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# Exploring Individual Differences in Photosynthesis and Respiration Knowledge

Abstract

A scientific conceptual understanding of photosynthesis and respiration provides an important basis for understanding nature and the regulations of life. Photosynthesis and respiration are complex processes, and learning about them requires a proper understanding of their various aspects, from molecular biology to the ecosystem level. This study explored conceptual understanding of and misconceptions about several fundamental aspects of photosynthesis and respiration. We also examined heterogeneity among students by identifying groups with different patterns of understanding of various aspects of the concepts. In all, 1310 students from the 7th through 11th grades answered 13 two-tier-type questions on various aspects of photosynthesis and respiration. Latent class analysis revealed four unique latent classes: high achievers, low achievers, moderate understanding of photosynthesis with low understanding of respiration, and moderate understanding of photosynthesis with varying understanding of respiration. More than 37% of the participants were assigned to the low achievers class, and less than 10% were assigned to the high achievers class. Respiration was less understood than photosynthesis. There were individual differences in class membership within grade levels; however, all four classes were present in all grade levels.

Keywords

Photosynthesis, Respiration, Misconceptions, Secondary education

## Introduction

Living is work, and work requires energy. Photosynthesis and cell respiration are the main cell metabolic processes used by almost all living things to produce and release energy, directly or indirectly. Therefore, they are among the most important processes studied in biology classrooms. Topics on photosynthesis and respiration in plants are included in school curricula worldwide (Australian Curriculum, Assessment and Reporting Authority, 2016; Çakir et al., 2002; Department for Education, 2015; Eisen & Stavy, 1993; Finnish National Agency for Education, 2017; Finnish National Agency for Education., 2019; Lin & Hu, 2003; Park et al., 2018; Skribe-Dimec & Strgar, 2017; TIMSS & PIRLS International Study Center, 2015; Yong & Kee 2017). Starting in primary school, pupils are taught to understand that not only animals but also plants are alive, too. In secondary school, these topics are taught in greater detail throughout several grades. Photosynthesis and respiration are fundamental processes in biology (Rakhmankulova, 2019). Thus, to understand life on Earth, a proper understanding of them is required (Janssen et al., 2014; Lumpe et al., 1995). Global problems like species extinction, deforestation and climate change are consequences of humankind's decisions, where proper biological understanding is not sufficiently considered. In addition, economic and political interests sometimes override biological understanding. Therefore, correct knowledge of photosynthesis and respiration in plants is an important basis for understanding the vulnerability of life and nature.

Photosynthesis and respiration are complex processes; therefore, learning about them requires a proper understanding of their various aspects (Neto et al., 2021). These biological topics can be described at the nano, micro, meso and macro scales (Goodsell et al., 2018; Pettersson et al., 2021) and from molecular biology to ecosystem points of view. At the molecular level, for instance, photosynthesis and respiration should be understood as biochemical reactions that take place in cells' special organelles, such as chloroplasts and mitochondria; these are processes in which chemical elements react. Additionally, it is important to understand that these processes are vital for every plant to obtain energy and food. Finally, they help maintain a stable ratio of oxygen and carbon dioxide on Earth and are the key mechanisms in food chains. All these perspectives are important, and comprehension of only some of them would inhibit a full conceptual understanding of the phenomenon as a whole. Furthermore, many misconceptions about these topics exist, and these misconceptions are stable and resistant to change (Çokadar, 2012; Jancaríková & Jancarík, 2022; Mikkilä-Erdmann, 2001; Authors, 2015). Misconceptions about photosynthesis and respiration can be found among different age groups (Skribe-Dimec & Strgar, 2017). Not only school students but also in-service teachers have serious misconceptions about these processes (Partosa et al., 2013). Overcoming persistent misconceptions does not happen by acquiring new pieces of knowledge.

Instead, it requires the restructuring of existing knowledge and beliefs—in other words, conceptual change (Vosniadou, 2012).

