybody in everyday life, useful information are conveyed to students about foods. This way, hopefully, we will be able to arouse their interest in the food industry and also in the different areas of food and nutritional science (e.g., food chemistry, food certification, food physics, nutritional biology, food technology).

5. References

- [1] Szabó, S. A., Izsák, M., Bozi, J. (2015): Általános - és középiskolás diákok kémia- és fizika-oktatása élelmiszer-vizsgálati kísérletek segítségével. (Teaching of chemistry and physics in elementary and high schools with help of food science experiments. *Élelmiszervizsg. Közl.*, (J. Food Investigation), 61 (2), 647-656., 2015.
- [2] Rózsahegyi, M., Wajand, J. (1999): *Látványos kémiai kísérletek. Mozaik Oktatási Stúdió, Szeged, 1999, p. 272.*
- [3] Öveges, J. (2008): *Kísérletezzünk és gondolkozzunk! Móra Kiadó, 2008.*
- [4] Z. Orbán, E. (2009): *Szerves kémia. Nemzeti Tankönyvkiadó, Budapest., 2009.*
- [5] Tóth, Z., Ludányi, L. (2010): *Kémia. Út a tudáshoz. Maxim Könyvkiadó, Szeged., 2010.*
- [6] Marx, Gy. (1979): *Jövőidőben. Egy fizikus írásai az iskoláról. Magvető Kiadó, Gyorsuló idő sorozat, Budapest.*
- [7] Papp, S., Kümmel, R. (1992): *Környezeti kémia. Tankönyvkiadó, Budapest.*
- [8] Szabo, S. A. (1993): *Radioecology and environmental protection. Ellis Horwood Ltd., Chichester, UK.*
- [9] Szabo, S. A. (1999): Food physics as an important part of food science and applied physics. *Int. Agrophysics*, 13(4) p. 407-409.
- [10] Szabó, S. A., Tolnay, P. (2014): Differenciálódás és integrálódás a tudományokban. *Magyar Sporttud. Szemle*, 15(1) p. 75-80.
- [11] Lásztity, R., Törley, D. (ed.) (1987): *Az élelmiszeranalitika elméleti alapjai. Mezőgazd. Kiadó, Budapest.*
- [12] Gasztonyi, K. (ed.) (1988): *Műszeres analízis. Kertészeti és Élelmiszeripari Egyetem, Élelmiszeripari Kar, Budapest.*
- [13] Szabo, S. A. (1980): Untersuchungen zum Zusammenhang zwischen pH-Wert und Azidität in Fruchtsirup und im Saft konservierter Gurken. *Lebensmittelind.*, 27 (8) p. 361-363.
- [14] <http://gyereketeto.hu/tanulas/otletek-szundore-5-nap-kemiai-jojo> (Hozzáférés: 2015. szeptember)
- [15] Felföldi, J. (1996): Firmness assessment of fruits and vegetables based on acoustic parameters. *J. Food Physics*, p. 39-47.
- [16] Szabó, S. A., Bende, E., Hajós, P. (1973): Új módszer sörök és üdítőitalok széndioxid tartalmának meghatározására. *Élelmiszervizsg. Közl.*, 19 (5) p. 249-256-
- [17] Szabó, S. A., Bende, E. (1975): Konduktometrische Bestimmung des Kohlensäuregehalts von Getranken. *Lebensmitt. Ind.*, 22 (3) p. 127-128.