**Supplementary Information**

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## S1. RESEARCH DESIGN

### S1.1 Written test instrument

The written tests, including open-ended questions following each of the five lessons, are presented below. While the structure of the questions remains consistent across lessons, the content varies according to each lesson's content focus. Starting from Lesson 4, a scaffolding strategy was applied by gradually fading the guiding prompts to encourage students to independently analyse the issue. However, the results from this lesson suggest that although fading support is necessary to foster autonomy, reducing scaffolding too quickly may limit students' ability to fully demonstrate their systems thinking skills. Therefore, in Lesson 5, the level of scaffolding was adjusted through the incorporation of a dynamic assessment approach, which enabled responsive support during the assessment to better balance guidance and independence. Following the questions, a rationale is provided to clarify how each question is purposefully constructed to assess relevant STS.

- **Written assessment**

- **Question of lesson 1: Lipid and fat**

Question 1: Analyze the impacts of consuming fat-based products in contemporary life. Provide a detailed explanation of each component and the relationships among them.

*The following guiding questions can be used to support your response to the above question:*

- What are the different applications of fats? Based on which scientific concepts are these applications developed? structure, physical and chemical properties, chemical equations,…)
- Why do we need to consume fats? Through which chemical properties and biological processes does the human body digest fats? Are all types of fats the same? What are the health benefits and risks associated with different types of fats? What accounts for these differences?

- Apart from its effects on individual health, how does fat consumption influence broader issues (animal, economy, and environment)? Provide a clear explanation of the factors contributing to these impacts
- When considering various aspects such as the scientific nature of fats, the consumption of fat-based products,..., which issue do you find becomes more apparent?

Q2: Based on your reflection on the issues discussed above, how should you personally use fat-based products in a way that is appropriate for your needs? Do you think this approach should be integrated into your everyday life?

Q3: In your opinion, the lack of nutritional knowledge has led to negative biases against fats, thereby promoting trends of eliminating fat from diets. How does this affect the issues you have previously analyzed (human health, the economy, the environment, and animal welfare)?

- **Question of lesson 2: Glucose and saccharose**

Q1: Analyze the impacts of consuming glucose and saccharose-based products in contemporary life. Provide a detailed explanation of each component and the relationships among them.

*The following guiding questions can be used to support your response to the above question:*

- What are the applications of glucose and sucrose? Based on which scientific principles have these applications been developed? (molecular structure, physical and chemical properties, chemical reactions,...)
- Why do we need to consume foods containing glucose? Through which chemical properties and biological processes does the human body digest sugars? Are all types of sugars the same? What are the health benefits and risks associated with each type of sugar? What accounts for these differences?
- What are the cultivation methods for natural food sources containing glucose and sucrose? Based on these methods, analyze their respective impacts on the environment and the economy.
- Apart from its effects on individual health, how does glucose and saccharose consumption influence broader issues (animal, economy, and environment)? Provide a clear explanation of the factors contributing to these impacts.
- When considering various aspects (the scientific nature, the consumption of glucose and saccharose based products,...), which issue do you find becomes more apparent?

Q2: Based on your reflection on the issues discussed above, how should you personally use glucose and saccharose-based products in a way that is appropriate for your needs? Do you think this approach should be integrated into your everyday life?

Q3: In your opinion, the lack of nutritional knowledge has led to negative biases against sugar, thereby promoting trends of eliminating sugar from diets. How does this affect the issues you have previously analyzed (human health, the economy, the environment, and animal welfare)?

- **Question of lesson 3: Starch and cellulose**

Q1: Analyze the impacts of consuming starch-based products in contemporary life. Provide a detailed explanation of each component and the relationships among them..

*The following guiding questions can be used to support your response to the above question:*

- What are the applications of starch? Based on which scientific principles have these applications been developed? (molecular structure, physical and chemical properties, chemical reactions,...)
- Why do we need to consume foods containing starch? Through which chemical properties and biological processes does the human body digest starch? Are all types of starch the same? What are the health benefits and risks associated with each type of starch? What accounts for these differences?
- What are the cultivation methods for natural food sources containing starch? Based on these methods, analyze their respective impacts on the environment and the economy.
- Apart from its effects on individual health, how does starch consumption influence broader issues (animal, economy, and environment)? Provide a clear explanation of the factors contributing to these impacts
- When considering various aspects (the scientific nature, the consumption of starch based products,...), which issue do you find becomes more apparent?

Q2: Based on your reflection on the issues discussed above, how should you personally use starch-based products in a way that is appropriate for your needs? Do you think this approach should be integrated into your everyday life?

Q3: In your opinion, the lack of nutritional knowledge has led to negative biases against starch, thereby promoting trends of eliminating starch from diets. How does this affect the issues you have previously analyzed (human health, the economy, the environment, and animal welfare)?

- **Question of lesson 4: Protein**

Q1: Analyze the relationship between the structural characteristics of proteins and the following components: their chemical properties, the metabolic processes in the human body, and their applications in human life, particularly in the textile industry. Be sure to clearly explain the content of each part in your response.

Q2: The current 'high-protein' trend has attracted considerable attention from young people due to the important role of protein in the human body. However, in your opinion, what could happen if this trend continues to grow while consumers lack proper nutritional knowledge? (which can help you reflect on how to use protein-based production appropriately for yourself). Provide a well-reasoned argument based on the physical and chemical properties of proteins.

- **Question of lesson 5: Polymer**

Q1: Analyze the impacts of consuming products made from polymers (polyethylene) in contemporary life. Present in detail the content of each part and the relationships among them (properties, applications, natural cycle, economic and environmental issues,...)

Q2: Based on your reflection on the issues discussed above, how should you personally use polyethylene-based products in a way that is appropriate for your needs? Do you think this approach should be integrated into your everyday life?

Q3: Nowadays, the trend of reducing the use of plastic products, especially those intended for single use, is becoming increasingly widespread as part of a shift towards more environmentally friendly lifestyles. In your opinion, how does this trend affect the issues you previously analysed (human health, the economy, the environment, and animal welfare)?

**b. The rationale**

With an open-ended format and a structured set of guiding questions, Question 1 not only encourages students to review their knowledge throughout lessons but also creates opportunities to assess a range of STS.

- This question is well positioned to assess STS 1 (Sustainability dimensions) as it directs students to analyze the impacts of a product across multiple dimensions (including health, environment, economy,...) which are explicitly embedded within the guiding questions. By prompting consideration of these diverse aspects, the question encourages learners to identify different dimensions of sustainable education, rather than approaching the issue from a single perspective.

- STS 2 (Nature as a system) can be assessed through prompts that guide students to analyze natural processes such as decomposition or the product's interaction with the human body or ecosystems. By being encouraged to explain how these processes take place, students are led to perceive the phenomenon as a sequence of interactions, both within each subsystem and with the natural environment.

- The potential to assess STS 3 (System components) lies in the guiding question that requires students to identify and describe all components of each subsystem such as molecular structure, physical and chemical properties, and functional characteristics.

- STS 4 (Dimension interconnections) also can be assessed through the guiding question toward analyzing interconnections between sustainability dimensions. This creates an opportunity for students to consider the relationships between the sustainability aspects they are otherwise addressing in isolation.

- Regarding STS 5 (Hidden dimensions), the question does not impose rigid content boundaries but instead allows students to expand their analysis based on their understanding. This flexibility creates space for learners to incorporate elements that are not immediately visible or explicitly stated, such as hidden costs or long-term consequences. Such an open approach enables the assessment of students' ability to recognize and integrate hidden or less obvious components of a system.

- STS 8 (System cycles) may also be assessed, as students are prompted to analyze processes like digestion, transformation, or decomposition—processes that are inherently cyclical within biological and environmental systems. Furthermore, when asked to evaluate the product's impact on human health, students are implicitly encouraged to trace cause-and-effect loops that reinforce cyclical patterns.

Subsequently, with open-ended format and strong emphasis on reflective thinking, questions 2 and 3 can create opportunities to assess a range of systems thinking skills related to purposeful action, affective engagement, and self-positioning within real-world systems.

