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Chemistry in a coffee cup: does coffee waste contain key elements for plant growth?

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Circle of life: Explore sustainability, the circular economy, and chemical analysis by evaluating coffee waste as a potential soil enhancer.

This activity was presented at the Science on Stage Festival 2024.

The "A Cup of Coffee" project, carried out by secondary school students aged 16–18 in Italy, introduces sustainability and circular economy[1] concepts through engaging STEM activities. This initiative demonstrates how coffee grounds, often discarded as waste, can become a valuable resource.[2,3] By turning classroom learning into an environmental challenge, students gain practical insights into waste recovery and energy production.

The project started with an analysis of the coffee waste produced at school. Students interviewed the school's barista and calculated the daily and annual amounts of coffee grounds generated. Using this data, they explored two main investigative paths:

- Nutritional content analysis: in the laboratory, students analyzed coffee grounds to assess their suitability as a soil enhancer. They tested for pH and nitrogen, phosphorus, and potassium contents – key nutrients for plant growth.
- Designing a circular recovery process: students developed a system to repurpose coffee grounds for anaerobic

digestion, producing biogas. The remaining solid residue was tested as a potential soil amendment, completing the circular economy model.

In this article, we focus on the first point, namely, the laboratory activities that are used to determine the nitrogen, phosphorus, and potassium contents.

Age Range: 14-16; 16–18 years

Curriculum Topics: Sustainability, chemistry, biology, environmental science, circular economy, and renewable energy. Chemistry topics covered include redox reactions, periodic table groups, elements vs compound, organic vs inorganic compounds, acid-base reactions, colorimetric analysis, flame tests, and stoichiometry calculations.

The challenge

Coffee grounds are part of a much larger problem that begins with the entire coffee production cycle, from picking the cherries to processing and roasting the beans to their use.[2,3] In this article, we have chosen to focus exclusively on the final stage of the cycle: what happens to the grounds after the coffee is brewed?

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Plants need certain key elements to grow, and if the soil doesn't have enough of them, fertilizers can be used to improve growth, in particular, nitrogen, phosphorus, and potassium.[4] Are these elements present in coffee grounds? If so, could they be recycled to make fertilizer?[5]

Activity 1: Preparation

The first step is to introduce students to the theme and explain the task of testing coffee grounds to determine whether they contain the essential elements required for use as a plant fertilizer. The coffee grounds must also be dried for use in the rest of the activities. Since this drying process can take some time, it should be started several days, at least, before the lesson.

Materials

- Spent coffee grounds (not too wet), e.g., from an espresso machine
- Large trays to spread out the coffee grounds
- An oven
- A balance
- An airtight container for the dried coffee grounds
- Coffee waste infosheet
- Plant nutrients infosheet
- Fertilizers infosheet
- Optional: fertilizers crossword

Procedure

The water content is determined by drying the coffee sample in an oven at 105°C. By using this method, it is found that used coffee grounds contain approximately 58% water.

1. Weigh the coffee grounds.
2. The coffee grounds should then be dried at room temperature in the laboratory for 24–48 hours; they are spread in thin layers and turned occasionally to allow for uniform drying. This can be started by students and completed by the teacher or lab technician.
3. Weigh the dried coffee grounds again and note the mass difference. Approximately 80% of the water in used coffee grounds can be removed in this way without heating.
4. A portion of the air-dried grounds is then weighed, placed in an oven at a maximum temperature of 105°C, cooled, and weighed again.
5. The difference in mass (initial – final) multiplied by 100 is calculated to give the percentage of water in the sample (8–10%).
6. For laboratory experiments, it is important to use fully dried coffee grounds to obtain reproducible results.

Discussion

Before or after drying, or while waiting for the grounds to dry, the teacher can introduce the problem of coffee waste to students and discuss whether coffee waste could be a source of the components of fertilizers. The coffee waste, plant nutrients, and fertilizers infosheets can be used as a basis for the discussion. Students can also try the fertilizers crossword as a recap exercise.