Few studies have examined students' conceptual understanding by considering all aspects of photosynthesis and respiration and their relationships. Although many studies have investigated misconceptions and conceptual change in biology among school and university students, there is almost no research on the heterogeneity of learners' understanding of the various aspects. Even within one class, the structure of students' conceptual understanding could vary. For complex concepts that include numerous interrelated aspects, conceptual change may occur through a variety of trajectories (e.g. Authors, 2015). However, little is known about the contributions of misconceptions and a lack of scientific knowledge to acquiring an adequate understanding of complex biological concepts, such as photosynthesis and respiration. Unobserved heterogeneity among learners could hinder the learning process and be an obstacle for teachers (Sinatra & Mason, 2008).

The aim of this study was to explore conceptual understanding of and misconceptions about several fundamental aspects of photosynthesis and respiration. In addition, we examined heterogeneity among students by identifying groups of learners with different patterns of understanding of various aspects of the concepts.

### *Misconceptions of Photosynthesis and Respiration*

Photosynthesis and respiration are closely related natural processes. A fully scientific and correct understanding of one of these processes is impossible without a complete understanding of the other. Understanding of photosynthesis and respiration has been widely investigated, taking into account their various aspects (Authors, 2023).

Various levels of misconceptions related to these processes have been reported among students of different ages. When it comes to photosynthesis, younger children often have a mistaken belief that plants eat through their roots (Roth, 1990). This misconception leads them to not recognise plants as autotrophic organisms (e.g. Mintzes & Wandersee, 2005). In fact, comprehending the energy transformation process in photosynthesis and respiration poses challenges for learners, from primary (Skribe-Dimec & Strgar, 2017) to secondary school (Balci et al., 2006; Marmaroti & Galanopoulou; 2006; Özay & Öztaş, 2003), and for teachers and student teachers (Authors, 2013) across Europe. In one study conducted at the secondary school level, the majority of students could not correctly explain the source of plant weight during plant growth, mentioning water and soil as sources, and only approximately one-fifth of the students were aware that plant weight increase is attributed to organic substances produced internally by the plants themselves (Özay & Öztaş, 2003). White and Maskiewicz (2014) reported similar results; only 10% of students could describe the role of cellular respiration in an energy and matter transformation process. This is not surprising, though; Partosa et al. (2013) studied 113 secondary in-service and pre-service teachers' conceptions related to photosynthesis and respiration, and both groups exhibited only a shallow and flawed understanding of these biological topics. On the other hand, in another study, pre-service elementary science teachers had difficulties in understanding the concept of respiration but had a strong understanding of photosynthesis (Akçay, 2017).

Another oft-reported misconception relates to inadequate understanding regarding the interrelations and differences of photosynthesis and cellular respiration processes. For instance, the two-tier test created by Haslam and Treagust (1987) was used to determine Australian 8th–12th graders' conceptual understanding of photosynthesis and respiration. The results showed that 8th–11th graders, and in some cases 12th graders, had very similar misconceptions about photosynthesis and respiration in plants. They were mainly mistaken about the nature and function of photosynthesis and respiration processes and their relationships. Several other studies have reported that the majority of secondary school students do not adequately understand the photosynthesis–respiration interrelationship (Marmaroti & Galanopoulou, 2006; Svandova, 2014). Brown and Schwartz (2009) revealed that pre-service elementary teachers could not explain the connection between respiration and photosynthesis in terms of matter cycle and energy. Furthermore, some studies have reported a misconception that plants respire only at night; the origin of this belief is presumably problems in understanding the interrelations of these two phenomena (Alparslan et al., 2003; Haslam & Treagust, 1987; Yenilmez & Tekkaye, 2006).

