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Tea-time chemistry

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Tea is a refreshing drink – and it can also help students to learn about important chemical reactions, as these simple experiments with infusions demonstrate.

Teas, including black, herbal, and fruit teas, are popular drinks and come in a wide array of varieties, matched by an impressive variety of colours once brewed. As many people will have noticed, adding substances to tea can change its colour – and a colour change can indicate a chemical change. In this article, we take a closer look at some chemical reactions – acid–base reactions, reduction/oxidation, and complex formation – that can be investigated by using simple and safe experiments with teas.

What is tea?

Tea is made by infusion: a physical method of extraction in which chemical compounds, such as oils and volatile organic compounds, dissolve in the infusing liquid. In the case of tea bags, the plant matter forming the material for infusion cannot pass through the bag, but smaller particles and compounds that cause colour and flavour can do so. Thus, the tea bag acts as a partially permeable membrane.

Traditionally, the term 'tea' referred to a product made by harvesting leaves from the tea plant (Camellia sinensis) that were then further processed. This product is now often referred to as 'black tea', because of its appearance before infusion. (This is distinct from tea served without milk, which confusingly is sometimes also known as black tea.) Today, however, many different plant-derived materials are marketed as teas, so in this article we use the term 'tea' to include all these products, and the term 'black tea' to refer specifically to traditional tea.

We devised the following tea-based activities for students aged 14–19. They are also suitable for ages 11–14 if there is less emphasis on the theory behind the chemical reactions.

The activities can be completed in one lesson (approximately 60 minutes), and we recommend that students work in groups of 3–4. Optionally, students can use the video feature on their cell phones to record and review the changes they see.

Preparation

The infusions should be prepared at the start of the lesson and allowed to cool down to room temperature before the activities are carried out. The activities can be introduced while the infusions are cooling. The following infusions should be prepared:

- Blue butterfly pea flower tea, prepared according to package instructions.
- Black tea from leaves or a teabag. This can be prepared according to packet instructions and diluted to a pale-yellow colour, or steeped at room temperature and the teabag removed once a pale-yellow colour is achieved.
- Hibiscus tea, prepared according to package instructions.

Activity 1: Blue tea as an acid–base indicator

In this activity, we explore the colour changes that occur when an acid and a base are added to a striking blue-coloured infusion of butterfly pea flower tea.

For remote teaching, this activity could be done by older students at home. In this case, small glasses or white cups can be used instead of test tubes, and sodium hydrogencarbonate should be used instead of ammonium hydroxide because it is safer to handle, although the colour change is less striking.

Materials

To prepare this activity, each group requires:

- Blue butterfly pea flower tea
- Half a lemon
- Household ammonia (ammonium hydroxide, NH_4OH, as 5% to 10% solution in water).
  Alternative: Baking soda (sodium hydrogencarbonate, $NaHCO_3$)
- Water
- Stirring rod
- Three test tubes
- Three small containers (e.g. plastic cups)
- Water boiler
- Dropper
- Teaspoon (if sodium hydrogencarbonate is used)

Procedure

Students should work through the following steps as a group:

1. Prepare an infusion of butterfly pea flower tea and allow to cool to room temperature. This should be done at the start of the lesson.
2. Squeeze half a lemon and collect the juice in a cup.
3. Pour a small amount (2–3 ml) of household ammonia (if used) into a cup.
4. Place approximately 20 ml of the infusion at room temperature into each of the three test tubes.
5. Using the dropper, add three to four drops of lemon juice to one of the test tubes, and three to four drops of ammonia to the other. Alternatively, instead of the ammonia, add a teaspoon of sodium hydrogencarbonate to the second test tube. Leave the third test tube as a control.
6. Shake the first and second test tubes gently to homogenize the mixtures.
7. Observe and record the changes that occur in the colours of the liquids contained in the three test tubes, if any.