Activity 1: Nitrogen analysis

Plants absorb nitrogen mainly in two forms: nitrate (NO_3^-) and ammonium (NH_4^+). These forms are created through natural processes like lightning, microbial action in the soil, and organic matter decomposition. In this activity, students perform simple tests to detect these two nitrogen species in coffee waste.

Activity 1.1: Testing reaction fumes

This activity involves detecting nitrogen in coffee grounds by producing ammonia gas through a chemical reaction. The activity takes about 30 minutes.

Safety notes

Handle NaOH (aq) with care, as it is caustic: wear protective gloves, lab coats, and eyewear. Waste disposal: sodium hydroxide waste must be collected separately in a clearly labelled container ("Basic Waste – NaOH"). Do not pour concentrated NaOH down the sink. Neutralize small amounts carefully with a dilute acid (e.g., acetic acid or hydrochloric acid) before disposal according to local regulations. Perform the activity in a well-ventilated area or in a fume hood to avoid inhaling fumes.

Materials

- Dried coffee waste
- Conical flask
- Spatula or spoon
- Sodium hydroxide solution (NaOH, 2 M)
- Devarda's alloy
- Small funnel
- Litmus paper
- Heating plate

Procedure

1. Place a measured amount of dried coffee waste in the conical flask.
2. Add a small quantity (e.g., a spatula tip) of Devarda's alloy.
3. Pour NaOH (aq) (2 M) into the flask using the funnel to minimize spills.
4. Heat the mixture gently to produce ammonia gas.
5. Test the gas using litmus paper held at the neck of the flask.
6. Observe the colour change. The litmus paper turns blue, indicating the presence of ammonia and, thus, nitrogen in the coffee waste.

Image courtesy of the author

Results/discussion

Why does ammonia indicate nitrogen content? When nitrate ions are reduced and ammonium ions are displaced, ammonia gas (NH_3) is released. Since ammonia contains one nitrogen atom per molecule, detecting it confirms that nitrogen is present in the original sample.

To detect nitrogen in the form of nitrate (NO_3^-), a redox reaction is used in a basic environment. In this reaction, the nitrate ion – where nitrogen has an oxidation state of +5 – is reduced to ammonia gas (NH_3), where nitrogen is in its lowest oxidation state (–3). This reaction is made possible by Devarda's alloy, which contains strongly reducing metals like aluminium, zinc, and copper.

The overall redox reaction can be written as:

$$3NO_3^- + 8Al + 21OH^- \rightarrow 3NH_3 + 8AlO_3^{3-} + 6H_2O$$

To confirm the presence of ammonium ions (NH_4^+) in a sample, a displacement reaction is performed. By adding a strong base, such as sodium hydroxide (NaOH), ammonia gas is released from the ammonium salt:

$$NH_4^+ + OH^- \rightarrow NH_3\,(g) + H_2O$$

In both cases, a positive result is indicated by the production of ammonia gas, which is confirmed using litmus paper. When exposed to NH_3, the paper changes colour due to an acid–base reaction – typically turning from red to blue, indicating the basic nature of ammonia.

In industry, similar chemical reactions are used in automated systems, such as Kjeldahl nitrogen analysis. These methods allow for fast, large-scale determination of nitrogen content in organic waste, supporting fertilizer production and nutrient recycling.

Activity 1.2: Nitrate analysis using an aquarium test kit

This experiment helps to determine the presence of nitrates in coffee waste. Nitrates are essential nutrients for plants but can cause water pollution in high concentrations. Using an aquarium test kit, students can measure nitrate concentration (range 1–25 mg/l). This method provides a simple and accurate way to analyze nitrates, making it useful for environmental monitoring and agricultural applications. This activity takes about 15–20 minutes.

Image courtesy of the author

Safety notes

Follow the safety notes in the instructions for your test kit. Wear protective gloves and eyewear. Handle all reagents carefully, as some can cause burns. Keep reagents away from children and store them securely. Work in a well-ventilated area.

Materials

- Dried coffee waste
- Aquarium nitrate test kit (i.e., ELOS AquaTest NO3-)
- Precision scale
- Beaker
- Filtration funnel
- Volumetric flasks
- Spatula or spoon
- 10 ml syringe (or graduated pipette)
- Distilled water
- Optional: nitrate worksheet

Procedure

1. Using a precision pocket scale, weigh a quantity of approximately 5–6 g of coffee waste.
2. Add an exact volume of 200 ml of distilled water. Stir occasionally for about 30 minutes and filter.