- The questions may be well suited to assessing STS 6 (Personal responsibility), as students are encouraged to propose practical solutions by positioning themselves within the system. The process of envisioning and articulating context-specific actions demonstrates that students are not only understanding the system at a conceptual level but are also recognizing their own role within it.

- STS 7 (Action relationships over time) may also be assessed as students are encouraged to anticipate how the system might develop in response to the solutions they propose. By considering possible future states and projecting the consequences of certain actions over time, students demonstrate the ability to think dynamically about systems. They also take in the knowledge they have learned as part of their personal experience.

- STS 9 (Empathy with others) may be indirectly assessed. Although the questions do not explicitly ask students to consider other people's perspectives, proposing realistic solutions often involves thinking about how others might be affected. If students choose to take this into account, their responses can reflect an emerging sense of empathy and awareness of different viewpoints.

- These questions also have the potential to assess STS 10 (Empathy with non-human beings). They provide an opportunity for students to develop empathy, rather than merely referring to it as a related factor. Students express their care for nature and non-human entities when considering the factors surrounding their proposed actions. When non-human elements are treated as integral parts of the system and evaluated alongside human interests, students demonstrate a more inclusive and holistic systems perspective.

- STS 11 (Sense of place) may also be assessed, as students are asked to propose solutions that are relevant to their own context. This process guides them to consider how the issue relates to the social, environmental, and cultural aspects of the place where they live. By connecting the system under study to the places they inhabit, students demonstrate an understanding that sustainability challenges are not abstract, but are embedded within real, lived spaces. This encourages the development of a grounded sense of place

- STS 12 (Personal practice) may also be assessed, as students are asked to propose actions that appropriate their real-life context. Although this skill is not easily assessed through the questions, the way students articulate their proposed actions—especially when these are closely connected to their personal situations—can show whether they are likely to apply these actions in practice. Such responses may reflect an early step in the potential application of systems thinking to students' own lives, although it remains uncertain whether these would translate into actual actions.

- Finally, the process of proposing solutions also provides an indirect opportunity to assess STS 1 (Sustainability dimensions) and STS 4 (Dimension interconnections). As students consider the impacts of their proposed actions on various dimensions (such as health, economy, and the environment,...), they continually revisit key aspects of sustainability (STS 1) and analyze how these dimensions interact within a complex system (STS 4).

**S1.2 Rubrics for assessing the 12 systems thinking skills**

| Systems Thinking Skills (STS) | Mastery | Developing | Emerging | Pre-aware |
|---|---|---|---|---|
| STS 1. Identifying the meaning and aspects of sustainability | Students clearly refer to more than two aspects of sustainability related to issue. | Students refer to two aspects of sustainability related to issue. | Students refer to one aspect of sustainability related to issue. | Students do not refer to aspects of sustainability related to issue. |
| **Example of student response** | Eating fat is good for our body, but eating too much can cause health problems like obesity. When people get sick, they have to spend a lot of money on medical treatment. Besides that, if we throw cooking oil away carelessly, it can pollute rivers and water in the environment. | We need to eat fat because it is important for the body, but eating too much or eating too many snacks can cause obesity, health problems because it is saturated fat, and waste money on hospital bills. | We need to eat fat because it gives energy to our body, helps build cells, and protects our organs. If we do not eat fat or only eat unhealthy fat from snacks, our body may get sick because it is hard to digest and use it properly. | Protein is made from amino acids through peptide bonds. Its chemical properties include protein decomposition, coagulation or denaturation, and hydrolysis reaction: protein + $H_2O$ → (acid or base, heat or enzyme) → amino acids. |
| STS 2. Seeing nature as a system | Students are able to look at the nature as a system considering most of the aspects of integral ecology and describe human–nature relationship in a holistic way. | Students are able to look at the nature as a system considering two or three aspects of integral ecology and try to describe human–nature relationship in a holistic way. | Students struggle to look at the nature as a system and only consider one or two aspects of integral ecology and describe human–nature relationship from mechanistic perspective. | No particular view of nature as a system. |
| **Example of student response** | No responses reached the mastery level. | Environmental pollution caused by plastic results from human | Plastic waste causes environmental pollution. | *Plastic is very convenient and cheap, so many people use it* |

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| | | overuse due to its convenience; since plastics cannot participate in natural decomposition, they accumulate, fragment, and disperse, entering the human body and food chains, harming organisms | When people use and throw away too much plastic, the environment is damaged and becomes unsafe for living things. | *every day for bags, bottles, and food containers. Because of its strong structure, it is difficult to decompose and can exist for a long time.* |
| STS 3. Identifying components of a system | Students are able to identify multiple components of a system in a clear way. | Students try to identify multiple components of a system. | Students are able identify one or two components of a system. | Students cannot identify components of a system. |
| **Example of student response** | Fat is used in daily life to make food and soap.<br>In food, there are many kinds of fat such as animal fat, sesame oil and olive oil.<br>Solid fat has only single bonds, so it is saturated fat, while liquid oil has double bonds and is unsaturated fat.<br>Trans fat is found in snacks and cakes and is created when unsaturated fat is hydrogenated, which changes its structure.<br>When fat reacts with NaOH, it forms RCOONa, which has cleaning ability and | Fat is used in daily life for food and soap.<br>There are different kinds of fat such as saturated fat, unsaturated fat and trans fat, which are found in animal fat, cooking oil and snacks.<br>Fat can react with NaOH to make soap.<br>When people eat fat, it is broken down in the body to provide energy.<br>After cooking, waste oil can be thrown away and may pollute | Fat is found in many foods such as cooking oil and animal fat.<br>It can give energy to the human body. | No responses reached the pre-aware level. |

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| | creates soap bubbles.<br>The human body is also a component of the fat system.<br>Fat provides energy, helps build cells and forms a fat layer to protect organs.<br>After eating, fat is broken down into fatty acids to perform these roles.<br>There are different types of fat such as saturated fat, unsaturated fat, trans fat, whole fat, refined fat and cold-pressed fat, classified by structure and processing.<br>In my opinion, trans fat and refined fat should not be eaten because they lose nutrients and can cause obesity, while other fats can provide nutrition if used properly.<br>Fat molecules have R groups and cannot dissolve in water.<br>When waste oil is poured into sinks or rivers, it can pollute water and reduce oxygen for aquatic organisms.<br>Using animal fat also increases animal slaughter, | water. | | |

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| | which can affect animal rights. | | | |
| STS 4. Analyzing interconnections among the aspects of sustainability | Students are able to critically analyze the interconnections among the components of a system by considering all aspects of sustainability. | Students are able to analyze interconnections by considering two aspects of sustainability. | Students struggle to analyze the interconnections among the aspects of sustainability. | Not analyzing the interconnections among the aspects of sustainability. |
| **Example of student response** | Polyethylene possesses durable properties due to its chemical structure and bonding, which makes it resistant to natural degradation despite the existence of environmental decomposition cycles. As a result, it tends to accumulate in the environment, contributing significantly to pollution. Microplastics from polyethylene can gradually enter the food chain and eventually reach humans, posing serious health risks. Nevertheless, polyethylene remains widely used because it is inexpensive and convenient, and it is present in many items around us | Plastic waste can pollute the environment, especially water and soil. When plastic breaks into small pieces, it can harm animals living there. This pollution can also affect human health because microplastics may enter food and drinking water. | Fat provides energy for the human body. It can also cause environmental pollution. | Fat provides energy for the human body so we should eat fat in meals. |
| STS 5. Recognizing | Students are able to identify many | Students able to identify some | Students struggle to | Students cannot identify hidden |

