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Science of Sugar

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Introduction

Scientists are often stereotyped as industrious intellectuals that toil away in secluded laboratories. This view is certainly held by children as many will illustrate a scientist to be a bespectacled man in a white coat that is surrounded by an array of scientific equipment.[1] Many children in the elementary grades may begin to perceive science as an abstract field of study that doesn't pertain to them. In truth, however, scientific phenomena are very much a part of a student's daily life. Cooking is an experience universally shared by children that can be used to tangibly engage them in scientific exploration. Within the context of cooking, sugar presents an interesting topic of study. Found in a variety of food items ranging from drinks to prepared foods, sugar is a substance familiar to children. This unit will lead fourth grade students in an investigation of sugar that shows them the significance of the substance's chemical properties. Through an interdisciplinary approach that emphasizes experiential learning, this unit will also engage students in the scientific process, familiarize them with the history of sugar, and allow them to develop an understanding of the health implications of sugar consumption.

Content Objectives

How We Taste Foods

As one of the five senses, taste plays a major role in the enjoyment of food. From a biological perspective, taste has helped humans find edible items to consume. Taste buds are capable of detecting sour, bitter, salty, and sweet tastes. Sour tastes are derived from acidic foods such as lemon juice or vinegar. A number of sodium and chloride salts are responsible for salty tastes, whereas sugars provide the sensation of sweetness. Alkaloids, such as caffeine, produce bitterness. Many alkaloids happen to be poisonous, and this may be why bitter notes in foods produce a strong negative response in many people.[2] It is widely believed that a fifth taste, known as umami, exists. Described as savory, umami is derived from the Japanese word for this taste and is found in foods such as tomatoes and parmesan cheese.[3]

Taste buds serve as the detectors for taste, and thousands of them can be found along the tongue and on the hard and soft palates of the mouth. While it was previously believed that taste buds detected a particular taste and were located in a specific region of the mouth, it is now understood that taste buds may detect a range of tastes to varying degrees. What the brain registers as taste is really a cumulative response from all of the taste buds.[4] Scientists are working to deepen their understanding for how taste buds function, but it is known that they detect tastes when the chemicals in foods bind to the cilia, or fine hairs, of a taste bud. These flavor molecules, which must be in a liquid such as water or saliva, provide a taste sensation. The mechanical process of chewing will release additional flavors as the enzymes in saliva react with the food to create new molecules that contribute to a flavor profile.[5]

The ability to taste food is further developed by the sense of smell. It is estimated that a staggering 80 percent of flavor is derived from odors that are smelled.[6] Humans are capable of detecting a scent when as little as 250 airborne molecules encounter a few dozen cells in the nose.[7] A flavor profile could have a chemical composition of hundreds of molecules, but only a few in very low concentrations may be responsible for the flavor's essence.[8] While it may be surprising that smell plays such a substantial role in tasting food, the back of the mouth does contain a connection to the nasal passage. It is at this juncture where olfactory cells detect the smells that contribute to the perception of flavors. Initially the smallest molecules are detected, and with chewing, larger molecules enter the nasal cavity. It is interesting that the sensitivity of noses is not universal. For instance, 40 percent of men and 25 percent of women are unable to detect the scent of truffles, and as a result, they are unable to experience the full flavor profile of this costly ingredient.[9] Scientists believe that the variance among an individual's nose sensitivity is one contributing factor for the diverse food preferences that people develop.[10]

The Scientific Classification of Sugar

Sugars are used by living things to store energy, and they belong to a broad family known as carbohydrates. These molecules generally adhere to a 2:1 ratio of hydrogen to oxygen which is identical to the chemical structure for water.[11] When they dissolve, they taste sweet and contribute four calories per gram. It is interesting to note that sugars do vary in their perceived levels of sweetness. This has potential nutritional implications as a lower quantity of a highly sweet type of sugar can be substituted for another to provide the benefit of having fewer calories without compromising taste.[12] While sugar is colloquially used as a generic term to reference a crystalline substance that is sweet, there are actually numerous sugars that exist.

Sugars are classified based on the number of ring structures they contain. These ring structures are known as saccharides.[13] Monosaccharides contain one ring structure and are commonly known as simple sugars. A common monosaccharide is fructose, which is the sweetest of the naturally occurring sugars. An interesting property of fructose is that it is highly soluble, meaning it is easily dissolved in water.[14]

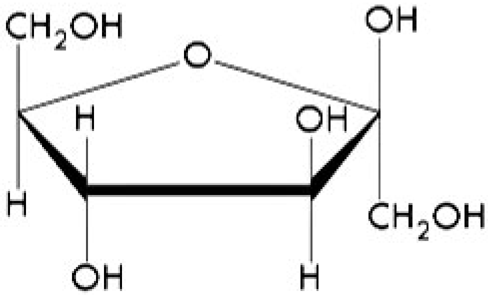

Figure 1: Molecular model of fructose. Unless otherwise marked, the vertices of the pentagon are carbon atoms. [15]

Glucose is another common monosaccharide, and it is the building block of complex carbohydrates.