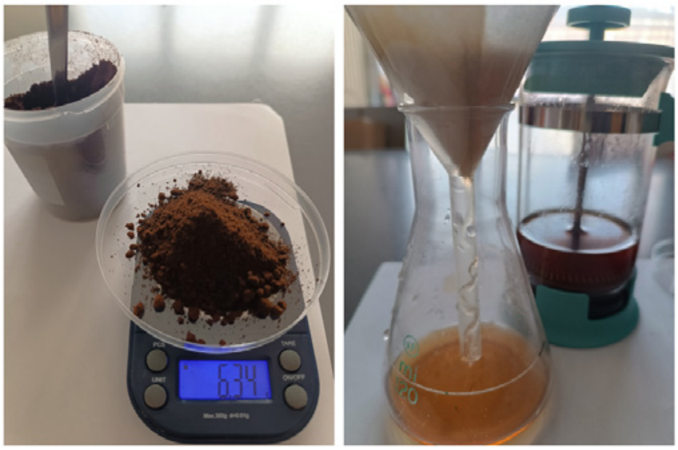


Image courtesy of the author

3. Remove 5 ml of solution with a syringe (or graduated pipette) and make up the dilute solution in a 100 ml volumetric flask (20× dilution).
4. Transfer 5 ml from this flask to a vial with a lid, add the reagents, close the vial, and shake the solution for 5 minutes.

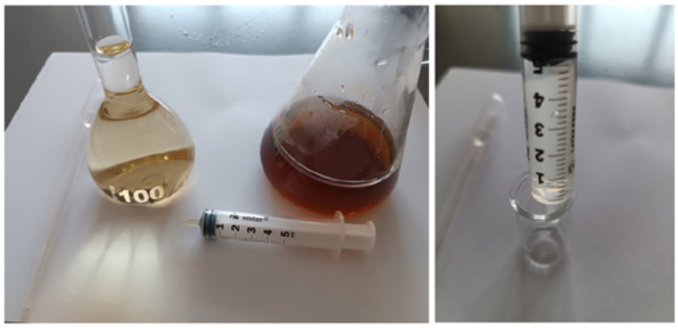


Image courtesy of the author

5. Place the vial on a white background next to the colour chart. Look from above into the open vial and compare the solution's colour to the chart.
6. The solution changes colour based on nitrate concentration. A deeper red or pink colour indicates higher nitrate levels.
7. Record the nitrate concentration corresponding to the colour.

Image courtesy of the author

Results/discussion

Have students answer the questions on the nitrate worksheet to put their readout in context. Worked examples can found on the nitrate answers sheet.

Activity 2: Phosphorus analysis

Phosphates, just like nitrates, are essential nutrients for plants and can behave in the same way in terms of environmental pollution. Plants take up phosphorus in the form of dihydrogen phosphate ($H_2PO_4^-$) and monohydrogen phosphate (HPO_4^{2-}) ions.

In this experiment, students use an aquarium test kit to measure phosphate concentration (range 0.05–1 mg/l) in coffee waste.

This activity takes about 15–20 minutes.

Safety notes

Follow the safety notes in the instructions for your test kit. Wear protective gloves and eyewear. Handle all reagents carefully, as some can cause burns. Keep reagents away from children and store them securely. Work in a well-ventilated area.

Materials

- Dried coffee waste
- Aquarium nitrate test kit (i.e., ELOS AquaTest PO4)
- Precision scale
- Beaker
- Filtration funnel
- Volumetric flasks
- Spatula or spoon
- 10 ml syringe (or graduated pipette)
- Distilled water
- Optional: phosphate worksheet

Procedure

1. Prepare 200 ml of coffee extract through soaking and filtering, as in Activity 1.2, or use the remaining solution from Activity 1.2 if doing the experiments on the same day.
2. Again, prepare a 20× dilution by removing 5 ml of solution with a syringe (or graduated pipette) and making the dilute solution in a 100 ml volumetric flask.
3. Transfer 10 ml from this flask to a vial with a lid, add the reagents, close the vial, and shake the solution for 5 minutes. Place the vial on a white background next to the colour chart. Look from above into the open vial and compare the solution's colour to the chart.
4. The solution changes colour based on phosphate concentration. A deeper blue colour indicates higher phosphate levels.
5. Record the phosphate concentration corresponding to the colour.