Other misconceptions found in studies regarding photosynthesis relate to chemical reactions, the role of chlorophyll (Marmaroti & Galanopoulou, 2006) and the location where photosynthesis takes place in a plant (Skribe-Dimec & Strgar, 2017) among secondary school students. In university-level introductory courses, results have shown a lack of basic understanding of photosynthesis, with students unable to correctly describe its role in plant metabolism (Parker, 2012). Other studies have reported similar results in the university context (Halim, 2018; Authors, 2015). Typically, only little age-related progress is reported for primary school pupils in understanding photosynthesis (Skribe-Dimec & Strgar, 2017). Barrutia and Ramón Díez (2019) showed that understanding of plant nutrition improves progressively among Spanish students from primary to upper secondary school; however, students in all age groups do not have a complete, scientific and correct understanding of plant nutrition (including photosynthesis), and even the oldest students have misconceptions.

Another study on pre-service science teachers' conceptual understanding of photosynthesis found that 93% had an insufficient understanding of photosynthesis, mainly about the products and reagents of the process (Karakaya et al., 2021). Urey (2018) found that pre-service teachers used one of two approaches to explain photosynthesis—biological or chemical—the majority giving priority to the chemical approach. Pre-service teachers who preferred a biological approach tended to have fewer misconceptions about photosynthesis than those who used the chemical explanation. Cakiroglu and Boone (2002) studied pre-service elementary teachers' conceptions of photosynthesis and reported that participants who had fewer misconceptions about photosynthesis tended to have high personal science teaching efficacy.

Separate studies evaluating the understanding of respiration have also been conducted. Al Khawaldeh and Olaimat (2010) investigated 11th graders' understanding of respiration. It was apparent that students struggled with the following aspects related to respiration: comparison between aerobic respiration and anaerobic fermentation, reactants in respiration and the energy production that occurs in plants and yeasts. Another typical misconception concerns the location of respiration: students have stated that respiration takes place only in plants' leaves because leaves have stomata and that, for animals, it occurs only in the respiratory system, in organs like the lung, gill and trachea. Even more students declared that plants respire only at night because they photosynthesise during the day and that these two processes are reversed versions of each other, as products of photosynthesis are reactants of respiration (Alparslan et al., 2003)

Probably the most common misconception related to cellular respiration is that it would be the same process as breathing (Fan et al., 2018; Rybarczyk et al., 2007). In addition, Songer and Mintzes (1994) found that college-level biology students thought that gas exchange and cellular respiration are the same processes and that plants do not respire at all.

***Present Study***

The above-described studies measured different aspects of photosynthesis and respiration but primarily presented averaged results regarding different variables that did not uncover qualitatively different subgroups among students. To overcome the limitations of traditional variable-centered analyses, this study applies a person-centered statistical analysis, namely latent class analysis (LCA). LCA belongs to a family of latent variable mixture models which aim to identify subgroups of individuals with similar patterns of responses on a single measure or across different measures (Hickendorff et al., 2018). Thus, individual differences within a group can be modelled as consistent patterns of performance within a set of coherent subgroups within that group. This contrasts with a variable-centered approach to statistical analysis that examines the relation between variables and provides mean values that are considered representative of the whole population. LCA and related analytic techniques have been used extensively in recent years to examine individual differences in students' conceptual knowledge in various domains, including science (e.g. Schneider & Hardy 2013). These approaches have been successful in uncovering hidden heterogeneity in students' performance on measures of conceptual knowledge that would be hidden using traditional variable-centered approaches and provided valuable insight into conceptual changes processes (Edelsbrunner et al., 2018; Schneider & Hardy, 2013). Thus, the present study examines students with different performances in various aspects of photosynthesis and plant respiration. In doing so, the study aims to answer the following research questions:

1. What are students' levels of success on a test measuring their understanding of aspects related to photosynthesis and respiration?

2. What kinds of latent classes of students are present based on their understanding of different aspects of photosynthesis and respiration?

