A Hands-on Solvent Extraction Learning Activity for High School Students

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As population of the earth rising, the need to produce cheap food is essential. It becomes more important for K-12 students to be familiar with basic fundamentals of food processing. The following interactive caffeine extraction from coffee activity gives K-12 students the opportunity to learn some food processing basic techniques. This activity was developed in collaboration with the National Science Foundation's outreach program at the University of Mississippi. Many of State mandated educational standards are followed to develop this hands-on activity and it can be used in any food or chemistry science class as a supplement.

The extraction of caffeine from coffee is a convenient, cheap, and effective example for teaching students the solvent extraction processes. The procedure is easy to perform and can be done using basic tools which are easy to purchase. This procedure has a number of advantages. It is fast and easy to perform and there are opportunities to teach the phase behavior of multi-phase solutions. Finally, the caffeine extraction from coffee can be presented in the high school classrooms or in the outreach activities.

The activity begins by discussing basics of the food science, processing and solvent extraction using caffeine consumption through the world as a model. Then, students will start the experiment and they will extract caffeine from coffee. The students are responsible for the keeping track of the extraction process and collecting data. The activity will finish with a series of calculations to determine the extracted amount of caffeine.

Audience:

The procedure for the extraction of caffeine from coffee was prepared for high school students.

Chemistry concepts:

Solvent extraction, phase separation, solvents, evaporation

Table of Contents

1. Introduction

Caffeine is the most widely used drug which is legal in most parts of the world. Caffeine can be found in coffee, tea leafs, cocoa beans, etc. It is stimulant and cause a mild dependency in some people. The withdrawal of caffeine may lead to headache and irritability. Caffeine improves performance by relieving or preventing drowsiness. It is soluble in water which makes it easy to make beverages such as tea, coffee, and cola. In 2005, almost 90% of North Americans were consuming caffeine-containing drinks daily; such as coffee, soda-pop, tea, etc.

Caffeine is a bitter white crystal. It is very soluble in water at its boiling temperature (0.66 g/mL) while it is relatively less soluble at room temperature which indicates pure caffeine crystals can be made by precipitation of the caffeine crystals at lower temperatures. It was isolated for the first time by a German chemist, Friedlieb Ferdinand Runge, in 1819. The chemical name of caffeine is 1,3,7-trimethylxanthine and it is an alkaloid. Alkaloids are organic compounds containing nitrogen and they have pharmacological effects on both humans and animals. Figure 1 shows the chemical structure of the caffeine.

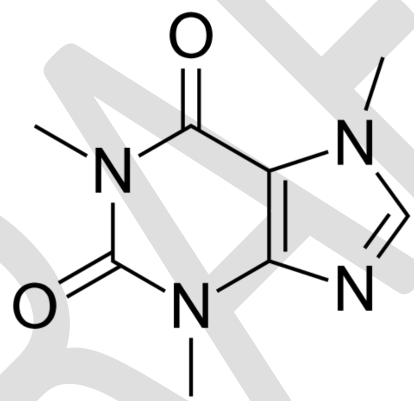

Figure 1. Caffeine chemical structure

Solvent extraction is a technique for separating materials. This method is based on the difference of the solubilities of compounds in solvents in which the liquids are not completely miscible. This method involves the movement one compound, known as solute, from a liquid into another liquid. For example the movement of caffeine, the solute, from water to an organic solvent. The solute enriched solvent is called the extract and the water depleted of caffeine is called the raffinate. Figure 2 shows a schematic diagram of a solvent extraction process.