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| hidden dimensions | hidden dimensions in a system by connecting to the issue clearly. | hidden dimensions in a system and making connection to the issue in a simple way. | identify hidden dimensions in a system. | dimensions in a system. |
| **Example of student response** | No responses reached the mastery level. | The improper consumption of fatty foods leads to various diseases due to visceral fat accumulation, resulting in high treatment costs; however, this contributes to the growth of the healthcare economy. | Eating too much fatty food can cause diseases, and it also makes people spend more money on treatment. | Eating too much fatty food can cause obesity and health problems. |
| STS 6. Recognizing own responsibility in the system | Students are able to make connection between the problem/issue and their personal life. | Students try to make connection between the problem/issue and their personal life. | Students struggle to make connection between the problem/issue and their personal life. | Students cannot make any connection between the problem/issue and their personal life. |
| **Example of student response** | I think that using brown rice and organic products is good for health, but they are expensive. At home, my mother is the one who buys food, so even though I know they are healthier, we still eat white rice. However, I will try to talk to my mother about switching if our family can afford them. | I know that brown rice and organic food are healthier than white rice. However, they are more expensive, so my family usually does not buy them. I think eating healthier food is important, but it is not easy to change our daily meals. | I think organic food are healthier for the body and can help prevent diseases. However, my family is used to using other foods that are not organic because they are more suitable for our conditions. | Organic food is healthier for the body and can help prevent diseases such as obesity and heart disease. |

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| STS 7. Considering the relationship between past, present and future | Students are able to make relationship between past, present and future clearly. | Students try to make relationship between past, present and future. They mostly consider two time spans (e.g. past and present). | Students struggle to make relationship between past, present and future. | Students cannot make relationship between past, present and future. |
| **Example of student response** | In the past, I used to use many plastic bags when shopping. Now I realize that plastic waste causes serious pollution, so I try to bring my own bag. In the future, I will continue reducing single-use plastics and encourage my parents to do the same. | I used to eat lots of oily food with trans fats, but now I think I need to eat more at home and eat healthier while still meeting nutritional needs. | I think I should eat less oily food and choose healthier meals to meet my nutritional needs. | Eating too much oily food with trans fats is unhealthy for the body. |
| STS 8. Recognizing cyclical nature of the system | Students are able to recognize cyclical nature of the system by giving examples (e.g. natural cycles). | Students try to recognize cyclical nature of the system in a simple way. | Students struggle to recognize cyclical nature of the system. | No explanation about cyclical nature of the system. |
| **Example of student response** | Organic waste is broken down by bacteria into carbon dioxide and water, which return to the environment and are taken up by plants again through the air and soil. | Organic waste can be broken down by bacteria into simple substances. These substances return to the environment and can be reused in nature | Fat is necessary for health, so people should consume fatty foods. But when consumed improperly, the skin becomes dry, requiring expensive moisturizers while the body still lacks essential | Fat is important for the body because it provides energy and helps protect organs. Eating too much fat can cause health problems. |

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| | | | nutrients. | |
| STS 9. Developing empathy with other people | Students are able to develop empathy with other people by explaining their reasons or needs behind their actions without blaming them. | Students try develop empathy with other people, but they give simple explanations about their needs or reasons. | Students struggle to make empathy with other people. | Students cannot develop empathy with other people. |
| **Example of student behavior** | Students actively listened to different system perspectives, articulated their own viewpoints, and engaged in constructive discussion of the system components. Based on the shared arguments, they collaboratively integrated relevant ideas from other groups into their own concept maps. | Students were able to present and justify their own group's system perspective and showed openness to the perspectives proposed by other groups. They agreed with alternative viewpoints and discussed a specific system component using group-based reasoning, focusing on exchanging arguments rather than engaging in disagreements. | Students initially rejected different system perspectives proposed by other groups and engaged in disagreements. With teacher intervention, they gradually became more willing to compromise. However, they did not fully accept with the different perspectives presented by other groups. | Students rejected different system perspectives from other students, leading to arguments and unwillingness to compromise in the Zoom out and Connect phase. |
| STS 10. Developing empathy with non-human beings | Students are able to state their connection with non-human beings and to whole nature. | Students try to state their connection with non-human beings in a simple way. | Students struggle to make connection with non-human beings. | Students cannot make connection with the non-human beings. |
| **Example of student response** | No responses reached the mastery level. | Using animal fat means animals have to be killed for food | If animal fat is used too much, more animals can be killed for | We need to eat foods that contain fat such as meat, oil and |

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| | | production. This can affect animal rights because animals lose their lives only to meet human needs. | food. | butter. |
| STS 11. Developing sense of place | Students are able to build multi-dimensional, holistic sense of place. They could attribute several meanings to the places (biophysical, social, cultural, political etc.). | Students try to build multi-dimensional sense of place. They could define the place as including two dimensions. | Students struggle to build multi-dimensional sense of place. They could define the place as including single dimension. | Students cannot build any sense of place. |
| **Example of student response** | Brown rice is healthier because it contains more fiber and nutrients, but it is more expensive and harder to buy. White rice is cheaper and easier for my family to use every day. Therefore, we usually eat white rice, but we sometimes choose brown rice when our budget allows. | We use white rice because it's cheaper and part of our habit, but I'll try to change that if my family's financial condition allows. | My family eats white rice because it is suitable. | White rice is commonly eaten in many families. |
| STS 12. Adapting systems thinking perspective to personal life | Students are able to adapt systems thinking perspective to their personal life by taking transformative actions. | Students almost start to adapt systems thinking perspective to their personal life by taking small steps. | Students struggle to adapt systems thinking perspective to their personal life. They describe simple actions for sustainability. | Students do not adapt systems thinking perspective to their personal life. |
| **Example of** | I won't eat | I realize that too | I think i | Protein is good |

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| **student response** | carelessly anymore. People used to tell me, but I didn't care. After this lesson, I understand why it causes obesity, so I'll change. | much fried food is unhealthy. Now I am starting to try to choose healthier food, such as eating home-cooked meals. | shouldn't eat too much fatty food because it can cause obesity. | for building muscles and repairing the body, but eating too much protein can cause constipation. |

## S2. TEACHING INTERVENTION

### S2.1 Systems thinking framework

The Talanquer & Szozda's framework provides a clear and structured instructional sequence[1] that may align effectively with the development of the 12 STS through its four pedagogical phases. Based on the characteristics of each STS and the functions of each phase in the Implementating stage[1], this study proposes potential alignments, as presented in the table below. While some STS may emerge across multiple phases, we highlight where each skill is most strongly initiated or reinforced.

| **Phases of implementation stage[1]** | **Systems thinking skills[2]** | **Rationale for the alignment** |
|---|---|---|
| Map out | STS 1 (Sustainability dimensions) | Students are required to recognise the socio-environmental issue not only from a scientific perspective but also by recognizing aspects related to sustainability dimensions. Through this process, students begin to recognize which subsystems (including those associated with sustainability) are relevant to the issue and recognise simple relationships among them. |
| | STS 2 (Nature as a system) | During the process of identifying subsystems related to the issue in the Map Out phase, students may be guided to initially integrate natural factors (such as environment, soil, and water) into the system. This can begin to foster a holistic perspective on natural systems that are directly relevant to the issue under consideration, as well as their inherent complexity. |
| | STS 3 (System components) | Students are expected to recognize the subsystems within the system and the factors that affect the system. These factors may be chemical, physical, biological, environmental, social, political, or economic. Although detailed analysis of component properties is not required at this stage, the process helps students begin to recognize the key elements that make up the system. |

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| | STS 4 (Dimension interconnections) | Although the Map Out phase does not require students to analyze detailed interactions among factors and subsystems, organizing these subsystems together within a system framework helps them recognize that sustainability dimensions are not separate or independent. This stage supports students in developing an initial awareness of how different domains are connected and dependent on one another, providing a foundation for more in-depth analysis in later phases. |
| Zoom in | STS 3 (System components) | Students are guided to examine each subsystem at the microscopic and submicroscopic levels through appropriate chemistry lenses. This process involves analyzing key components, such as molecules, cells, or chemical and biological structures and identifying their properties. |
| | STS 5 (Hidden dimensions) | Students are guided to access subsystems at the microscopic and submicroscopic levels, where many components are not readily observable. As students are guided to analyze processes such as molecular bonding or metabolic pathways at the cellular level, they begin to identify hidden components or mechanisms that are not apparent at the surface. These components often serve as foundational drivers of system behavior but can only be revealed through deeper-level examination. |
| | STS 8 (System cycles) | Students engage with dynamic processes within subsystems, such as nutrient cycles, metabolic pathways, or biological feedback mechanisms. These phenomena unfold over time, often exhibiting cyclical or continuous processes. This aligns with the Zoom In phase's emphasis on examining systems across different scales in space and time. |
| Zoom out | STS 4 (Dimension interconnections) | Students are required to connect the subsystems together in order to zoom out from the submicroscopic scale to the macroscopic world, thereby analyzing and explaining the issue from an integrated perspective. This task prompts students to examine the nature and directionality of interactions among these dimensions. When students are encouraged to reflect on the multidimensional impacts across the previously analyzed subsystems (particularly in terms of sustainability), they begin to move beyond isolated listing and toward constructing integrated understanding across the three pillars of sustainable development. |
| | STS 5 (Hidden dimensions) | Students are encouraged to synthesize previously isolated analyses of individual subsystems in order to construct a more comprehensive view of the system as a whole. This process creates the cognitive conditions for students to identify features |

