C2 Carbohydrates as providers of energy for metabolism – Starch and sugar

This experiment is an introductory experiment to the overall topic of digestion and metabolism in the human body. It is suitable as a qualitative introduction to the topic of digestion for the age group up to 16 years. However, further study of the topic of metabolism necessitates considerable basic knowledge of organic chemistry and biochemistry, which cannot be assumed until the age group 16+ or acquired then. The materials supplied allow eight groups of students to conduct the experiments simultaneously.

1 Main question

This series of experiments will give students insight into the metabolism of carbohydrates in the human body. It will be shown that many of our foods contain carbohydrates in the form of starch, sucrose, and glucose. The experiments also deal with the enzymatic cleavage and subsequent degradation processes of polysaccharides, and also relate to the combustion processes in experiment C1 (We burn sugar – Cellular respiration and respiratory chain). These processes will now be discussed from the perspective of sugar, the substrate that is to be oxidized. In order to improve knowledge of the familiar phenomena, the chemical structure of monosaccharides and polysaccharides can be dealt with as well as their chemical reactions: oxidation of the aldehyde group, hemiacetal formation in the transition from the chain to the ring shape, and formation of acetals during condensation of glucose molecules, and (enzymatic) hydrolysis as the reverse of this reaction. Students will become systematically acquainted with the characteristic detection reactions for carbohydrates and the principle of catalyzed reactions.

2 Integrating the experiment into the teaching context

2.1 Basic principles

Students are frequently already familiar with the subject of nutrition from elementary school. They already have prior knowledge of what we need to eat in order to be active. Food provides the energy for life. Students have already learned about the main constituents of food – sugar, fats, and proteins – and can combine them to prepare a balanced and healthy meal, for example, for breakfast. In the lessons building on this knowledge, relationships will be established between the subject areas of nutrition, substance transport, respiration, and energy conversion. What does nutrition have to do with blood circulation and respiration? The relationship between absorption, transport, and release of substances and energy should be included explicitly when dealing in detail with the nutrients carbohydrates, fats, and proteins and their digestion.

2.1.1 Qualitative access at age levels 10 to 16

Different nutrients have different functions in the body. **Carbohydrates** act principally as energy providers to maintain the work of the muscles, the activity of all organs of the body, and body heat.

From whole grain bread to glucose: Digestion of carbohydrates begins in the mouth. The nutrients contained in food are not accessible directly to cell metabolism, and therefore a number of substance conversion stages are required. The breakdown of food and the subsequent absorption of the nutrients are part of the overall process known as digestion. The first stages of digestion start in the mouth. While the teeth mechanically grind up the food, the salivary glands secrete saliva, which has two important functions. First, it contains mucus to soften and lubricate the morsels of food for swallowing, and second, it contains the enzyme amylase, which acts on the chain-shaped starch molecule (see Fig. 4) and, in a reversal of condensation, breaks this chain into shorter units until maltose is formed (→ Hydrolysis of starch). Students can experience this phenomenon directly by chewing a piece of bread for a long time (see subexperiment 2). The well-chewed food (bolus) then passes down the esophagus into the stomach (see experiment C4 [pH value of beverages – How acidic is it in the stomach?]). In the stomach, the enzyme in saliva that serves to cleave the starch is deactivated by stomach acid (also see below in Section 2.5 Experimental variations). Here, other enzymes and mechanisms must come into operation. This is a good example for the students to learn that the digestive enzymes are effective only in certain pH ranges.

The carbohydrates pass from the intestine into the blood. Food is forced from the stomach into the small intestine by contraction of the muscles of the stomach wall. The individual sections of the small intestine (for example, the duodenum) ensure maximum decomposition of the food constituents and resorption of the glucose molecules. For this purpose, the maltose must be broken down into glucose molecules by additional enzymes in the intestine (→ Hydrolysis). The glucose is absorbed into the intestinal cells by means of active transport, and from there diffuses into the blood of the portal veins. The blood transports the glucose to the cells (for example, muscle cells), where it is consumed and oxidized to water and carbon dioxide in the processes of cellular respiration (glycolysis, citric acid cycle) (see Experiment C1 [We burn sugar – Cellular respiration and respiratory chain]). These oxidation processes supply ATP as a chemical energy store that can be used universally in metabolism.
Other disaccharides such as sucrose are also broken down into their monosaccharides by corresponding enzymes in the intestine. If too many carbohydrates are absorbed with food, the excess glucose is converted into fat by the liver and stored in the body as a reserve. If there is a long-term imbalance between energy intake and energy requirement, this process leads to overweight. Finally, in the colon, water and minerals are extracted from residual food that cannot be utilized, so that the bolus thickens and is then expelled from the body through the rectum and anus.