    2.1. Which aspects of photosynthesis and respiration differentiate the different latent classes?

    2.2. How frequently do different latent classes occur among different grade levels?

## Methods

### *Participants*

A total of 1310 Lithuanian students participated in the study. It was conducted during the autumn semester of 2021. Students in the 7th, 8th, 9th, 10th and 11th grades participated. This included 174 (13.3%) 7th graders, 126 (9.6%) 8th graders, 372 (28.4%) 9th graders, 432 (33%) 10th graders and 206 (15.7%) 11th graders. A total of 57.8% were female and 42.2% were male, with a mean age of 15.1 (standard deviation [SD] = 1.98) years. This study was approved by the university's ethics committee (blinded for peer review). Parents were provided with an appropriate consent form (approved by the ethics committee) through mediation by school administrators. The form specified that they could withdraw their consent at any time without any consequences. Students could refuse to answer the test questions.

To reach a variety of participants, 17 schools from different Lithuanian counties (including large cities, small towns and rural areas) were selected. There were two steps in the selection procedure.

Initially, all university partner schools with students in the 7th to 11th grades were contacted, and 13 of the 94 partner schools agreed to participate. Additional schools were contacted, since these schools represented only 7 of the 10 counties. The second step involved sending invitations to 107 additional schools, and 7 of those schools accepted. All 10 counties in Lithuania were represented by the 20 schools. However, three schools refused to participate in the study when it commenced. Consequently, 17 schools from nine counties participated.

Traditionally, a sample size of more than 500 is considered sufficient for latent variable mixture models, although Wurpts and Geiser (2014) noted that with higher quality indicators, a smaller sample size may suffice. Therefore, our sample size complies with even the most rigorous LCA criteria.

***Measurements***

Two parts were included in the test. During the first part, students were asked to provide background information (grade, gender and age). The other component was a conceptual understanding test (Haslam & Treagust, 1987), which featured 13 two-tier questions covering a range of various aspects related to photosynthesis and respiration (Table 1). The test was created based on student misconceptions identified by examining the relevant literature, by student interviews and by student responses to open-ended questions (Treagust, 1986). A selection of items for photosynthesis and respiration aspects was based on the first tier. The students had to justify their answers after each question. A double-translation process was used for the preparation of the conceptual understanding test. First, the original English version (Haslam & Treagust, 1987) was translated into Lithuanian by an expert in biology. Second, another expert in biology translated the Lithuanian text back into English. The similarity to the original was checked. The Lithuanian translation was double-checked by two biology teachers and two biology scientists to ensure that all questions were suitable for Lithuanian curricula and updated according to the latest scientific research. Two Lithuanian schools were involved in the pilot test in 2021. In addition to taking the test, several students participated in semi-structured interviews to gain a deeper understanding of how they interpreted the questions. Based on the results of the pilot test and the students' comments, the final clarified Lithuanian version of the test was developed (please see the appendix), including all original test questions. The original version of the test had a Cohen's alpha of .72 (Haslam & Treagust, 1987). The Lithuanian version of the test had a reliability of .74. The reliabilities of the photosynthesis and respiration sub-tests were .63 and .69, respectively.

**Table 1**

*Aspects of the Test and Questions*

| Aspect | Questions |
|---|---|
| Photosynthesis is a process that occurs during light conditions. | 1, 4 |
| Photosynthesis inhibitors | 11 |
| Benefits of photosynthesis to a plant and ecosystem | 12, 10 |
| Respiration is an ongoing continuous process. | 2, 3, 8 |
| Respiration takes place in all plant cells. | 5 |
| The benefits of respiration to a plant and ecosystem | 7, 9 |
| Respiration in plants and animals | 6, 13 |

The study participants completed the test individually in front of their teachers during one lesson. One lesson was allotted for completing the test (45 minutes). At the first tier, the students were required to choose only one answer from several options. Among the answers, only one was scientifically correct; the rest were described as synthetic models or misconceptions (see Vosniadou, 2012). Taking the answers given in the first tier and analysing the logic behind them, the students were asked to explain why they chose the answers below in the second tier. Several answers were provided, but students could choose only one. The second tier contained only one scientifically correct answer; the rest were synthetic models or misconceptions. There was also an option for students to write their own short answers in the second tier.