Discussion

Discuss the following questions with your students:

- What changes occur in the water when the tea infusion is made?
- What colour is the tea infusion?
- What colour changes did you see in the liquids, if any, when lemon juice and ammonia (or sodium hydrogencarbonate) were added?
- How does the addition of (i) lemon juice and (ii) ammonia (or sodium hydrogencarbonate) affect the acidity of the solutions?
- Did the colour of the solution change as its acidity vary? If so, how?
- Do you think the prepared infusion is an acid-base indicator?
- Do you know any other homemade acid-base indicators?

Explanation

In the activity, students should see the following colour changes (see figure 1):

- When lemon is added, the blue tea turns purple and.
- When ammonia or sodium hydrogencarbonate, the tea turns green.

These colour changes occur because butterfly pea flower tea contains molecules called anthocyanins (see text box). These molecules alter the wavelength of light they absorb, and therefore their colour, depending on the pH of the solu-

Anthocyanins and chromophores

Anthocyanins are a group of water-soluble pigments responsible for the red, blue, or purple colouration of many flowers, fruits (including blueberries and raspberries), and vegetables (such as red cabbage).[1] These pigments are also partly responsible for autumn leaf colours.

The region of these pigment molecules that produces the colour is called the chromophore. In the chromophore region, the energy difference between two molecular orbitals falls in the range of the visible-light spectrum. Adding a hydrogen ion to a chromophore can change its wavelength of absorbance, and thus its colour. Because the acidity of a solution (or pH value) depends on the concentration of hydrogen ions, chromophores – and the plant material containing them – potentially act as natural acid–base indicators.

There are many examples of colour changes involving pH-sensitive anthocyanins and other vegetable dyes. Figure 2 shows an example.

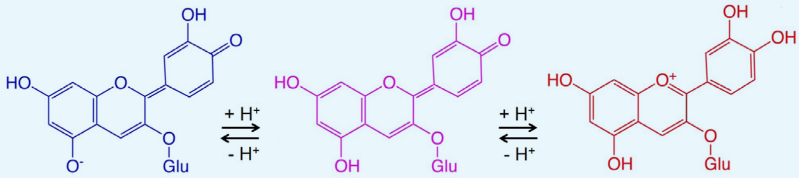

Figure 2: Different forms of the anthocyanin cyanidin-3-glucoside, in solutions of varying pH. The colour of the molecule represents that of its aqueous solution.
Image courtesy of Marisa Prolongo and Gabriel Pinto

Here, two reversible reactions, each involving adding a hydrogen ion to the molecule, cause a colour change at each step. Acidic conditions (low pH) drive the reversible reactions to the right (blue to red), while basic conditions (high pH) drive the reversible reactions to the left (red to blue).

tion they are in. Lemon juice contains citric and other acids, so adding this to the tea produces a more acidic (lower pH) solution and a visible colour change. Adding a weak base such as ammonium hydroxide or sodium hydrogencarbonate decreases the number of hydrogen ions, leading to a lower acidity (higher pH value) and another colour change.

Figure 1: Infusion of butterfly pea flower tea (left); after adding lemon juice (centre); and after adding ammonia (right).
Image courtesy of Marisa Prolongo

Activity 2: Identifying tannins in black tea

This experiment uses a solution containing iron(III) ions to produce a colour change indicating the presence of polyphenols such as tannins in tea. The solution should be prepared by the teacher before the class by dissolving a teaspoon of iron(III) chloride hexahydrate in 50 ml of water. Alternatively, a steel pan scourer or steel wool can be used, although in these cases the colour change will be slower. When using the iron(III) solution, it is instantaneous.

Materials

Each group of students will need the following materials:

- Black tea leaves or tea bag
- Water at room temperature
- Stirring rod
- Two test tubes
- Aqueous iron(III) solution
- Small container (e.g. plastic cup)
- Dropper

Procedure

Students should work through the following steps:

1. Prepare a weak infusion of black tea using hot or room-temperature water. Allow to cool if hot water is used. This should be done at the start of the lesson.
2. If necessary, dilute the prepared infusion with water until it is a pale brown-yellow colour.