2.1.2 More detailed approach for the age group 16+

Carbohydrates can be differentiated into monosaccharides, disaccharides, and polysaccharides depending on their chemical structure. Monosaccharides can be regarded as oxidation products of polyvalent alcohols. They consist of a carbon chain with three to six carbon atoms and contain an aldehyde or ketone group that determines their chemical reactions. The remaining carbon atoms contain hydroxyl groups. Glucose is of particular importance as a substrate for cell metabolism (see experiment C1). It can exist in chain or ring shape, and both shapes are mutually convertible (hemiacetal formation, see Fig. 2). In an aqueous solution, the chain shape occurs as only a small proportion.

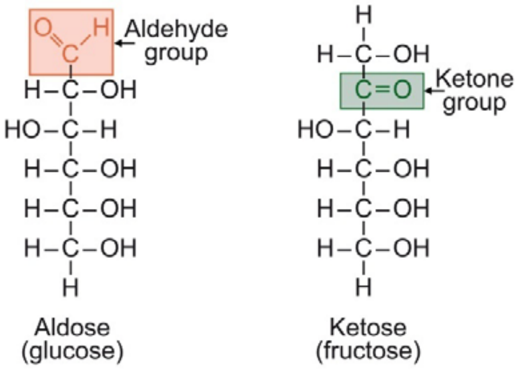

Fig. 1: Glucose and fructose as examples of monosaccharides.

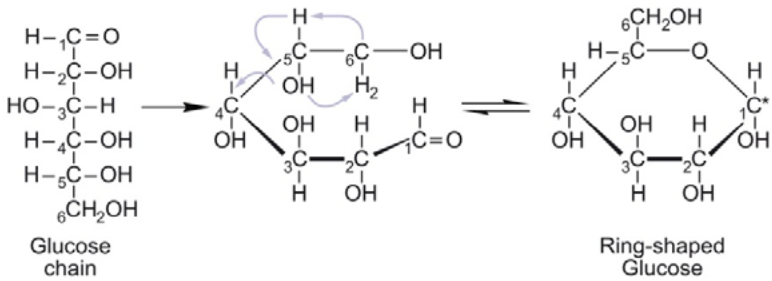

Fig. 2: Ring closure with the glucose molecule (hemiacetal formation).

Disaccharides are created by the combination of two monosaccharide units. One hydroxyl group reacts with the hemiacetal group, releasing water (acetal formation). This reaction is illustrated in Fig. 3 using the example of the combination of glucose and fructose; it results in sucrose, our most common domestically used sugar.

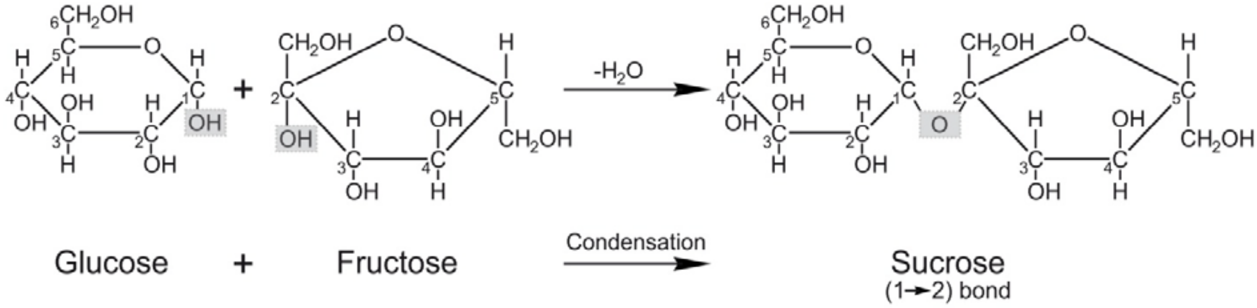

Fig. 3: Glucose and fructose react to produce sucrose.