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| | | that are not readily observable within each isolated subsystem - such as delayed feedback, gradual accumulation over time, or indirect consequences. These are hidden aspects of the system that only become evident when students examine the system as an interconnected whole. |
| | STS 7 (Action relationships over time) | To construct an explanation for the issue under examination, students are guided to move beyond a linear or present-focused approach by examining the connections between past, present, and future actions. This process fosters temporal reasoning and awareness of long-term impacts, enabling students to develop the capacity for decision-making within complex systems, thereby preparing them for the next phase of learning. |
| | STS 8 (System cycles) | The Zoom Out phase further deepens STS 8 by prompting students to reason about how components change over time at the whole-system level. Rather than observing only the cycles or processes within a single subsystem, students are guided to consider delayed feedback, indirect cause–effect chains, and cumulative changes. These elements reflect the dynamic and nonlinear nature of complex systems, enabling students to recognize subtle temporal changes and incorporate them into a more comprehensive systems analysis. |
| Connect | STS 6 (Personal responsibility) | Students are prompted to reflect on their own roles, actions, and choices in relation to the system they have analyzed. By positioning themselves within the system, they begin to recognize the reciprocal influence between individual behavior and the sustainability of the system. This process fosters awareness of personal responsibility and civic engagement. |
| | STS 7 (Action relationships over time) | Students are required to revisit the entire system they have analyzed as a way to summarize and reinforce their learning. This process not only helps review key knowledge, but also fosters reflective thinking. Through this reflection, students can identify aspects that require adjustment and propose more appropriate solutions to the issue under consideration in the future. |
| | STS 9 (Empathy with others) | Students may be encouraged to consider the social impacts of the issue, particularly when constructing community-oriented solutions. This process can help foster students' empathy toward groups affected by the system, thereby initiating the development of awareness related to social justice. |

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| | STS 10 (Empathy with non-human beings) | When students are asked to reflect and propose system-based solutions, they may be encouraged to consider the environmental impacts of the issue, including effects on non-human elements such as animals, plants, or ecosystems. This broader perspective can help initiate awareness of ethical responsibility toward nature |
| | STS 11 (Sense of place) | Students may be provided with opportunities to connect their systems understanding with familiar real-life contexts such as their school, community, or local environment. When students are asked to propose actions within these settings, they develop a deeper understanding of the specific biophysical, psychological and socio-cultural dimensions of the place. |
| | STS 12 (Personal practice) | Students may be provided with opportunities to connect the system to their own personal lives. When asked to propose actions or personal orientations based on their system analysis, they begin to adjust how they evaluate situations and select appropriate solutions by considering multiple dimensions surrounding themselves. This process helps guide their personal behaviors in ways that are more appropriate, responsible, and sustainable. |

**S2.2 Mandatory learning outcomes in Grade 9 curriculum**

| Topic | Learning outcomes (in the curriculum) | Core content |
|---|---|---|
| Lipid and fat | 1) Define the concepts of lipids and fats, their occurrence in nature, the structural characteristics, and the general formula of simple fats $(RCOO)_3C_3H_5$. | - The concept of lipids and fats<br>- Natural occurrence of lipids and fats<br>- General formula of simple fats |
| | 2) Present the physical properties of fats (aggregate state, solubility) and their chemical properties (saponification reaction). Write the corresponding chemical equations. | - Physical properties of fats (aggregate state, solubility)<br>- Chemical properties of fats (saponification reaction) |
| | 3) Explain the role of lipids in cell structure composition and energy storage within the body. | - Biological role (cell structure, energy storage). |
| | 4) Present the applications of fats and propose measures for appropriate fat consumption in the daily diet to maintain a healthy body and prevent obesity. | - Application of fats<br>- Dietary recommendations. |
| Glucose and saccharose | 1) State the elemental composition and general formula of carbohydrates. | - Composition and general formula of carbohydrates |

| Topic | Learning outcomes (in the curriculum) | Core content |
|---|---|---|
| | 2) State molecular formula, natural occurrence, and physical properties of glucose and saccharose. | Glucose and saccharose:<br>- Molecular formula<br>- Natural occurrence<br>- Physical properties |
| | 3) Present the chemical properties of glucose (silver mirror reaction, alcoholic fermentation) and saccharose (hydrolysis reaction catalyzed by acids or enzymes). Write the corresponding chemical equations using molecular formulas. | - Chemical properties of glucose: silver mirror reaction, alcoholic fermentation<br>- Chemical properties of saccharose: hydrolysis reaction catalyzed by acids or enzymes |
| | 4) Perform/observe the silver mirror experiment. | Silver mirror experiment |
| | 5) Present the roles and applications of glucose (an important nutrient for humans and animals) and saccharose (an important raw material in the food industry). Demonstrate awareness of the importance of reasonable saccharose consumption. Identify foods rich in saccharose and fruits rich in glucose. | - Roles and applications of glucose: important nutrient for humans and animals<br>- Roles and applications of saccharose: an important raw material in the food industry<br>- Importance of reasonable saccharose consumption<br>- Foods rich in saccharose and fruits rich in glucose |
| Starch and cellulose | 1) State the natural occurrence and physical properties of starch and cellulose. | Starch and cellulose:<br>- natural occurrence<br>- physical properties |
| | 2) Present the chemical properties of starch and cellulose: hydrolysis reaction; the color reaction of starch paste with iodine. Write the chemical equations for the hydrolysis reaction using molecular formulas. | - Hydrolysis of starch and cellulose<br>- The color reaction of starch paste with iodine |
| | 3) Perform (or observe via video) experiments on the hydrolysis reaction and the color reaction with iodine; describe the experimental phenomena, make comments, and draw conclusions about the chemical properties of starch and cellulose. | - Hydrolysis experiment of starch and cellulose<br>- The color reaction experiment of starch paste with iodine |
| | 4) Present the applications of starch and cellulose in daily life and production, the formation of starch and cellulose, and their roles in green plants. | - Applications of starch and cellulose<br>- Formation and roles of starch and cellulose in green plants |
| | 5) State the importance of starch and cellulose formation in green plants. | - Importance of starch and cellulose formation in green plants |
| | 6) Identify starch-rich food sources and know how to consume starch appropriately. | - Starch-rich food sources<br>- Appropriate consumption |
| Protein | 1) Define the concept, molecular structure (amino acids, peptide bonds), and molecular weight of proteins. | - Concept of protein<br>- Molecular structure and weight of protein |

| Topic | Learning outcomes (in the curriculum) | Core content |
|---|---|---|
| | 2) Present chemical properties of protein: Hydrolysis, coagulation (by acid/base/heat), decomposition. | Chemical properties of protein: Hydrolysis, coagulation (by acid/base/heat), decomposition. |
| | 3) Perform/observe experiments: coagulation, decomposition. | - Coagulation, decomposition experiment |
| | 4) Distinguish protein (wool, silk) from other substances (nylon). | Differences between protein (wool, silk) from other substances (nylon) |
| | 5) Present the role of protein in the human body. | Role of protein in the human body |
| Polymers | 1) Define the concepts of polymer, monomer, chain links..., the structure, and the classification of polymers (natural polymers and synthetic polymers). | - Concepts of polymer, monomer, chain links<br>- Structure of polymers<br>- Classification of polymers |
| | 2) Present the general physical properties of polymers (state, solubility). | Physical properties of polymers (state, solubility) |
| | 3) Write the chemical equations for the preparation reactions of PE (Polyethylene) and PP (Polypropylene) from monomers. | - Preparation reactions of PE (Polyethylene)<br>- Preparation reactions of PP (Polypropylene) |
| | 4) Define the concepts of plastics, fibers, rubber, and composite materials, and explain how to use and preserve some household items made of plastics, fibers, and rubber safely and effectively. | - Concepts of plastics, fibers, rubber, and composite materials<br>- How to use and preserve some household items |
| | 5) Present the applications of polyethylene; the environmental pollution issues associated with the use of non-biodegradable polymers (polyethylene), and ways to minimize environmental pollution when using polymer materials in daily life. | - Applications of polyethylene<br>- Environmental pollution issues<br>- Measures to minimize environmental pollution when using polymer |

**S3. ANECDOTAL RECORD (FIELD NOTES on classroom observation)**

The following notes are taken from the anecdotal records.