3. Pour approximately 20 ml of the infusion into each of the two test tubes.
4. Add 3–4 drops of diluted iron(III) chloride to one of the test tubes. Alternatively, pour about 50 ml of infusion into a beaker, then add steel wool and heat to boiling, shaking gently to homogenize the mixture.
5. Leave the second test tube as a control.
6. Observe and record the changes that occur in the first test tube.

Discussion

Discuss the following questions with your students to explore the key concepts:

- Did the colour of the infusion change when the iron compound was added?
- Did the transparent appearance of the liquid also change?
- Does the final appearance of the liquid remind you of writing ink?
- Do you have any idea of what type of compound has been formed?
- Have you heard of tannins? Do you know any other examples of foods/drinks in which they are present?

Explanation

In the activity, the tea darkens when iron(III) ions are present, changing from pale brown to black, with the appearance of ink (see figure 3). The compounds responsible for this change are polyphenols, which react with the iron ions. Tea contains a number of polyphenols, including tannins that give it bitterness and astringency, and an example of these polyphenols is gallic acid and its derivatives, which are part of the structure of several tannins. The chemistry involved is rather complex, but in short, the gallic acid reacts with iron(III) ions to form ferric pyrogallate, a black insoluble complex ion.

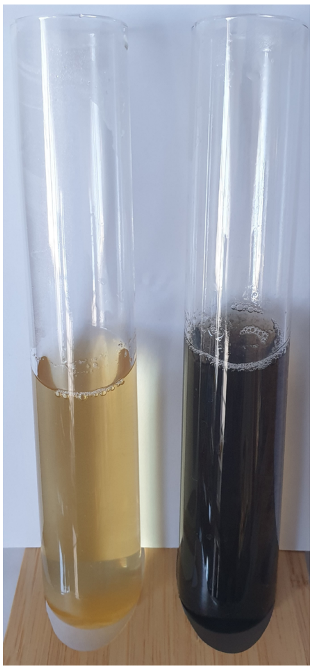

Figure 3: An infusion of black tea (left), and after adding a solution of iron(III) chloride (right)

Image courtesy of Marisa Prolongo

This activity can be used as a starting point to discuss how transition metal complexes are formed (the type of bonding involved, what ligands are, and how pH changes affect formation).

Figure 4 shows an example of a complex of gallic acid and iron(III), with two molecules of water acting as co-ligands to complete the octahedral coordination sphere.[2]

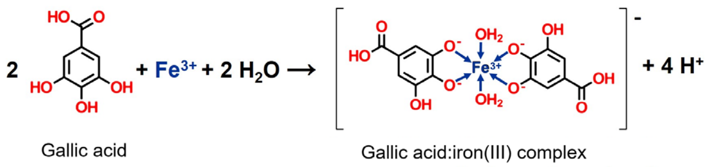

Figure 4: Formation of a gallic acid and iron(III) complex

Image courtesy of Marisa Prolongo and Gabriel Pinto

You can also test other infusions for the presence of polyphenols, for example, those based on rooibos. Different colours, from dark brown to dark blue, may result depending on the iron(III) complexes formed.

Activity 3: Redox reactions with hibiscus tea

In a previous article for *Science in School* ,[3] we introduced the idea of colour changes due to oxidizing and reducing agents (in that case caused by chemical reactions between glucose lollipops and permanganate salts).

In this activity, we look at colour changes due to the action of oxidizing and reducing agents on hibiscus tea. Here, sodium percarbonate acts as the oxidizing agent and sodium dithionite as the reducing agent.

Materials

Each group of students will need the following materials:

- Infusion of hibiscus tea
- Sodium percarbonate (also known as sodium peroxycarbonate), $2Na_2CO_3{\cdot}3H2O_2$
- Sodium dithionite (also known as sodium hydrosulfite), $Na_2S_2O_4$
- Water
- Water boiler
- Stirring rod
- Three test tubes
- Three small containers (e.g. plastic cups)
- Dropper
- Teaspoon

Procedure

Students should work through the following steps:

1. Prepare a hibiscus infusion and let it cool down to room temperature. This should be done at the start of the lesson.
2. Dilute the prepared infusion with water until pale in colour (to better appreciate the colour change) and introduce approximately 20 ml of this liquid into three test tubes.
3. Add a quarter teaspoon of sodium percarbonate to one of the test tubes and shake it gently to homogenize the mixture.
4. Repeat with a quarter teaspoon of sodium dithionite, adding this to the second test tube and shaking it gently to homogenize the mixtures.
5. Leave the third test tube as a control.
6. Observe and compare the final colours of the liquids in the three test tubes.