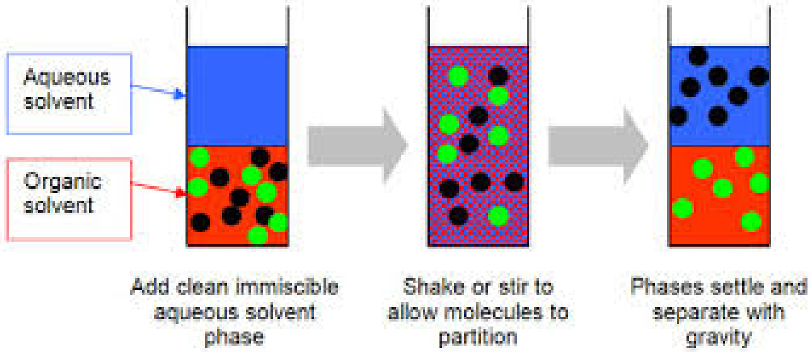

Figure 2. A schematic diagram of solvent extraction process

Caffeine is soluble on both water and alcohols; however, it is more soluble in alcohols than in water. Therefore, alcohols can be used to extract caffeine from coffee solution in water. For this activity, rubbing alcohol will be used as a solvent to extract caffeine. But, rubbing alcohol is miscible in water and will not separate into two phases as shown in in the right-hand-side of Fig. 2. To overcome this problem, sea salt is used which is an ionic compound. Water is a polar solvent and "likes" salt ions more then it "likes" alcohol. In fact, this preferences of water for salt ions over alcohol causes a reduction in the miscibility of alcohol as sea salt is dissolved into the water. The result is that rubbing alcohol is immiscible in the salty water. Scientifically, this chemical phenomena is called "salting out." It should be noted that the rubbing alcohol should be at least 90% pure which can be found easily in the shopping centers such as Walmart and Walgreen's.

2. Activity

Tell students that they are going to be a chemical engineers for the day and they will make caffeine from coffee. Show them the materials that they will work with. Explain the activity and solvent extraction method for separation. Discuss that sometimes it is difficult to find proper solvents for special extraction purposes. Break the students into groups and give them materials with hand-outs. After explaining the hand-out and procedure, let them to start the experiment.

3. Hand-outs

In this hands-on activity, the extraction of caffeine from coffee into rubbing alcohol. After completion of the extraction procedure, the alcohol will be evaporated to determine caffeine. Table 1 shows the required materials for each group. In addition, Figure 3 shows the step by step procedure diagram.

Table 1. Required materials for each group

Material	Quantity	Comments
Coffee	10 g	
Beaker (500 mL)	2	
Weighing scale	1	
Heater	1	
Spoon	1	
Graduated cylinder (100 mL)	1	Should be plastic or non-reactive
Filter paper	1	
Funnel	1	
Sea salt (without iodine)	80 g	
Rubbing alcohol	200 mL	Purity should be 90%
Turkey baster	1	
Aluminum foil		
Metallic plate	1	

Detailed procedure for caffeine extraction from coffee:

1. Weigh the empty beaker
2. Add 5 to 10 grams of coffee to the beaker
3. Add 300 mL water using graduated cylinder
4. Mix the coffee solution using spoon
5. Heat up the solution until it is close to boiling point
6. Mix the solution every 5 minutes
7. Do not let the solution to boil because, caffeine is sensitive to heat and it decomposes at higher temperatures
8. Add 80 grams of sea salt and mix the solution until salt is completely dissolved in the solution
9. Leave the coffee sludge to cool down to the room temperature
10. Use paper filter, funnel, and a beaker to separate coffee grounds from the solution
11. Add 200 mL of rubbing alcohol using graduated cylinder
12. Mix the solution for 10 minutes
13. Leave the solution for 15 minutes for phase separation
14. After 15 minutes the solution should be separated in two phase: Alcoholic phase which contains caffeine and aqueous phase which contains water and coffee