In Lesson 1, when discussing food consumption, students focused on health-related aspects. Initial reports from some groups contained statements such as, “Saturated fat is also good for health”. Some students explained that: “*Excessive fat consumption leads to internal fat accumulation, which causes health problems and costly treatments*”. In the Zoom Out and Connect activities of Lesson 1, some students said, “*Fat may cause water pollution*”. Other students’ responses were like “*I shouldn’t eat too much fat; I should eat at home and exercise regularly*”, and some pointed out that “*fat layers reduce oxygen for aquatic animals*”.

In Lesson 2, during the Map Out activity, students were asked to identify subsystems related to the lesson topic. Student A stated, "*I think we should examine human health*" or "*If PE pollutes the environment, maybe it also harms living organisms, so we should consider this factor*". Many students identified new aspects they discovered, such as "*healthcare economy*" or "*employment issues*". Students noted that "juicing fruits removes fiber, making it similar to refined sugar and thus less healthy so not all fruit-based options are necessarily beneficial" or that "organic farming not only benefits the environment but also supports farmer livelihoods". Additionally, some students showed recognition of cyclical feedback loops, such as "the cumulative health effects of dietary choices".

Additionally, some students selected and organised relevant elements into their concept maps without teacher prompts. Their concept maps included multiple components and connections among system constituents, and students began posing questions to the teacher and other groups. For instance, student B posed the question: "*Fats, starch, and glucose all provide energy, so how can they be connected? I already see the link between starch and glucose in the concept map, but what about fats?*".

In Lesson 3, when discussing system relationships, evaluating issues, and proposing solutions, students expressed differing viewpoints. After each group presented, disagreements emerged, and students rejected opposing perspectives, despite the presence of counterarguments in Lesson 1 and 2. However, following the teacher's intervention, emphasising mutual respect and the legitimacy of multiple perspectives, the teacher reminded students to listen to different viewpoints. Beginning with Lesson 3, students continued to critique each others' ideas, listened to other groups' presentations before responding, and referred to peers' arguments during discussion.

In the same lesson, some examples students offered include: "*Through metabolism, starch provides energy, but eating too much leads to fat accumulation, so we need to exercise more. Alternatively, we could consume resistant starches like whole grains or brown rice, but they're more expensive, so we have to choose based on our situation*". Some students also expressed concerns, stating: "*Such choices may be good, but not everyone can afford them. My family eats white rice because it is cheaper and has become a habit, but I will try to change that if our financial situation allows*".

In subsequent lessons, students identified and structured components in their concept maps, and teachers provided feedback. In Zoom Out activities, students added additional components and connections to their maps. When the topic of "*animal rights*" was introduced, several students raised their hands and leaned forward.

In Lesson 5, some students pointed out that "*environmental pollution destroys habitats*" or "*plastic waste causes marine creatures to become entangled or ingest plastic*". Some students stated, "*We use plastic because it's cheap, but when it stays in the environment, it breaks down very slowly and affects the nature system, it harms animals, plants, water, and eventually comes back to harm us too*". Statements such as "*Because of its properties, plastic is durable, cheap, and widely used, so it's very hard to replace*" were articulated by some students. Particularly, natural cycles were articulated, such as the "*natural degradation cycle*" and "*biological food chain*".

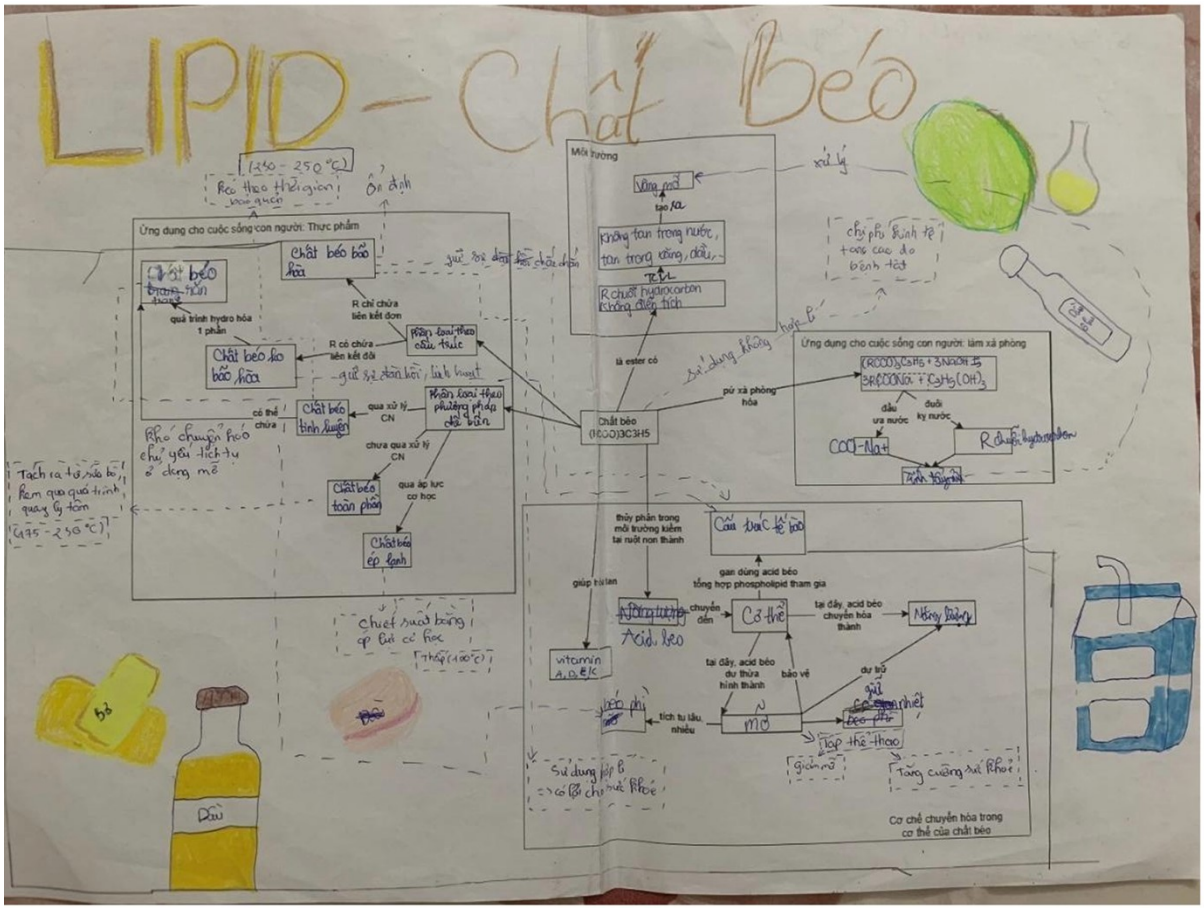
In Lessons 2, 3, and 5, when asked to propose a context-appropriate solution while reflecting on the system map they had constructed, some students suggested choosing healthier food options. Others

evaluated how solutions might apply to others, as in the comment, "*Workers often eat out because they need energy to keep working, and they don't gain weight because they are constantly active*".