Discussion

Discuss with your students the following questions:

- Did the colour of the infusion change when (i) sodium percarbonate and (ii) sodium dithionite were added?
- From the chemical point of view, what are oxidizers and reducers?
- In this activity, which substance is the oxidizing agent (acting on the tea), and which is the reducing agent?

Students can also be asked to do their own research to investigate how this activity relates to bleaching products. For example:

- Search for information about bleaches and fabric whiteners on the internet. What chemical substances are typically used in these products?
- Look for information about the presence of dithionite and percarbonate salts on the labels of laundry products sold in supermarkets. What do you find?

Explanation

The hibiscus tea discolours (bleaches) almost completely with sodium dithionite, but not with sodium percarbonate (figure 5).

Figure 5: Hibiscus infusion (left), and after adding sodium percarbonate (centre) and sodium dithionite (right)
Image courtesy of Marisa Prolongo

Chemical bleaches are products used to remove colour from fabric and to clean stains. They react with many coloured organic compounds, including natural pigments. Oxidizing agents are most commonly used, but some reducing agents are also used.

Sodium percarbonate is a typical peroxide-based oxidizing bleach. The peroxide group gives rise to very reactive oxygen species, and these are the active bleaching (and oxidizing) agents. They break apart chemical bonds in the chromophore region of the pigment molecules (see text box), changing their colour.

A reducing bleach, such as sodium dithionite, works by converting the carbon–carbon double bonds in the chromophore to single bonds, thereby decreasing the oxidation state of the carbon.

Safety note

Although most of the reagents are common household chemicals, some, such as ammonium hydroxide solution, sodium percarbonate, and sodium dithionite, can be irritants or corrosive. Teachers should follow their local health and safety rules and the advice on the product label. A lab coat, gloves, and safety glasses should be worn by all students to avoid contact of the chemicals with skin and eyes. Particular care should be taken with the iron(III) chloride. See also the general safety note on the *Science in School* website. All waste is safe for disposal down the drain.

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References

[1] Rusishvili M et al. (2019) Unraveling the molecular mechanisms of color expression in anthocyanins, *Physical Chemistry Chemical Physics* **21**: 8757-8766. doi: 10.1039/C9CP00747D

[2] Rattanakit P, Maungchang R (2019) Determining Iron(III) Concentration in a Green Chemistry Experiment Using Phyllanthus emblica (Indian Gooseberry) Extract and Spectrophotometry, *Journal of Chemical Education* **96**: 756-760. doi: 10.1021/acs.jchemed.8b00817

[3] Prolongo M, Pinto G (2018) Colourful chemistry: redox reactions with lollipops. *Science in School* **43**: 41–45.

Resources

- A video demonstrating the activities suggested in this article: https://youtu.be/hO6-KV0_Wdw
- Detailed information on the effect of acidity on the molecules in butterfly pea tea: https://www.beyondbenign.org/lessons/equilibriumle-chateliers-principle/
- Learn more about oxidizing and reducing agents through colourful reactions between lollipops and permanganate salts: Prolongo M & Pinto G (2018) Colourful chemistry: redox reactions with lollipops. *Science in School* 43: 41–45.
- A German-language book with ideas for chemical reactions using everyday products: Schwedt G (2009) Experimente mit Supermarktprodukten: eine chemische Warenkunde. Wiley-VCH. Translated into Spanish under the title Experimentos con productos de supermercados: merceología química.
- Investigate antioxidants in food and drinks: Farusi G (2009) Looking for antioxidant food. *Science in School* **13**: 39–43.
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Marisa and Gabriel are Scientix Ambassadors. They have taken part in many workshops for teacher training, and in national and international science festivals presenting experiments for STEM education.