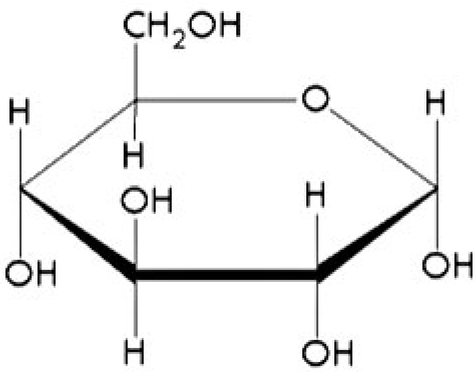

Figure 2: Molecular model of glucose. Despite having the same chemical formula as fructose, they are different monosaccharides. Observe how their molecular structures vary.[16]

It is interesting to note that both glucose and fructose share the same chemical formula, $C_6H_{12}O_6$, but are different monosaccharides due to the variance in the geometric arrangement of their molecular structure.[17]

Disaccharides are two monosaccharides that are joined together. A common example of a disaccharide is sucrose, which is the molecule that is typically associated with the term “sugar”. This white crystal is composed of one fructose bonded to a glucose.

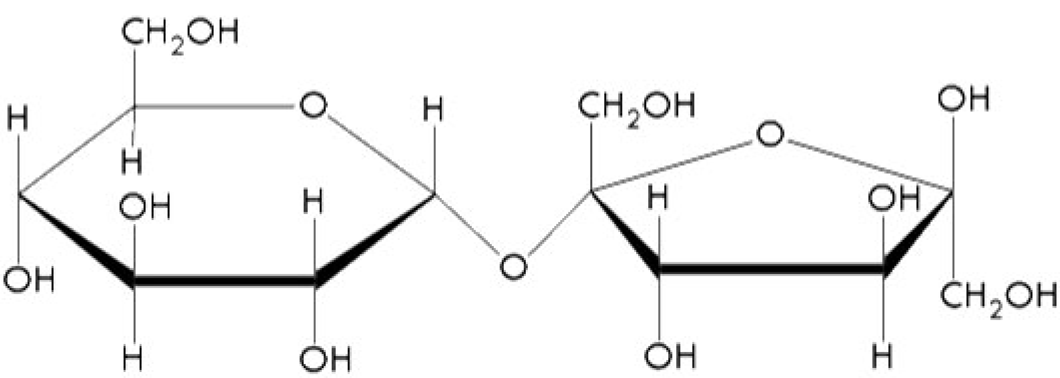

Figure 3: Molecular model of sucrose. Notice how a glucose is bonded to a fructose molecule.[18]

Lactose is the disaccharide that occurs in the milk of mammals, and its concentration will vary depending on the mammalian species. For instance, cow milk contains 4.5 percent lactose whereas human milk contains 7 percent lactose.[19] Maltose is another common disaccharide, and this sugar is created during the malting of grains, specifically barley.[20]

Polysaccharides are larger sugars typically arranged in a chain. Known among scientists as glycans, polysaccharides can be quite large and may be composed of thousands of monosaccharides joined together.[21] A significant number of polysaccharides are possible as monosaccharides can be arranged in any order, and these resulting combinations produce different molecules.[22] Another factor contributing to the large universe of polysaccharides is that hydroxyl groups, (the components of the sugar composed of a hydrogen bonded to an oxygen), can be joined to different sections of each simple sugar's ring.[23] These changes produce different geometric arrangements of the molecule which means each iteration is a different polysaccharide.

Plants produce a couple polysaccharides that are relevant to a discussion on cooking. Cellulose is a polysaccharide that is created by plants to provide strength and structure to their cell walls. It can range in size from approximately 7,000 to 15,000 monosaccharides.[24] Cellulose has internal hydrogen bonds that lead it to form chains that are highly ordered. Its linear shape causes cellulose to pack closely together and this makes the molecule both stable and insoluble.[25] Humans, and most animals, are unable to break apart the bonds within cellulose for digestion. This property is what makes it an important source of dietary fiber.[26] Termites and cattle are among the few animals capable of digesting cellulose as they contain bacteria in their guts that process this polysaccharide.[27] Starch is another plant product that plays a significant role in cooking. Used by plants to store energy in the form of small granules, starch is really composed of two polysaccharides - amylose and amylopectin. In contrast to cellulose, starch has fewer internal bonds and this leads it to have a more open and spiraling configuration. When packed together, it does so in a weaker and looser fashion leading it to serve as an energy source for both plants and animals.[28]

Releasing the Energy of Sugars

A combustion reaction allows humans to consume sugars as a source of energy. Enzymes facilitate this process in the human body by converting the sugars into usable forms. Each enzyme is uniquely matched to its respective sugar, and humans are capable of digesting most monosaccharides and disaccharides.[29] For example, sucrase is the enzyme that allows for the digestion of sucrose. Other carbohydrates that humans can digest for energy include lactose and starch.[30]

Humans lack the enzymes necessary to process large sugars, and a couple of these have interesting implications. Raffinose is a polysaccharide used by plants to store energy in seeds and beans. When humans consume this sugar, it cannot be digested until it reaches specific bacteria in the colon. A result of this process is carbon dioxide gas which can lead to awkward social interactions.[31] The disaccharide lactose is digested when it reaches the lactase that lines the walls of the small intestine. For individuals missing this enzyme, lactose will not be digested. It then proceeds to the large intestine where it becomes lactic acid. This leads to the cramping and abdominal discomfort that characterizes lactose intolerance.[32]