If two glucose molecules combine with the release of water to produce a disaccharide, the result is maltose.

A prominent example of plant polysaccharides is starch (see Fig. 4), which consists of linked glucose residues. About 25% of these are soluble starch (amylose). The amylose forms long chains that coil up into an α-helix. By contrast, the insoluble component (amylopectin, approx. 75%) is highly branched with additional bonds between shorter chain sections. Glycogen, the storage for carbohydrates in animals, is comparable in structure to amylopectin. Starch (amylose) can be specifically detected using iodine. Iodine is deposited inside the α-helix of the starch molecule. This results in a complex that has a distinctive color ranging from deep blue, blue-violet to black, depending on the iodine concentration.

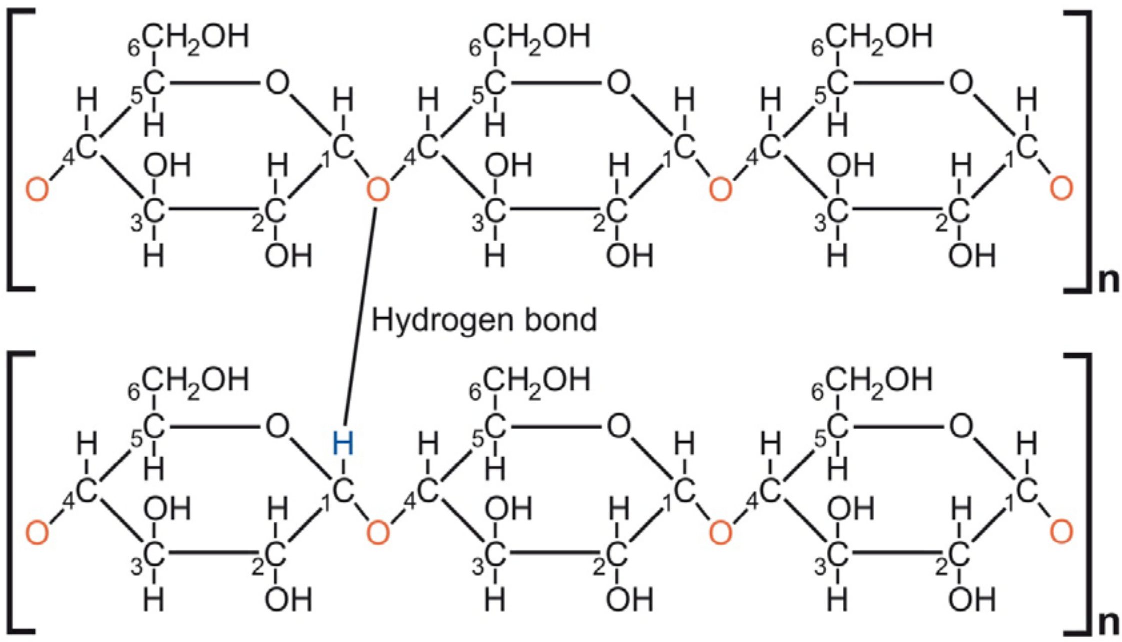

Fig. 4: Section of a starch molecule.

The enzyme reactions (e.g., amylase) and associated kinetics can be dealt with to intensify knowledge of metabolic physiology. Membrane physiology is also a topic for the 16- to 18-year-old age group. The glucose transporter in the intestinal lumen is a suitable example for discussing secondary active transport.

2.2 Relevance to the curriculum

In the age group from 10 to 16 years, the main focus of attention is on the human biology aspects of nutrition and digestion. Extracting and verifying starch from potatoes, for example, can be conducted as qualitative experiments. The same applies to the catalytic combustion of sugar, which illustrates the principle of cellular respiration and energy conversion (see also experiment C1). It is also advisable to brush up on prior knowledge with respect to simple combustion processes (candles, burning of sugar with or without a catalyst).
The chemistry of carbohydrates should not be dealt with in detail until the age group 16+. This includes the structure and reactions of carbohydrates and discussion of the detection reactions at the molecular level. Basic knowledge of organic chemistry is essential for this (alcohols, aldehydes, ketones: structure and reactions; forms of isomerism). The interdisciplinary component is also provided through oxidation and reduction of carbohydrates within the biological context of cellular respiration.