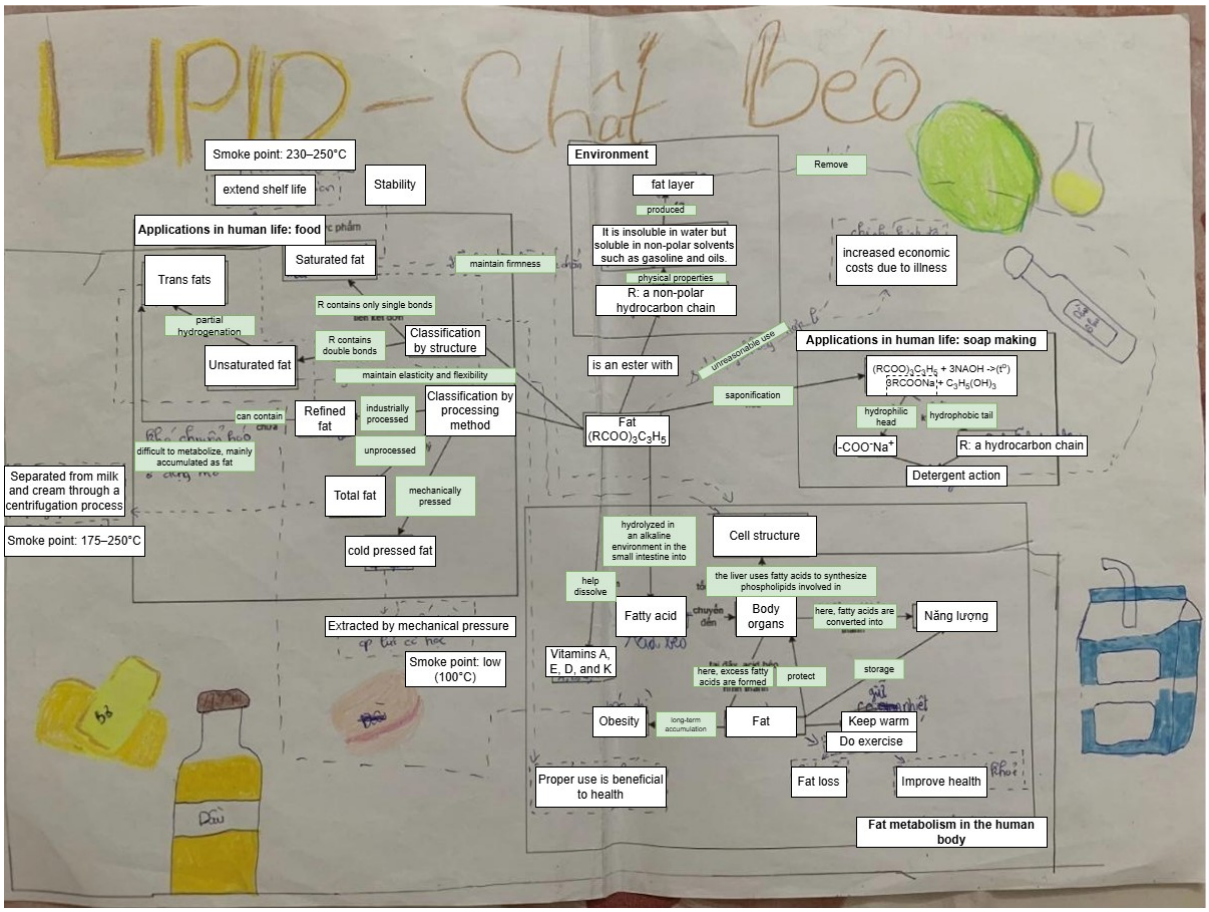
Finally, in Lessons 1–3, many students stated that they adopted healthier lifestyles. After Lesson 2, fewer students brought sugary drinks to class. Some students stated "*I will live a healthier life*". By Lesson 5, students referred to their everyday choices and discussed possible long-term consequences of those choices during class discussions.