Sugars Used in Cooking

Sucrose: Commonly Known as Table Sugar

Sugarcane is one of the primary sources for refined sugars that are used in cooking. There are in fact six species of sugarcane, and they are all grasses that belong to the *Graminaea* family. Of the species used for sugar production, *Saccharum officinarum* is the most widely grown. When at full maturity, its stalks have a height of fifteen feet and can reach a maximum thickness of two inches.[33] Sugarcane has an approximate sugar content of 13 percent in its fluid, an atypically high amount that makes it an ideal candidate for sugar production.[34] Within eighteen months of its first planting, sugarcane will reach its full maturity. Sugarcane can grow again after being harvested, but it will become progressively less productive. After several seasons, it will ultimately need to be replanted.[35]

An extensive process is utilized to refine and produce sucrose. In a sugar mill, harvested sugar cane is shredded and pressed to extract sugar cane juices. These juices contain a variety of compounds such as tannins, carbohydrates, and proteins which must be filtered out as they affect sugar's taste.[36] This is achieved by clarifying sugar using heat and lime, and then boiling it until the solution thickens into a syrup. The evaporating water creates a sugar solution that is very concentrated. It will eventually reach a point where the sugar can no longer be held in solution, and the sugar will precipitate as crystals. This mixture is then spun through centrifuges to drive off the remaining liquid from the crystals. At this point, the sugar is wet and brown. It also contains a variety of miscellaneous items such as fiber, soil particles, and yeasts. Two additional purification cycles that follow the aforementioned process occur in a refinery.[37] Granular carbon is added and works to decolorize the sugar by behaving like activated charcoal. The final crystallization process makes individual sugar crystals of uniform size, and yields a sugar that is 99.8 percent pure.[38]

In 1747, a Prussian chemist was able to extract sugar crystals from the juices of white beets. The purity of the crystals, and the average yield from a white beet, were comparable to that of sugarcane.[39] This discovery remained largely dormant until 1811 when the French, out of economic necessity, applied the technology to lessen their dependence on sugar from British colonies.[40] Using sugar beets to produce sucrose is comparable to the refining process utilized with sugarcane. One exception is that sugar beet refineries have an additional challenge of removing the impurities from the beets that produce foul tastes and smells.[41] In the United States, sucrose is refined from both sugarcane and sugar beets. Temperate climates, such as those of Minnesota, produce sucrose derived from sugar beets. Tropical climates, such as those found in Florida, produce sucrose extracted from sugarcane. Current domestic production of sucrose from sugar beets is 55 percent with 45 percent of domestic sucrose originating from sugarcane.[42]

Molasses

Molasses is one of the byproducts of the sucrose refining process. Different grades of molasses are produced when the centrifuges separate the liquid (which is the molasses) from the crystallized sugars during each purification cycle. Each cycle produces a successively darker molasses with diminishing taste appeal. The first boiling produces a light molasses that is commonly used as table syrup.[43] The second boiling darkens the molasses, but it is still palatable to humans. The final cycle produces the darkest molasses, commonly known as blackstrap, which is typically used in animal feed due to its concentration of minerals. Despite popular claims touting the nutritional benefits of molasses, it should be noted that they are insignificant. In a tablespoon of blackstrap molasses, the most concentrated form, there is only one-thirtieth of the daily recommended intake of vitamin B. Iron and calcium are both at one-sixth of their daily allowances. The lighter molasses contains approximately half of the aforementioned nutrients.[44]

Corn Syrup

Corn syrup is made by treating corn starch with an acid or an enzyme. The result is a syrup that contains glucose and maltose. The proportion of these sugars within the syrup are contingent on the extent to which the chemical reactions with an enzyme or acid are allowed to proceed. Advanced progression of the reaction will yield more glucose and maltose making the syrup sweeter.[45] When all of the starch is converted into glucose, this can be known as "dextrose" due to its ability to bend polarized light to the right when in a solution.[46] These dextrose molecules can be rearranged using an enzyme to become fructose. These are also known as "levulose" since they will bend polarized light to the left when in a solution.[47] Corn syrups with a high fructose content are used by the food industry to sweeten products such as soft drinks. The reaction between corn starch and the enzyme can be diminished to allow for the preservation of longer sugar chains. The resulting syrup will be more viscous as the chains become entangled and prevent the motion of other molecules.[48] Thick corn syrups are used to make foods chewy, and they also assist in preserving foods by reducing moisture loss.[49]

Other Sugars

There are several other sugars that are commonly used in cooking. Superfine sugar has very tiny sucrose crystals that have the functional ability to dissolve quickly.[50] Brown sugar is typically made by lightly coating white sugar crystals with molasses. It can range in color from light to dark brown. Since brown sugar traps air between groups of crystals, it should be packed down before measuring.[51] Powdered sugar is sucrose that is ground very finely. To prevent clumping, it often contains 3 percent cornstarch.[52] Honey is the sweetener that ancient human civilizations used in foods before refined sugar was developed. It is composed primarily of fructose, glucose, and water.[53]

Synthetic Sweeteners

A variety of synthetic sugars exist that serve to produce sweetness. They primarily are used as substitutes for sucrose to limit consumed calories, or to reduce costs in food production. Saccharin is a sweetener that was first discovered in 1879, and it is perceived to be 200 to 700 times as sweet as sucrose. Many individuals claim it has a metallic aftertaste. It also happens to be calorie-free as it is not absorbed by the body to be used for energy.[54] At one point, saccharin was linked to a study that indicated it increased the risk for cancer in rats. After a series of legislative battles and FDA proposals, the federal government declared in 2001 that there was insufficient evidence for the carcinogenic effects of saccharin in humans.[55] Aspartame was accidently discovered in 1965 when a chemist observed that his fingers were sweet from a combination of aspartic acid and phenylalanine. While it does possess the standard four calories per gram, it has a perceived sweetness to be 160 times that of sucrose. This allows less aspartame to be used when it substitutes for sucrose.[56] Certain individuals with a rare medical condition called phenylketonuria must limit their intake of phenylalanine. This is why products that use aspartame must come with a warning label.[57]