### *Data Analysis*

The success rates in the photosynthesis and respiration tasks were compared using a one-sample t-test. LCA was used to analyse whether there were subgroups of students with different achievements (correct vs. incorrect) in the different tasks of the photosynthesis conceptual test. Two biologists familiar with photosynthesis and respiration concepts classified the conceptual understanding test answers as either correct or incorrect. Each question consisted of two parts (answer and explanation). Very few students used the option in the second tier to write an explanation in their own words. All these answers were evaluated individually by the authors and scored as correct or incorrect. The question was scored as correct only if both parts were answered correctly. Based on these categories (correct and incorrect), LCA was conducted. When using multiple-choice questions, there is always the possibility of random correct answers. Thus, scoring based on both parts of the questions is a more robust indicator. In addition, in a test focusing on conceptual change, it is insufficient to remember or be able to recocognise the correct answer; the combination of correct answer and relevant explanation for this answer is closer to what is meant by scientific knowledge.

Mplus version 8.0 was used to conduct the LCA (Muthén & Muthén, 1998–2017). Maximum likelihood was used with robust standard errors to estimate the model, which is a full information method capable of handling missing data. We used 1000 and 100 random start values in the first and second steps of the model estimation, respectively, to ensure the validity of the solution. To determine the most appropriate number of latent classes and the best-fitting model, statistical indicators and substantive theory were used together for model fit evaluation (Authors, 2018; Nylund et al., 2007). The number of classes was decided based on multiple fit values—Akaike Information Criteria (AIC), Bayesian Information Criteria (BIC), and Entropy—and likelihood ratio tests—the Bootstrapped Likelihood Ratio Test (BLRT) and Lo-Mendell-Rubin Likelihood Ratio Test (LMRT). An entropy value close to 1 indicates a higher level of certainty in the classification of individuals into classes, and lower AIC and BIC values indicate a better fit of the model to the data. The likelihood ratio tests that reach statistical significance suggest that the k-class model is more appropriate than the k-1-class model (e.g. a statistically significant result for the 4-class model suggests it is a better fit than the 3-class model).

Latent classes were cross-tabulated with grade levels (7–11), and the significance of the relationship between the frequencies was measured using the chi-squared test. Standardised residuals comparing the observed and expected frequencies are presented for each cell.

## Results

### *Student Success Rates*

The students' success in the test measuring their understanding related to photosynthesis and respiration and the differences in students' scores between different grades are presented in Table 2.

**Table 2**

*Average Success Rates in Photosynthesis and Respiration Tasks and Results of One-Sample t-Test*

| | 7th grade | 8th grade | 9th grade | 10th grade | 11th grade | Total |
|---|---|---|---|---|---|---|
| Photosynthesis | | | | | | |
| M (SD) | .57 (.23) | .60 (.27) | .63 (.23) | .64 (.23) | .69 (.25) | .63 (24) |
| Cronbach's α | .596 | .617 | .616 | .612 | .712 | .632 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Respiration | | | | | | |
| M (SD) | .46 (.15) | .50 (.21) | .48 (.18) | .49 (.19) | .54 (.20) | .49 (.19) |
| Cronbach's α | .468 | .740 | .636 | .681 | .725 | .668 |
| | | | | | | |
| t | 4.76 | 5.11 | 11.40 | 13.78 | 10.84 | 21.45 |
| df | 173 | 125 | 371 | 431 | 205 | 1309 |
| p< | .001 | .001 | .001 | .001 | .001 | .001 |

The reliabilities of the photosynthesis and respiration subscales were acceptable, with the exception of the respiration subscale among 7th graders. The success rate was higher in photosynthesis tasks than in respiration tasks, and the same significant difference was found for all grade levels. Success in the photosynthesis questions improved with grade level as expected. For the respiration questions, success improved steadily, except for 8th grade, which was more successful than grades 9 and 10.