## S4. EXAMPLES OF STUDENTS' CONCEPT MAPS

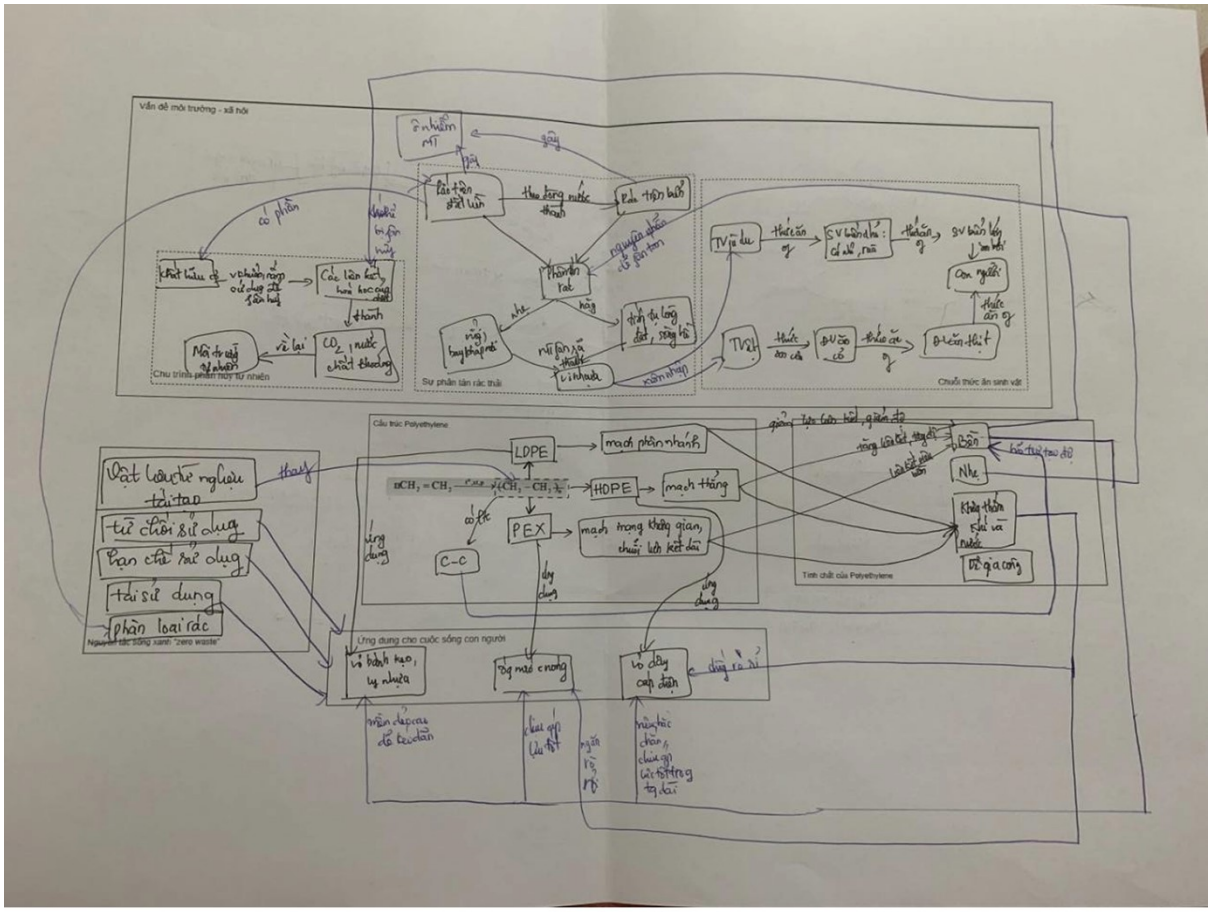
### Lipid and fat – Local version



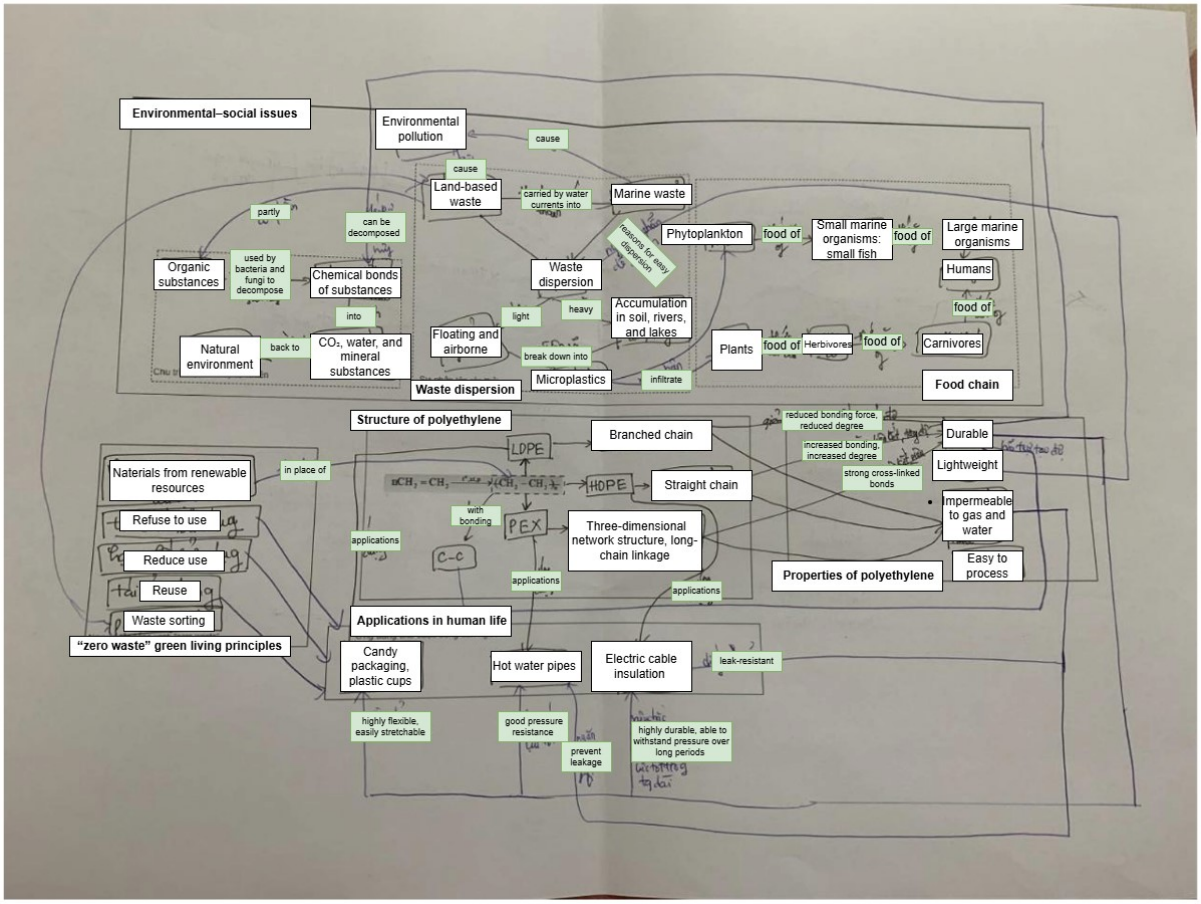
## Lipid and fat – English version



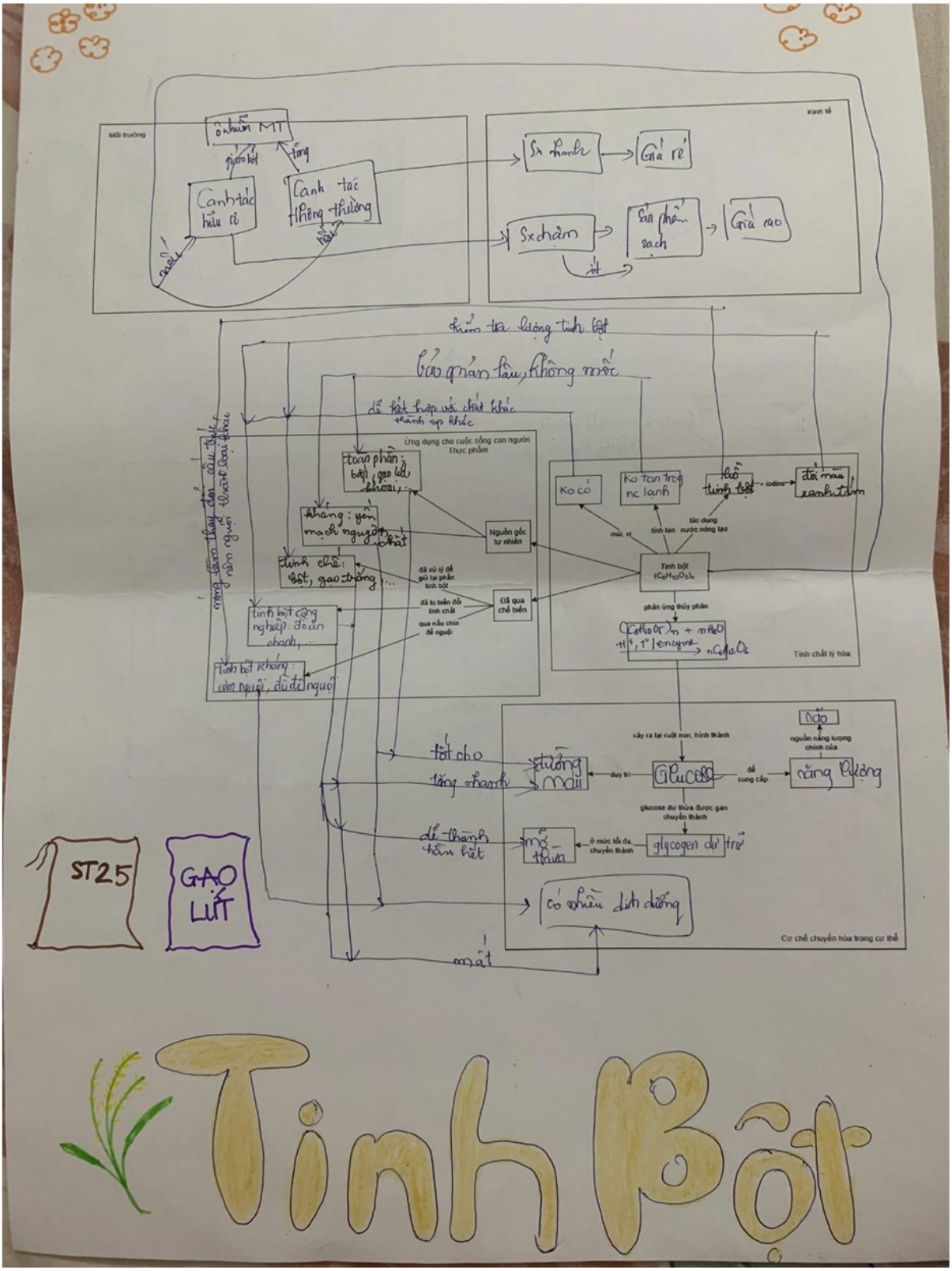
**Polymers – Local version**



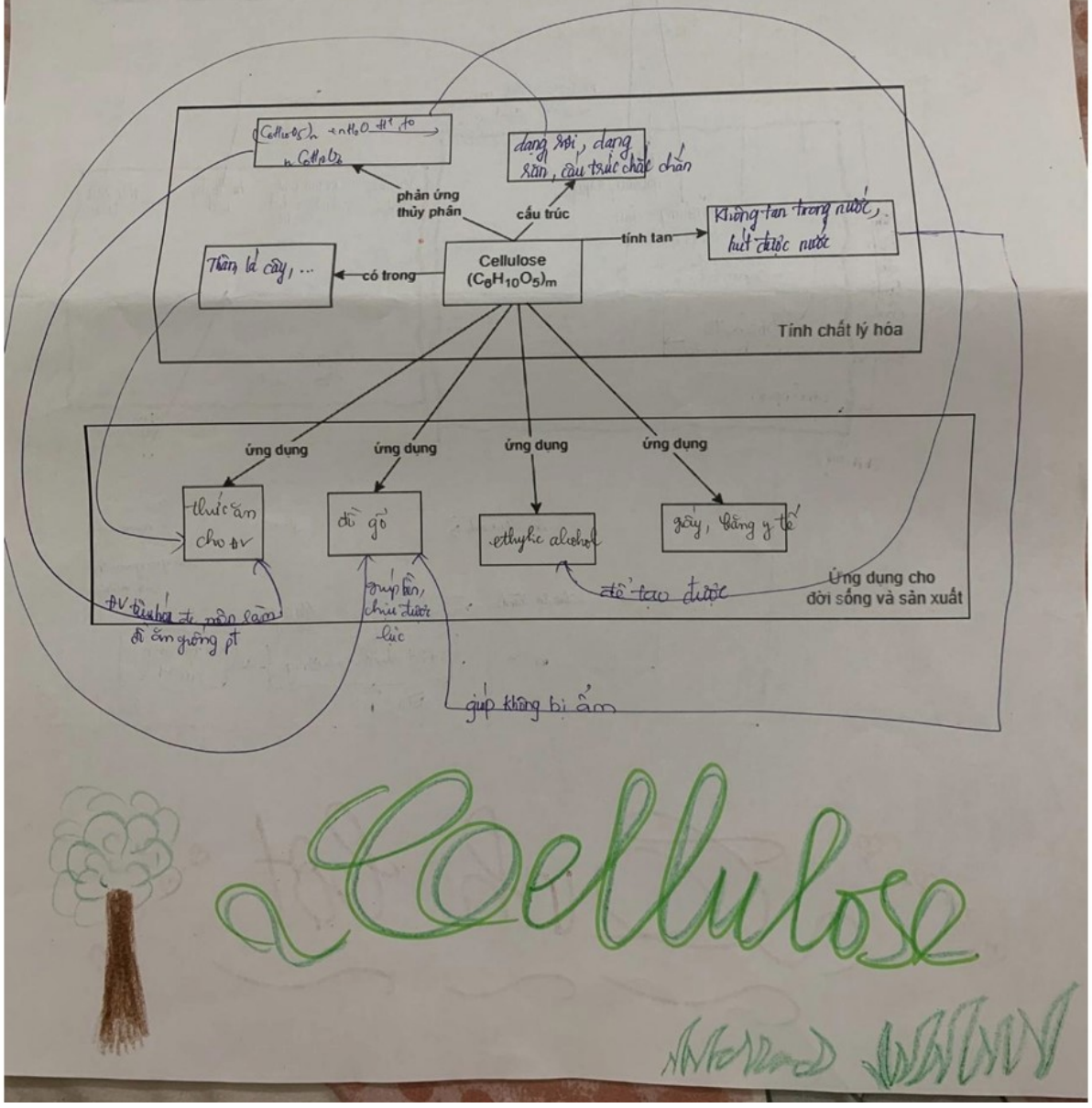
## Polymers – English version



**Starch and cellulose – Local version**

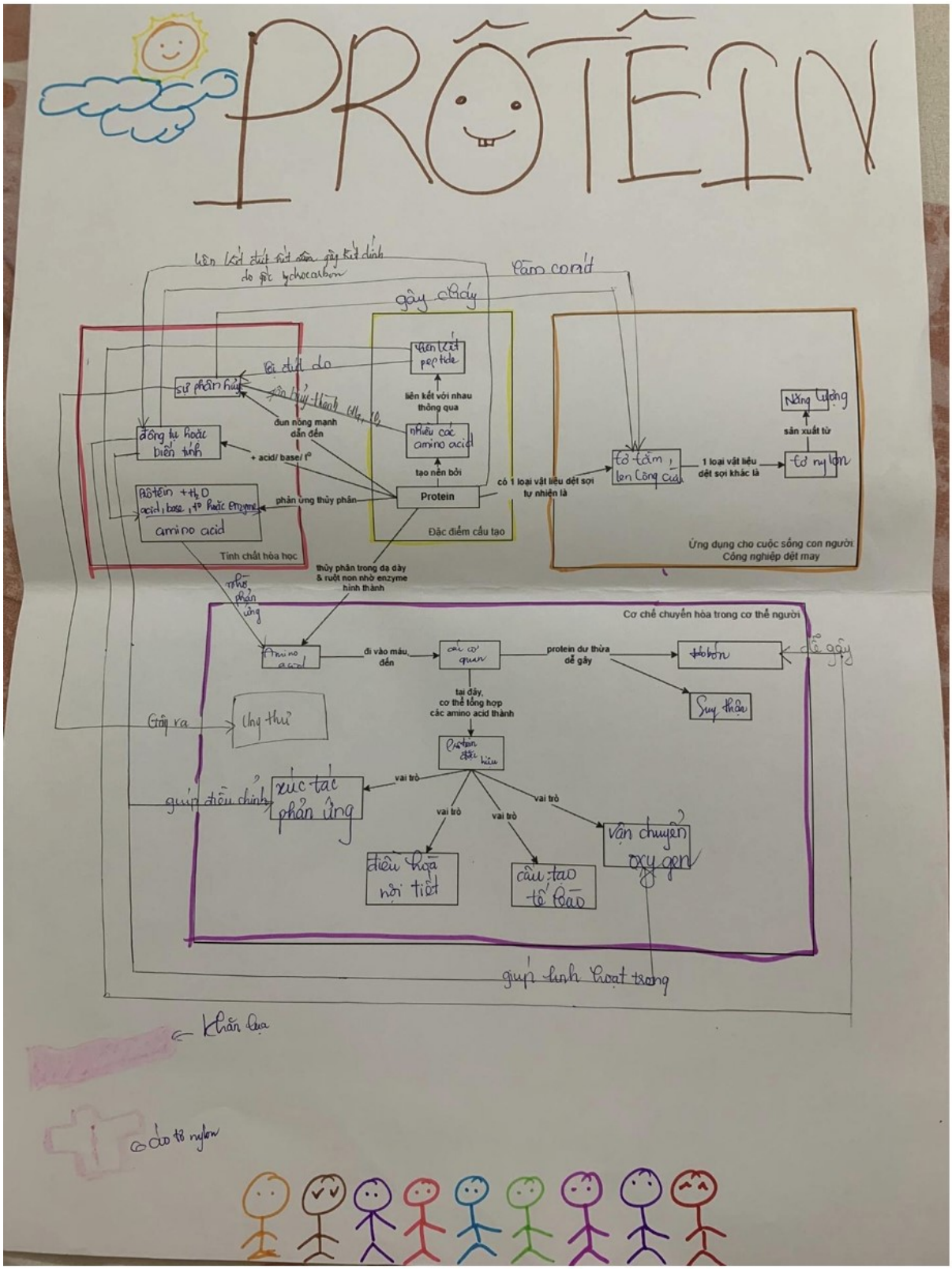

Môi trường
ô nhiễm MT
giảm bớt
tăng
Canh tác hữu cơ
Canh tác thông thường
Kinh tế
Sx nhanh
Giá rẻ
Sx chậm
Sản phẩm sạch
Giá cao
Thử tác dụng tinh bột
Báo quản tầu, không mốc
để kết hợp với chất khác
thành sp khác
Ứng dụng cho cuộc sống con người
Thực phẩm
Toàn phần: bột, gạo lứt, thóc...
Không: yến mạch nguyên chất
Tinh chế: bột, gạo trắng...
Tinh bột công nghiệp đồ ăn nhanh...
Tinh bột không: làm nguội, dễ tiêu nguội
Nguồn gốc tự nhiên
Đã qua chế biến
đã xử lý để giữ lại phần tinh bột
đã bị biến đổi tính chất qua nấu chín để nguội
Không có
Ko tan trong nc lạnh
Khó tiêu tinh bột
Iodine
Tạo màu xanh tím
mùi, vị
tác dụng nước nóng tạo
Tinh bột
phản ứng thủy phân
Tính chất lý hóa
Não
nguồn năng lượng chính của
xảy ra tại ruột non, hình thành
Glucose
duy trì
để cung cấp
năng lượng
tốt cho
tăng nhanh
cơ bắp
glucose dư thừa được gan chuyển thành
để thành mỡ thừa
ở mức tối đa chuyển thành
glycogen dự trữ
có nhiều dinh dưỡng
mất
Cơ chế chuyển hóa trong cơ thể
ST25
GẠO LỨT
Tinh Bột

# Cellulose




# Cellulose

**Protein – Local version**



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2. Karaarslan Semiz, G.; Teksöz, G., Developing the systems thinking skills of pre-service science teachers through an outdoor ESD course. *Journal of Adventure Education and Outdoor Learning* **2020,** *20* (4), 337-356.