Current trends are encouraging the development of other sweeteners with no added calories. In 1999, sucralose gained federal approval to be used as a sweetener. At 600 times as sweet as sucrose, minimal amounts can be used. Sucralose also provides an additional benefit of contributing no calories as it is not broken down by the body.[58] Strong societal demand continues to exist for sucrose alternatives to have more natural origins. The food industry has recently turned to the leaves of the stevia plant which contain steviol glycosides that are 100 to 350 times as sweet as sucrose. Similar to prior sweeteners, this product is stymied by claims that it leaves a bitter, metallic aftertaste.[59]

Chemical Behaviors of Sugar

Solubility of Sugar

One of the unique properties of sugar is that it is highly soluble, or dissolves easily, in water. To better understand this chemical behavior of sugar, here are a few key ideas about water. Within a water molecule, two hydrogens are bonded covalently with oxygen. In covalent bonds, two atoms share electrons through an overlap of their electron clouds. The geometrical shape of a molecule depends on the types of atoms bonded together. This is significant because a molecule's shape affects how it interacts with other molecules.[60] In the case of water, the covalent bonds lead the molecule to form a shape that resembles the letter "v."[61] Imagine an obtuse angle with a measure of 105 degrees where the oxygen is serving as the vertex, and the hydrogens are points on the respective rays. Different atoms have different affinities for electrons which influences the chemical properties of the molecule. In water, oxygen has a stronger affinity for electrons than hydrogen, thus producing a slightly negative charge around the oxygen. The area surrounding both hydrogen atoms is slightly positive as a result. This uneven distribution of charge and the associated geometry of the covalent bond results in water being a polar molecule.[62] In addition to the covalent bonds within a molecule of water, hydrogen bonds exist between individual molecules of water. Hydrogen bonds are attractions between a hydrogen with a slightly positive charge to an atom with a slightly negative charge. These bonds are common in nature and are sufficiently weak to result in frequent rearrangements of the hydrogen bonds.[63] The behavior of hydrogen bonds contributes to water's fluid nature.

There are several characteristics about sucrose that, when combined with water's polarity, allows it to be highly soluble. Similar to water, sucrose has covalent bonds between oxygen and hydrogen, and this results in polar molecules. Additionally, its molecular structure contains hydroxyl groups (-OH) that stick out to permit the formation of hydrogen bonds with water.[64] When this occurs, a molecule of sugar is dissolved. Sucrose is also capable of squeezing into the open lattice framework created by the shifting hydrogen bonds among water molecules.[65] It should also be noted that given equal volumes of sucrose and water, there will be fewer molecules of sucrose. When comparing one cup of sucrose to one cup of water, there will be one twenty-fifth as many sucrose molecules as there are water molecules.[66] The larger number of atoms in sucrose leads it to occupy more space which results in fewer molecules being present. This means there are vastly more water molecules available to form the hydrogen bonds that will dissolve the sucrose molecules.

Hygroscopic Property of Sugar

Sugar is a hygroscopic substance which means it is able to attract water or moisture from its surroundings. The reason for this is similar to why sugar is so soluble in water - the hydroxyl groups will easily bond with water. Sugar's hygroscopicity allows it to have a variety of practical applications in cooking. When baking, sugar helps baked goods retain moisture. This allows for the production of moist cookies and cakes.[67] Sugar also will help finished baked products draw in moisture from the air to remain tender and fresh.[68] When making ice cream, sugar helps to prevent the formation of large ice crystals.[69] It does this by helping to lower the freezing temperature of water past 32 . This allows for the rapid formation of very small ice crystals that provide frozen treats with a texture that is perceived to be smooth and creamy.[70]

Caramelization

Caramelization is a complex process that results in the browning of sugar to produce rich, deep, and complex flavors. It begins with hydrolysis, a reaction that involves heating a sugar with water. In this reaction, the water reacts with the oxygen atom that is joining a disaccharide or polysaccharide together and breaks them into their constituent simple sugars.[71] Using sucrose as an example, hydrolysis will break it into glucose and fructose. There will also be the loss of a water molecule.[72] When this solution is heated further, a degradation reaction will occur. This means that the sugar rings will open, and will result in the formation of new molecules.[73] These chain-like molecules are known to be acids and aldehydes.[74] As the reaction proceeds with the continuous application of heat, the solution will change from a clear liquid to successively darker shades of yellow that will eventually become brown. Polymers are forming at this stage that produce the characteristic brown hue of caramelization. Scientists are still investigating the complex reactions that occur during caramelization, but it is believed that the chemical bonds are altered in a way that causes them to absorb light and create color.[75]

Maillard Reactions

When sugars are heated in the presence of proteins, a series of complex reactions occur that are collectively termed Maillard reactions. Credited to Louis-Camille Maillard, a physician fascinated with biochemistry, this type of browning is responsible for the flavors found in foods such as bread crusts, soy sauce, chocolate, and roasted meats.[76] Scientists are still studying Maillard reactions, and their complexity is the result of a variety of sugars reacting with numerous amino acids (the building blocks of proteins). Additionally, the products from the reaction of any given sugar and amino acid pair are contingent on temperature.[77] These permutations allow for the possibility of numerous flavors.