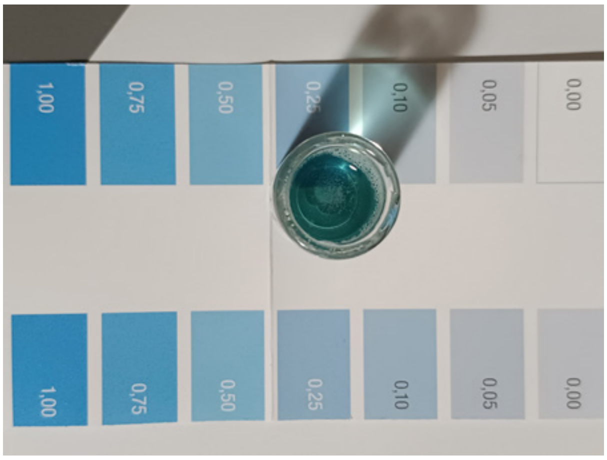


Image courtesy of the author

Results/discussion

Have students answer the questions on the phosphate worksheet to put their readout in context. Worked examples can found on the phosphate answers sheet.

Optional extension

As an optional extension, phosphate levels can also be estimated using a more advanced UV/Vis spectrophotometric method.[6] A common approach involves the formation of a blue-coloured complex between orthophosphate ions and ammonium molybdate, followed by reduction with ascorbic acid. The intensity of the resulting blue colour is directly proportional to the phosphate concentration and is measured at specific wavelengths, typically around 890 nanometres. It is even possible to build simple spectrophotometers for this purpose.[7]

Activity 3: Potassium analysis

Potassium (K) is one of the three main nutrients that plants need to grow, along with nitrogen (N) and phosphorus (P). Unlike nitrogen or phosphorus, potassium does not become part of the plant's cells or structures.

In this activity, students test for the presence of potassium in coffee waste ash using a flame test.

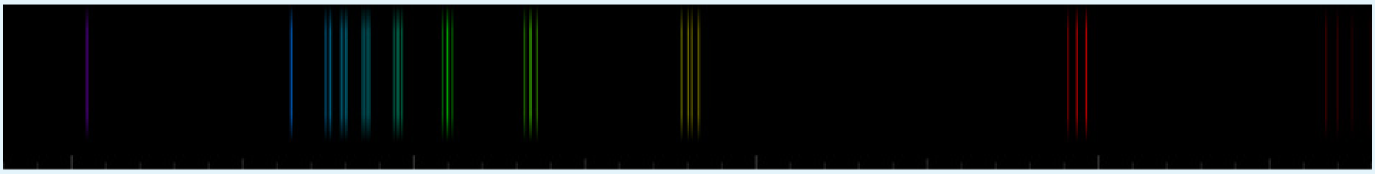
This activity takes about 20 minutes (for the simple activity with a Bunsen burner and cobalt blue glass) or 2 hours if building a DIY spectroscope.

Tips for best results

If both potassium and sodium are present, a blue filter (such as cobalt glass) is needed to block the strong yellow light from sodium and allow the red–violet light from potassium to be seen more easily.

Even better, you can observe the potassium emission line using a hand spectroscope. If you don't have one, you can build your own using a CD[8] or construct a DIY smartphone spectroscope.[9] A smartphone camera may not detect infra-red, but it is possible to see the red/violet line, depending on the device's sensor.

The potassium emission line appears as a weak violet or red line in the near infrared, around 766 nanometres. Because of its position in the spectrum and possible interference from other emissions, such as sodium, it can be difficult to observe. The setting must be dark, and spectroscopes (if used) must be well calibrated.