Topics and terms: aldehyde, carbohydrate, catalysis, chain and ring shape of molecules, disaccharide, energy conversion, enzyme amylase, glucose, (hemi)acetal formation, hydrogen bond, hydrolysis, isomerism, ketone, metabolism, monosaccharide, oxidation, polysaccharide, resorption, starch, sucrose, sugar

2.3 Skills

The students will …

- know the constituents of food and know which foods they are contained in.
- know the path taken by food through the body.
- be able to carry out detection reactions for carbohydrates and explain the observed phenomena.
- be able to explain the structure of carbohydrates in technical terms (if necessary, with structure formulas and reaction equations).
- be able to summarize the basic principles of energy conversion through catabolism.
- be able to apply the principle of sugar combustion to the metabolic processes.

2.4 Explaining the experiment in the teaching context

2.4.1 Subexperiment 1: Potatoes contain starch

This optional experiment is a preliminary step to understanding that carbohydrates such as starch are an important component of many foods.

2.4.2 Subexperiment 2: Hydrolysis of starch

This experiment demonstrates two processes: first, the verification of starch and, second, the enzymatic hydrolysis of the soluble component of starch, amylose, by the enzyme amylase in human saliva. The presence of starch is verified by the deposition of polyiodide ions from the iodine solution in the spiral-shaped amylose chain (see above). This causes the characteristic violet coloring of the solution.
The salivary amylase can act on any point in the chain as endoamylase or α-amylase:

$$(C_6H_{10}O_5)_n + (n-1)\ H_2O \rightarrow n\ C_6H_{12}O_6$$

Important note: The iodine tincture (brown) contains too much iodine in its undiluted form. As a result of the excess iodine, most of the starch changes color to black, and a small part to blue. The blue-colored starch component together with the brown excess iodine solution forms a gray-green coloring of the aqueous phase.
Problems also occur if the starch solution contains too much starch. Then the saliva does not convert all of the starch to glucose. As more iodine is added, the colors changes increasingly to blue or to a mixed gray-green color.

Fig. 5: Too much iodine and/or starch.

Fig. 6: Right concentration of starch and iodine. A small drop of diluted iodine solution will already result in the first blue coloration.

We therefore suggest that the teacher prepare the precisely measured starch solution (see in Section 4.4 Apparatus and materials).
If all starch molecules have split into glucose molecules, the glucose could be verified, for example, by using Fehling's test (not covered in this experiment).

2.5 Experimental variations

The experiments for detection and hydrolysis of starch do not require much material or time, and can be integrated into lessons as student experiments that can be conducted individually or in pairs. Subexperiment 1 can be omitted, if necessary, if there is no suitable material available (potato, bread, cassava, etc.). Because of the complexity of the overall topic of nutrition, digestion, and cell metabolism, there are teaching methods available to spur students to action. These methods provide additional materials for background information in addition to the experimental approach. Typical examples of such approaches could be learning at workstations or group puzzles. These methods are likewise well suited to allow for the different pace of learning and learning progress of individual students.

If the required chemicals are available, an additional experiment to deactivate the amylase can be performed:

- Fill two test tubes each with approx. 3 ml of starch solution.
- Add a few drops of acid to the first test tube (for example, citric acid).
- Add a few drops of copper sulfate solution to the second test tube.
- Add some saliva to each test tube.
- Shake the two test tubes occasionally and wait approx. 15 minutes.
- Then add the same amount of diluted iodine solution to each test tube as was added in the previous experiments.

Optional: Additional experimentation options for subexperiment 1
Optionally, starch could also be isolated from potatoes. In this connection, see also the instructions under Section 3, "Additional information on the experiment".