One of the prerequisites for Maillard reactions to occur is that extremely high temperatures must exist. The application of heat degrades sugars and amino acids into smaller sugars and amino acids. The sugar rings open and aldehydes and acids react with amino acids. At this point, a spectrum of chemicals is developed. These molecules react with each other, and new flavor compounds emerge.[78] When cooking meat, this happens on the surface with frying, roasting, baking, or broiling. Due to the water content in a piece of meat, the temperatures in its interior can never exceed the boiling temperature of water. This inhibits the extreme temperatures necessary for browning to occur. The need for high temperatures is also the reason why foods that are boiled will never brown.[79]

History of Sugar

Used for centuries by human societies, sugar has a dynamic past. Sugar was originally refined in India around 500 BC, and the technique was brought to the Middle East by traders. It was initially introduced to Spain by conquering Arab armies, and was later spread throughout Europe by returning Crusaders.[80] The Spanish and Portuguese introduced sugarcane to the New World through the construction of sugar plantations on their colonial holdings. It was Christopher Columbus that first planted sugarcane in the West Indies during his second voyage in 1493.[81] With expanding naval prowess and ambitious imperial designs, the British established colonial outposts in North America. One result of Britain's expanding empire was the creation of sugar plantations in the Caribbean that eclipsed those of their Iberian counterparts.[82]

The sugar industry came to be a significant contributor to the British colonial economy, and it cultivated critical domestic industries. Extensive networks of finance and commerce emerged that advanced the nation's economy.[83] A dark undercurrent of this economic development was the creation of an infrastructure that facilitated slavery. Due to the intensive demands of sugarcane harvesting, colonial powers exploited indigenous peoples, and eventually African slaves, as a labor source.[84] During the time period when slave labor was utilized to process sugar in the Americas, an estimated twelve million people were enslaved from Africa.[85] Sugar and slavery became intricately intertwined and came to form the triangular trade model of mercantile economies. The widespread use of slave labor on sugar plantations is largely believed to have facilitated the introduction of slavery into the American South.[86] The gruesome toll of slavery caused abolitionist groups to call for its end. When Britain abolished the slave trade to its colonies in 1807, sugar plantations began using a contract labor system.[87] Continued cultivation of sugar, and technological innovations such as the introduction of white beets as an additional source of sugar, eventually led to its widespread availability.

Historical Uses of Sugar

The initial uses for sugar reflected its scarcity. Ancient civilizations in the Mesopotamian region used honey to create sweet treats. Scraps of parchment from 1400 BC contain a recipe for a dessert that rolled honey, dates, almonds, and sesame seeds.[88] Arab apothecaries, and eventually their medieval counterparts, used sugar as a medicine to treat a variety of ailments. Sugar was also used to combine compounds, and it functioned as a sweetener to mask the bitter taste of medicines.[89] Due to its status as an imported spice, sugar was attainable only by aristocrats and served as a symbolic representation of their wealth and power. Precursors to pies and cakes were served as desserts at extravagant banquets, and candied nuts and fruits were given as parting gifts to guests.[90]

As sugar gradually shifted from a luxury good to a commodity, increased availability led to new and innovative uses. When the Spanish expanded their colonial empire in the sixteenth century, they discovered the rich chocolate drink that was consumed by the Aztecs. By adding sugar and milk to the beverage, the Spanish sweetened the traditional base that was created by crushing cacao beans to a thick paste. Admiring the exquisite taste profile of this treat inspired by the New World, the Spanish royals shrouded it in secrecy for years.[91] The expansion of the sugar trade, specifically by the British, led to an increased supply of sugar. A royal confectioner is credited with developing the first eggy custard that would serve as the base for ice cream.[92] By the nineteenth century, the wide availability of sugar renders it a commodity. Home cooks begin to devise recipes for cupcakes and cookies that become the staples of any dessert repertoire.[93] The Industrial Revolution, and advances in food chemistry technology, led to the eventual mass production of hard candies, chocolates, and prepared baked goods that line the shelves of contemporary markets.[94]

Health Implications of Sugar

Sugar is a ubiquitous part of modern life. Commonly found in beverages, desserts, and prepared foods, it's a substance that is difficult to avoid. Sugar also features prominently in the lexicon of popular culture. Novels such as *Charlie and the Chocolate Factory* highlight sugar's allure. Common terms of endearment often invoke or have associations with sugar. The wide availability of sugar combined with a cultural affinity for sweetness has led Americans to consume significant quantities of added sugar. The Centers for Disease Control and Prevention calculates that American males and females over the age of twenty consume 74 pounds and 50 pounds of sugar on an annual basis, respectively.[95] American boys and girls between the ages of two and nineteen consume even more than their adult counterparts. The CDC pegs their annual consumption at 75 pounds and 59 pounds, respectively.[96] To place these amounts in perspective, reports published by the USDA[97] and the WHO[98] suggest that calories derived from added sugars should not exceed 10 percent of daily caloric intake. Americans are surpassing these guidelines with recent estimates suggesting that people over the age of six have added sugar representing 14 percent of daily calories.[99]