### ***Latent Classes***

**Table 3**

*Fit Indices of the Models Differing in the Specified Number of Latent Classes*

| Number of classes | AIC | BIC | LMRT | BLRT | Entropy |
|---|---|---|---|---|---|
| 2 | 19376 | 19515 | .001 | .001 | .70 |
| 3 | 19006 | 19219 | .001 | .001 | .74 |
| 4 | 18900 | 19185 | .001 | .001 | .80 |
| 5 | 18850 | 19208 | .06 | .001 | .67 |
| 6 | 18817 | 19246 | .16 | .001 | .69 |
| 7 | 18800 | 19302 | .24 | .001 | .73 |

After estimating two- to seven-class solutions for the LCA, the most appropriate model was determined to be the four-class model (Table 3). First, the four-class solution held the minimum BIC value, though no minimum AIC was found. Second, the LMRT was not statistically significant for the five-class model, suggesting that it did not improve for the four-class model, though the BLRT remained statistically significant for all estimated models. Finally, differentiation in the classes and substantive theory were deemed sufficient to interpret the results (Authors, 2018). Four unique latent classes were identified: *high achievers, low achievers, moderate photosynthesis with low respiration (ModPhotLowResp)* and *moderate photosynthesis with varying respiration (ModPhotVaryingResp)* (Figure 1).

**Figure 1**

*Probability of a Correct Answer for the Latent Classes Based on All Dichotomous Items of the Conceptual Change Test.*