Additional experiment on the combustion of sugar:
The subexperiment "Sugar can be burned" from experiment C1 demonstrates first that sugar can be oxidized (burned), and second that a catalyst is necessary for this. Students will first try unsuccessfully to light a sugar cube. They will then light a sugar cube with paper ash sprinkled over it in the metal cup from a tea light, holding a test tube over the flame for a few seconds. This leads to the conclusion that a catalyst is required to burn sugar. This provides a good starting point for discussion of the enzymatic processes in human metabolism.

3 Additional information on the experiment

You will find additional media for preparing or for further study of this experiment on the Siemens Stiftung Media Portal:
https://medienportal.siemens-stiftung.org

4 Notes on conducting the subexperiments

4.1 Facilities

The experiments can be conducted by the students on their own under the supervision of a teacher in any well-ventilated classroom.

4.2 Time required

	Preparation	Execution	Analysis
Subexperiment 1	5 min.	10 min.	7 min.
Subexperiment 2	5 min.	10 min.	7 min.

4.3 Safety aspects

The students may conduct the experiments only in the presence and under the supervision of the teacher.
The teacher is to point out to the students that the provided materials may be used only according to the respective instructions.
For these experiments, watch out for the following potential dangers and make your students aware of them:

- Make sure that no damage can occur to water-sensitive materials and apparatus.
- Working with a flame can result in burns or fires. Before a lighter is used for the first time, the teacher must check that it is working properly and, above all, adjust the flame height.
- Cardboard or newspaper should be placed on non-chemical-resistant desks to avoid iodine stains.
- Iodine is harmful to health only if large amounts are absorbed in the body (through ingestion, inhalation, or skin contact). It is still used in medicine in small amounts for disinfection. Anyone suffering from an iodine allergy should always avoid skin contact!

According to the international hazardous substance labeling (GHS): “Caution”

Hazard Statements: H332, H312, H400
Precautionary Statements: P273, P302, P352

4.4 Apparatus and materials

Required materials that are not supplied:

- 1 knife
- Newspaper or cardboard as surface to work on
- Tap water, or distilled water, if available
- Vegetables or food containing carbohydrates, for example potatoes, cassava, white bread
- One lighter per student group (if possible, a gas igniter) or matches
- Instructions for making a 0.1% starch solution (by the teacher):
  Suspend 0.1 g starch (about the size of a pea) in 100 ml of distilled water and heat the water to boiling. Cool the clear solution to room temperature before it is used.

Supplied:
The apparatus and materials supplied are sufficient to allow **eight** groups of students to conduct the experiments simultaneously.
The following materials included in the kit are needed for **one** group of students:

Material	Quantity
Iodine tincture (iodine/potassium iodide solution), dropper bottle	2x for entire class
Plant clip (as test tube holder)	1x
Plastic cup, 100 ml	1x
Plastic cup (clear), 500 ml	2x
Starch (“potato flour”)*	1x
Tea light	1x
Teaspoon	1x
Test tube, glass, 13 cm	2x
Test tube clamp	1x
Test tube stopper	1x

*It is best for the teacher to prepare the 0.1% starch solution needed for the experiment before the experiment is started because experience shows that this is too difficult for the students.

Fig. 7: Supplied apparatus and materials for one group of students.

4.5 Cleanup, disposal, and recycling

All apparatus and nearly all materials from the kit can be reused. Therefore, after the students have completed the respective experiment, they should put the apparatus and materials back in the appropriate boxes and return them to the kit. This practice will ensure that you and your colleagues will find everything again quickly the next time the kit is used.
Apparatus that become dirty during the experiment, such as cups, bowls, spoons, and test tubes, should be cleaned before being returned to the kit. We recommend that you have the students do this immediately after they have completed the experiment.
Also make sure that the apparatus are in working order for the next time. For example, recharge used accumulators immediately (It makes sense to charge the accumulators even if they will not be used for an extended period.).
Materials that cannot be reused, such as used pH test strips and filter paper, should be disposed of properly.
The waste that accumulates during this experiment can be disposed of in the regular trash or poured down the sink.
Exception: The amounts of iodine used in the experiment are minimal; nevertheless, you should dispose of the residues from the starch hydrolysis experiment as inorganic chemical waste.