Added sugar consumption has a variety of direct and indirect health implications. Sugar is known to produce tooth decay as specific kinds of bacteria use it as a food source. These bacteria produce acids that erode tooth enamel which leads to the development of cavities. The length of time that sugar is in contact with these bacteria matters. Sticky or hard candies prolong the exposure of teeth to sugar and provide the bacteria with a greater food supply.[100] Consuming added sugar has also been linked to obesity as exceeding the body's caloric needs will result in the creation of fat. It is obesity that then places individuals at greater risk for conditions such as cardiovascular disease and type II diabetes. The medical community has given specific attention to fructose consumption as it is metabolized primarily in the liver. When fructose is consumed in liquid form, such as in soda, the liver must work harder to metabolize the sugar. Studies have shown that when this fructose inundation occurs in laboratory rats, the fructose is converted to fat. This causes insulin resistance, the primary problem associated with obesity that links it to heart disease and type II diabetes. There is speculation that this phenomenon may also be a mechanism that causes cancer.[101] Additional studies are probing for whether added sugar consumption directly increases an individual's risk for the development of serious ailments. A study published in *JAMA Internal Medicine* shows that a diet where added sugar represents a higher percentage of daily calories increases mortality associated with cardiovascular disease.[102] This multi-year investigation shows that people who received more than 20 percent of their daily calories from added sugar were twice as likely to die from cardiovascular disease as an individual that adhered to the USDA and WHO guidelines of added sugars contributing less than 10 percent of daily caloric intake.[103] Further research and study by the scientific and medical communities will be needed to deepen society's understanding of sugar's role in human health.

Teaching Strategies

Science Notebooks

Students will utilize science notebooks to record their observations and reflections. These tools will contain their notes, and will serve as a repository for their learning activities. Interacting with notebooks provides students with the opportunity to reflect and consider the scientific principles being explored in class. They also function as a means to collaborate with others by serving as a medium for sharing ideas. Science notebooks provide students with flexible opportunities to express their understanding through written language or visual images.

During this unit, students will learn a variety of techniques that will develop their critical thinking and organizational abilities. By utilizing tools such as tables, diagrams, and sentence starters, students can improve their observational skills. They will learn how to gather evidence that is relevant and appropriately detailed to arrive at a conclusion.

Experiential Learning

Through hands-on learning and classroom demonstrations, this unit will immerse students in experiences that will guide their understanding. Engaging students in tangible explorations offers them the opportunity to make real connections with science content. They are able to envision and actively participate in a shared learning environment. Experiential learning also helps students frame their conceptual understanding through a common unit theme.

Students will engage in explorations that inform their understanding of sugar's chemistry, and will learn how chemical properties influence sugar's role in cooking. Each activity is sequenced to develop each student's schema about sugar. The classroom activities have an additional purpose of introducing students to laboratory safety procedures, and how to work collaboratively as a team.

Experimental Design

At various points in this unit, students will be able to thoughtfully engage in the construction of an experiment's design. Using the same processes applied by engineers and scientists, they will work collectively to construct a functional experiment. Students will gain familiarity with the following components of the design process: developing a research objective, constructing hypotheses, adhering to clear procedures, identifying variables, establishing a control group, collecting data, and analyzing their work. They will use evidence to support the development of a scientific claim, and will consider avenues to improve their work in the future.

Classroom Activities

The following is a series of learning activities that will allow students to tangibly develop an understanding of sugar's chemical properties. Whenever possible, these activities will provide students with opportunities to work collaboratively to discover a scientific idea. Potential opportunities for further investigation are also mentioned, and any of the activities can be adapted to suit the intellectual curiosity of participating students.

This unit does include explorations that utilize a heat source. Before embarking on these activities, work with students to devise safety procedures given this piece of equipment. From a logistical perspective, securing a heat source can be challenging for the classroom teacher. Laboratory hot plates are typically available within schools, but they may not produce the controlled heating necessary for cooking applications. Consider acquiring an induction cooktop burner to use as a heat source. These portable electric appliances have features that allow you to set a given cooking temperature. As food will be involved, it is also advisable to verify the presence of any food allergies among students.

Dissolving Sugar in Water

This activity serves as the introduction to the unit, and engages students in a point of inquiry regarding sugar. It will also provide students with preliminary experiences in working as a team, and will engage them in foundational ideas regarding experimental design.

The materials that are needed for this activity are:

For the class	For each team
- measuring spoons	- 1 cup of water
- measuring cups	- a stirring spoon
- supply of sugar	- a container (large enough to allow students to dissolve sugar in one cup of water)

Before beginning this lesson, arrange students in small teams using any grouping strategy that suits classroom dynamics and learning needs. Ask the class the following question: How much sugar can be dissolved in a cup of water? Have students share their ideas with their teammates, and then conduct a quick class discussion.

Based on their comments, it may be a good opportunity to introduce students to the importance of accuracy and precision in science and cooking. Share with them that scientists always make detailed measurements so that their work is accurate and reproducible. Measuring tools provide accepted standards that are used by everyone. The tools that they will use are measuring spoons and cups. Depending on student familiarity, it may be beneficial to review the units and fractional values associated with these tools.