Simulated emission spectrum of neutral Potassium based on data from the National Institute of Standards and Technology Atomic Spectra Database (NIST ASD)

Image: NIST/Wikimedia Common, Public Domain

Safety notes

Handle HCl (aq) with care, as it is corrosive: wear protective gloves, safety goggles, and a lab coat and use only in a well-ventilated area or fume hood.

Disposal instructions: do not pour concentrated HCl down the sink. Neutralize with a dilute sodium bicarbonate solution in a fume hood. Dispose of neutralized solution according to your local hazardous waste regulations.

Use a Bunsen burner with caution: keep it away from flammable materials, never leave it unattended, and always use a blue flame for best results and safety.

Be careful with hot nickel wire. Use pliers or tongs and allow it to cool before touching. Clean it between tests with dilute HCl and a flame.

Materials

- Coffee ground ash, water-soluble solid inorganic fertilizer, or a potassium salt like KCl
- Hydrochloric acid (HCl, 2 M)
- Test tube
- Cobalt blue glass or hand spectroscope
- Nickel–chromium wire
- Bunsen burner

Procedure

1. Prepare ash from coffee grounds by incinerating them. If this isn't possible, test a water-soluble inorganic fertilizer. A potassium salt like KCl can be used as apositive control.
2. Partly fill the test tube with acid.
3. Dip the nickel–chromium wire into acid and then into the ash or salt.
4. Hold the wire in the Bunsen burner flame and observe the colour. To see the colours clearly, the test should be done in a darkened room.
5. View the flame through cobalt blue glass to enhance the violet hue, which is characteristic of potassium, or (ideally) observe the potassium emission line with a hand spectroscope.

Observation

A red–violet-coloured flame or the near-infrared emission line confirms the presence of potassium.

Flame test with potassium

Image: Skyr/Wikimedia Commons, CC BY 4.0

Flame tests are based on the property of some elements emitting visible light when they are excited by absorbing energy from the flame. The excited electron quickly returns to its ground state and releases energy as light of a specific colour.

Ask students why the cobalt blue glass helps when observing the potassium flame.

Answer: cobalt blue glass acts as a filter that absorbs the intense yellow light emitted by sodium, which is often present as a contaminant. This makes it easier to see the faint violet flame of potassium, which would otherwise be masked by sodium's brightness.

Optional extension

Potassium levels could also be estimated simply through atomic absorption spectrophotometry with a spectrometer. [10]

Conclusions

These results can act as a springboard for an interdisciplinary project on coffee waste. Encourage students to research the problem of coffee waste. By adopting circular economy practices, the coffee sector can transform this waste into valuable resources. For example, coffee residues can be used to produce biogas, fertilizers, compost, biofuels, and even materials like biochar and packaging materials.[11,12]

To share their findings, students can make posters and videos, engaging both their peers and the wider community to promote awareness of sustainability and encourage practical waste-recovery initiatives, aligning with sustainable development goals on responsible consumption and climate action.