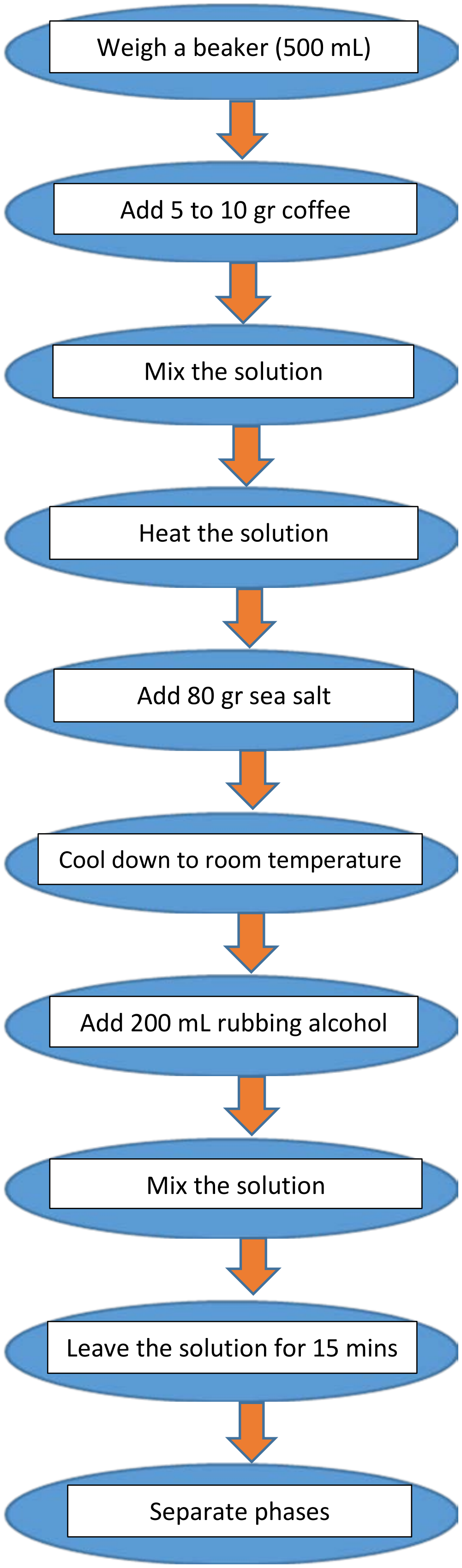

Figure 3. Step by step procedure

15. Select a piece of aluminum foil which is enough for covering the metallic plate
16. Cover the metallic plate with aluminum foil
17. Weigh metallic plate and aluminum foil
18. Separate the alcoholic phase of solution from the aqueous phase by a turkey baster
19. Pour the alcoholic phase into the metallic plate
20. DO NOT ADD ALCOHOL TO THE SOLUTION BEFORE IT IS AT ROOM TEMPERATURE
21. Heat the metallic plate until all of the alcohol evaporates
22. Be careful to turn off the heater right after the whole alcohol evaporates.
23. Leave the metallic plate on the heater until it cools down to room temperature
24. BE CAREFUL ABOUT HOT SURFACES SUCH AS HEATER SURFACE
25. Weigh the metallic plate again to determine how much caffeine you have extracted

4. Questions

1. Complete the following conversions (1000 mg = 1 g):
   2.14 g = mg
   0.27 g = mg
   6.45 g = mg
   7.23 mg = g
   9.14 mg = g
   1.56 mg = g
2. The caffeine structure is shown in the introduction (Figure 1). However, to avoid confusion and simplify the structure, some of the carbon atoms are not shown. This is common in the chemistry. Redraw the caffeine structure and show all of the atoms including carbon and hydrogen atoms.
3. Determine the chemical formula for the caffeine. For example, C_4H_{10} is a chemical formula.
4. Use the chemical formula from previous question and determine caffeine molecular weight.
   Here are atomic molecular weights: C=12 g/mol, H=1 g/mol, N=14 g/mol, O=16 g/mol.
5. What is the color of your caffeine sample? what color it should be?
6. Why your caffeine sample's color is different?
7. How much coffee did you use for the extraction?
8. How much caffeine did you extract?
9. A regular dark coffee has 40 to 45% caffeine. What is the caffeine percentage in the coffee sample? Interpret your results

10. Notes for instructors

This activity is both fun and instructive for students and they will enjoy conducting science with hands-on activities. This procedure needs no special equipment except a hood for evaporating solvent if available.

Table 2. Experimental data for ten groups doing the experiment

Run	Coffee (g)	Caffeine (g)
1	4.97	2.15
2	6.09	3.12
3	6.98	3.14
4	6.95	3.44
5	5.33	2.34
6	5.66	2.53
7	5.20	2.43
8	6.90	2.85
9	5.59	2.82
10	5.15	2.46

11. Safety concerns

The most import safety concern for this activity is the flammability of the rubbing alcohol. Therefore, special attention is required during alcohol evaporation period. Furthermore, students should be careful about the hot surfaces such as heater. In addition, safety goggles and gloves should be worn throughout this activity. Rubbing alcohol is flammable and nontoxic, but it is toxic if consumed directly. A laboratory hood should be used for evaporation of the solvent.

12. Helpful notes

- Tap water can be used for the experiment.
- Caffeine will decompose at higher temperatures. Therefore, the coffee sludge should be moved from heater before solution boils.
- The coffee sludge should be cooled down to room temperature. Higher temperatures lead to loose of solvent and less caffeine extraction.
- Almost 90% of the students should obtain some caffeine.