Have students arrive at a team consensus regarding how much sugar they think will dissolve in one cup of water, and have them record this hypothesis in their science notebook. After showing students how to use the measuring tools, have them gather one cup of water and their hypothesized amount of sugar. Prompt students to observe what happens when they add the sugar to the water. They should then record their findings in a labelled diagram. Ask students how they know if the sugar is dissolved. For any groups that have undissolved sugar, have the class consider if anything can be done to help it dissolve. Suggest the idea of stirring if it is not volunteered by a student.

Demonstrate to the class that it is possible to dissolve a surprisingly large amount of sugar in water. Inform students that heating the water to its boiling point easily allows two cups of sugar to be dissolved in one cup of water. Have students record their observations of this class demonstration in their science notebooks. This sugar solution can be reserved to grow sugar crystals in the next exploration of this unit.

Growing Sugar Crystals

Students will have an opportunity to fully engage in the experimental design process with this exploration. Given a fixed amount of materials, they will grow sugar crystals. Reserve two sessions to plan and set-up the sugar crystal growth jars. Students will monitor the emergence of their crystals over the course of a week.

While this exploration allows students to identify and then test a variable that will impact the growth of sugar crystals, here is some background information to help in planning this activity from San Francisco's Exploratorium.[104] Sugar crystals will form in solutions where there is a ratio of sugar to water that is at least 2:1. Using this guideline, heat one cup of water until it boils, and then stir in two cups of sugar until fully dissolved. Pour this solution into a jar that is approximately eight ounces. Tie a piece of string to a pencil, and lay the pencil over the mouth of the jar. The other end of the string should now be suspended about half-way into the sugar solution. The wet, suspended end of the string can be dipped in sugar and returned to the jar. This helps provide a place for sugar crystals to begin forming. Allow the crystals to grow undisturbed for a week. Consider covering the jar with a paper towel or coffee filter to prevent dust from entering. If you plan on allowing students to consume the rock candy after the exploration, ensure that all materials and handling procedures comply with food safety guidelines.

The materials will vary depending on which variable students choose to test. The following is a suggested list of items to have available:

Required materials	Materials dependent on selected class variable
- water supply	
- sugar supply	
- heat source	- containers (to hold sugar solution)
- stirring spoon	- suspension materials (the object where sugar crystals will form)
- three-quart saucepan	
- measuring scale	

Planning Session

Begin this exploration by informing students that the sugar solution created in the prior lesson is the foundation for many types of candy. Display an image of rock candy for students, and tell them that it is composed of sugar crystals. Provide them with a general idea on how the sugar crystals are formed. Tell them that their challenge is to work collaboratively to grow their own sugar crystals.

Have students discuss in their teams what they think affects the growth of sugar crystals. Inform students that they are identifying the variables of their experiment. As a class, arrive at a consensus for a relevant variable to test. Perhaps students believe that the quantity of sugar dissolved in the solution affects crystal growth. Alternatively, students may believe that the container where the sugar crystals grow is significant. In this case, provide students with a range of containers (e.g. plastic containers, glass jars) to use in their trials. Yet another possible variable is the object where sugar crystals will form. If this variable is selected, different teams of students can try suspending a piece of string, a wooden craft stick, or a paperclip in their sugar solution. Regardless of the variable they choose, emphasize that all other conditions must be constant to ensure they are evaluating the impact of their selected variable. Have students record the designated class variable and draft a potential procedure in their science notebooks.

Set-up Session

Review the identified class variable and have groups share their drafted procedures. Revise the steps for clarity and accuracy. Help student teams create their sugar crystal growth jars. Remind students that besides the tested variable, all other components must be kept constant. Students should create a chart in their science notebook that allows them to track the growth of their sugar crystals. Over the course of a week, provide students with time to record their observations.

Concluding Session

Ask students how they can evaluate the results of their trials. Suggest that the class needs to identify a way to measure the results. Allow students to discuss various ideas in their teams, but guide them to the idea of weighing the crystals. After you demonstrate how to measure objects using a scale, student teams should weigh their crystals. Have students record the class results in their science notebook using a chart. Upon analyzing their collected evidence, have students evaluate their results.

Visually Representing Sugar

This activity will help students develop a concrete understanding for the amount of sugar found in packaged foods. Using sugar cubes, they will visually represent the sugar content in their favorite snack or beverage item. This lesson can also be extended to include explorations of nutrition labels along with the mathematical concept of percentages.

For this exploration, have a supply of sugar cubes available for the class. Calculators may also be helpful if students need computational assistance. Students will need to bring in their favorite beverage or sweet snack.

Begin this activity by having students predict how much sugar is in the food item they brought to class. Show students how nutrition labels provide people with information about what is in their food. Demonstrate how to locate the entry for sugar on a nutrition label. Students will use this information to determine the number of sugar cubes needed for their representation. While there is some variance, one sugar cube is generally equal to four grams of sugar. Assist any students with calculating the number of sugar cubes for their snack item. Have students round their solution to the nearest whole sugar cube. Students should then gather the number of sugar cubes that represent the sugar content in their favorite snack. In their notebooks, have students reflect on what they discovered.

Why Some Sodas Float

Using diet and regular versions of a soda, students will observe that the presence of sugar causes the regular soda to sink in a basin of water. This activity can be extended to include discussions on density.

Each team of students will require a twelve ounce can of diet soda, a twelve ounce can of its regular counterpart, and a container of water that is large enough to contain both soda cans.