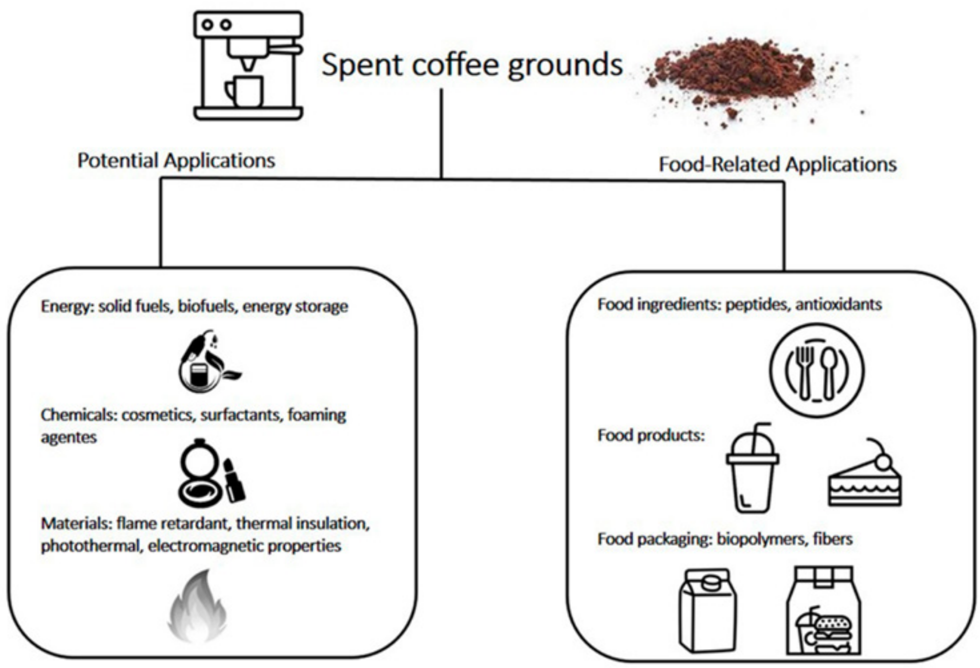


Image taken from Ref. [11]

A student experiment on the use of coffee grounds as a fertilizer
Image courtesy of the author

The project has potential for further expansion. You can use some of the suggested resources to learn more about some aspects of fertilizers. Schools could introduce composting initiatives to make compost from the coffee waste, providing additional hands-on STEM learning opportunities. Students might also investigate the effects of coffee grounds on different soil types, thereby encouraging interdisciplinary collaboration and deeper inquiry. «

References

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[10] Bastién N et al. (2014) Camping burner-based flame emission spectrometer for classroom demonstrations. *Journal of Chemical Education* **91**: 1655–1660. doi: 10.1021/ed4008149

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[12] Pongsiriyakul K et al. (2024) Upcycling coffee waste: key industrial activities for advancing circular economy and overcoming commercialization challenges. *Processes* **12**: 2851. doi: 10.3390/pr12122851

Resources

- Watch a video summary of the project 'A Cup of Coffee'.
- Read about importing coffee into the EU.
- Learn about the EU's strategy for transitioning to a circular economy in the new circular economy action plan.
- Watch a slow-motion video on the reaction of potassium in water.
- Check out this video on the Broadbalk experiment, which compares the impact of farmyard manure and various inorganic fertilizers.
- Read this detailed article on the Haber process
- Watch these short explainer videos on the Haber process:
  - https://www.youtube.com/watch?v=NWhZ77Qm5y4
  - The Haber Process Explained - LabXchange
- Learn about the 'three sisters' crop system.
- Watch a video on how nitrogen-fixing bacteria can benefit farmers in agriculture.
- Extract keratin from wool and learn about its use as a raw material for biobased products: Zambrotta M (2024) Extract value from wool waste: keratin and the circular economy. *Science in School* **69**.
- Investigate the properties of so-called superfoods: Frerichs N, Ahmad S (2020) Are 'superfoods' really so super? *Science in School* **49**: 38–42.
- Use baker's yeast to demonstrate biofuel cells in the classroom: Grandrath R, Bohrmann-Linde C (2023) Simple biofuel cells: the superpower of baker's yeast. *Science in School* **66**.
- Learn about a variety of biochemical aspects of honey through a series of simple experiments: Scheuber T (2023) To bee or not to bee: the chemistry of honey. *Science in School* **65**.
- Discover the science of limonene: Butturini F, Fernández JJ (2022) Citrus science: learn with limonene. *Science in School* **58**.
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- Learn how some of the elements used in modern technology are scarce and finite resources: Furze J, Harrison T (2021) Elements in danger! *Science in School* **54**.
- Discover how mealworms could offer a sustainable alternative source of animal protein: Bonin L, Jeran M (2024) Towards sustainable nutrition: could mealworms provide a solution? *Science in School* **66**.
- Learn how biomimicry can be an inspiring teaching tool that engages students by solving real-world problems: Dawson R (2024) Biomimicry: a nature-based approach to designing sustainable futures. *Science in School* **69**.
- Discover simple adaptations of experiments to make chemistry accessible to students with vision impairment: Chataway-Green R, Schnepp Z (2023) Making chemistry accessible for students with vision impairment. *Science in School* **64**.
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