Have students predict what they think will occur when each of the soda cans is placed in the container of water. Lead students in a discussion about the variables that are controlled in this demonstration. Potential student ideas could be that the volume and brand of the sodas are the same. Have students conduct the exploration. Prompt students to share with their group possible explanations for what they observed.

If students haven't guessed the primary reason, inform them that sugar is the cause for the sunken can of regular soda. Direct students to the nutrition labels of each soda can, and review how to find the entry pertaining to sugar. While there is some variance among brands, most regular sodas contain over thirty-five grams of sugar. Have students compare the amounts of sugar between the diet and regular sodas. They can even use the equation from the prior exploration to envision these quantities as sugar cubes. As an aside, students may notice that diet sodas have zero grams of sugar. This is the result of beverage companies using synthetic sweeteners to flavor sodas. Since synthetic sweeteners have perceived sweetness levels that greatly exceed that of table sugar, food and beverage companies can use trace amounts to mimic sweet flavors.

Caramel Apples

This activity serves as a capstone to this curriculum unit on sugar. Students will see how energy, in the form of heat, can cause complex chemical reactions to occur.

Due to the use of a heat source and the need to be vigilant with the preparation of caramel, this exploration is best done as a teacher station. Using a candy thermometer helps to gauge the caramel's temperature, and ensures that the optimal consistency and level of caramelization have been achieved.

As students observe the caramel being prepared using the following recipe adapted from *Serious Eats,*[105] have them make observations regarding the chemical changes that transform the sugar.

Ingredients

- 12 or so small apples (best if refrigerated cold)
- ½ c. of water
- 1 ⅓ c. of sugar
- 1 ⅓ c. of heavy cream

Materials

- skewers
- wax or parchment paper
- three-quart saucepan
- heat resistant utensils
- candy thermometer

Caramel Apples Procedure

1. Wash the apples and then skewer them vertically about mid-way through their core.
2. In a three-quart saucepan, combine water and sugar over medium heat.
3. Stir until the sugar dissolves and the solution reaches a rolling boil.
4. Simmer until the solution turns a tawny golden hue, or your preferred level of caramelization. Note that the coloring may not be uniform. Point out to students that the color change is a visual representation of chemical changes occurring during the caramelization reactions. Do not allow the solution to begin smoking, as this indicates that the caramelization process has gone too far. Resist the temptation to stir during this stage. Stirring will deposit sugar against the sides of the pot, and this creates sites where burning is more likely to occur.
5. Add the heavy cream. There will be rapid bubbling. As a point of interest, you can mention to students that the addition of the heavy cream now creates another complex series of chemical reactions known as Maillard reactions.
6. Reduce heat to medium low and stir constantly until the solution reaches about 250 . Use your best judgment to avoid burning the caramel. You may need to stop heating before 250 .
7. Remove the caramel from heat, and allow it to cool to around 225 . Avoid having the caramel thicken, as this will make it difficult to create an even and smooth layer of caramel during the apple dipping process.
8. Lightly dip apples into the caramel, and give them a quick swirl. Permit the excess to drip off. Place apples on wax paper to set.

Resources

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Materials List

The following is a summary of materials that are needed in this unit. The initial activity on dissolving sugar will require: measuring spoons, measuring cups, sugar, water, spoons, and containers large enough for students to dissolve sugar in a cup of water. The growing sugar crystals exploration will need: water, sugar, a heat source, a stirring spoon, a three-quart saucepan, a scale, jars to hold sugar solution, and suspension materials where the crystals will form (e.g. string, wooden craft sticks). To represent the amount of sugar in packaged foods you will need sugar cubes and calculators. The next activity on detecting sugar in sodas will need twelve-ounce cans of diet and regular soda, water, and containers. The final activity on caramel apples will need the following materials: apples, water, sugar, heavy cream, skewers, wax paper, a three-quart saucepan, a stirring spoon, measuring spoons, measuring cups, a candy thermometer, and a heat source.

Appendix

Implementing District Standards

This curriculum unit will address the following Next Generation Science Standards:

3-5-ETS1-1 Define a simple design problem reflecting a need or a want that includes specified criteria for success and constraints on materials, time, or cost.

3-5-ETS1-3 Plan and carry out fair tests in which variables are controlled and failure points are considered to identify aspects of a model or prototype that can be improved.

Students engage in these engineering design standards when collaborating with peers on growing sugar crystals. Given a fixed amount of raw materials, students will explore factors that contribute to the emergence of sugar crystals. At this grade level, it is important for students to: develop a coherent plan for testing an identified variable, understand the importance of experimental controls, and be able to devise metrics to evaluate results.

This unit will also indirectly address the following standard:

4-PS3-2 Make observations to provide evidence that energy can be transferred from place to place by sound, light, heat, and electric currents.

While not an explicit focus of the unit, students will be able to observe how energy, in the form of heat, is able to affect foods through several of the explorations. When dissolving sugar in water, they will initially see how heat causes the temperature of water to rise. Students will also see how heat allows a surprisingly large amount of sugar to be dissolved in water to create a saturated solution. This standard is again alluded to when students experience how heat begins the caramelization process for the preparation of caramel apples.

Endnotes

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46. McWilliams, *Foods: Experimental Perspectives*, 134.
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57. Wolke, *Einstein Told His Cook*, 37.
58. Wolke, *Einstein Told His Cook*, 38.
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60. McGee, *Food and Cooking*, 630.
61. McGee, *Food and Cooking*, 578.
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