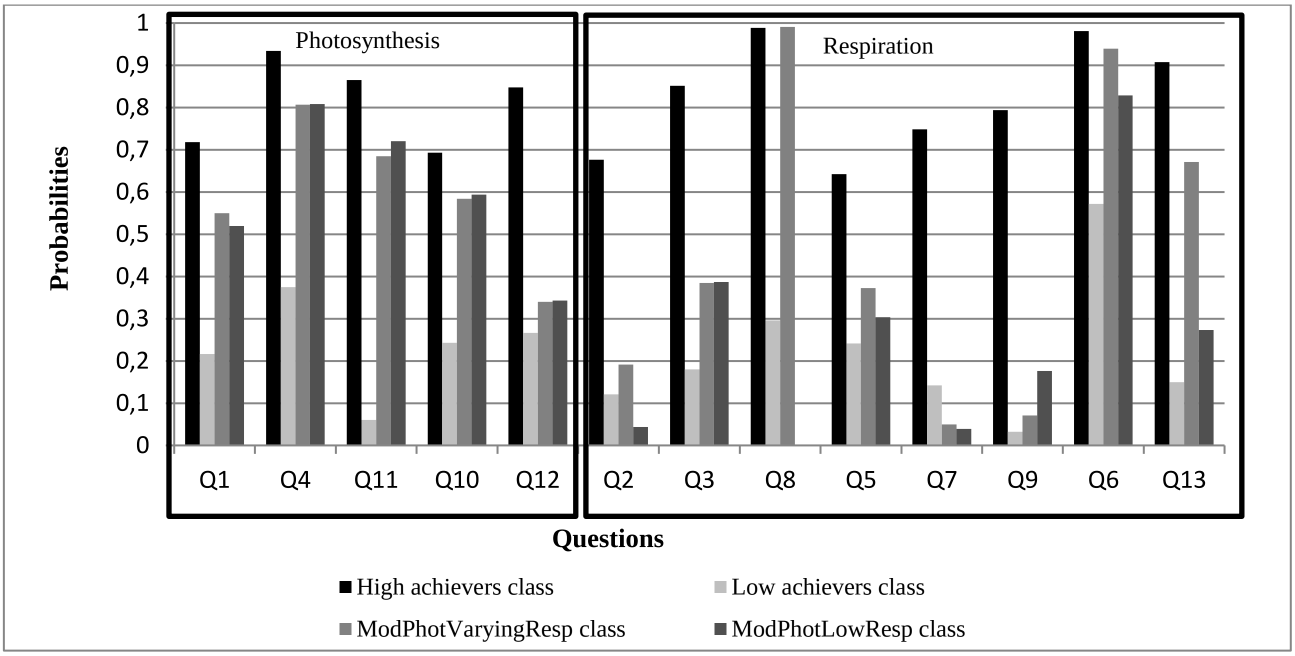


Figure 1 details the probabilities of a correct response for each item for the different latent classes. As can be seen, the *high achievers class* showed the best success rate among all latent classes. Students in this class tended to have a correct scientific understanding of photosynthesis and respiration processes according to almost all aspects. However, only 8.6% of the study's sample belonged to this class. The *low achievers class* was the opposite of the *high achievers class*. Students who belonged to this class tended to have an incorrect understanding of the photosynthesis and respiration processes; they showed a very low success rate on 12 of 13 questions. The *low achievers class* was the largest of the four classes, and 37.5% of the study population belonged to it. Two other classes, the *ModPhotVaryingResp class* and the *ModPhotLowResp class*, were located between the *high achievers class* and the *low achievers class*. The *ModPhotVaryingResp class* tended to have a correct scientific understanding of some aspects of the photosynthesis and respiration processes but an incorrect understanding of other aspects of these processes. The *ModPhotVaryingResp class* was the second-biggest class, followed by the *low achievers class*. Of the study participants, 32.9% were assigned to the *ModPhotVaryingResp class*. The *ModPhotLowResp class* was between the *ModPhotVaryingResp class* and the *low achievers class*. The *ModPhotLowResp class* tended to have a level of understanding of photosynthesis similar to that of the *ModPhotVaryingResp class* but a worse understanding of respiration compared to the *ModPhotVaryingResp class*. The

*ModPhotLowResp class* was the third-biggest class, following the *low achievers class* and *ModPhotVaryingResp class*. Among the participants, 21% were assigned to the *ModPhotLowResp class*.

### *Different Classes' Understanding of Photosynthesis*

The *high achievers class* showed a high level of conceptual understanding of photosynthesis in all questions. Only in Q10, related to the benefit of photosynthesis, the *high achievers class* tended to have a slightly lower success rate (69%) than in other questions. However, in Q12, dedicated to the same aspect, the success rate was higher. The *low achievers class* showed a very low success rate for all questions related to photosynthesis. An extremely low success rate, less than 6%, was observed for Q11, which was related to the aspect of photosynthesis inhibitors.

The *ModPhotVaryingResp class* had a 55% and 81% chance, respectively, of correctly answering Q1 and Q4 about photosynthesis as a process during light conditions. Linking the success rate to Q1 and Q4, this class had a 45% chance of getting both questions right. This class also had a 69% chance of choosing the correct answer to Q11, which was dedicated to photosynthesis inhibitors, and a 58% chance of correctly answering Q10, which was related to the benefits of photosynthesis. However, this class had a 34% chance of correctly answering Q12, which was also dedicated to the benefits of photosynthesis. Linking the success rate to Q10 and Q12, the *ModPhotVaryingResp class* had a 20% chance of getting both questions right.

The *ModPhotLowResp class* had a very similar success rate for all questions related to photosynthesis. Q4, Q10 and Q12 yielded the same success rates as in the *ModPhotVaryingResp class.* The success rates for Q1 and Q11 were not the same, but the difference was only approximately 5%. Therefore, the *ModPhotVaryingResp class* and the *ModPhotLowResp class* were very similar regarding their understanding of photosynthesis.

### *Different Classes' Understanding of Respiration*

The *high achievers class* exhibited an overall good conceptual understanding of respiration. However, it did not perfectly understand that respiration in plants takes place in all cells; the success rate for Q5 was 64%. In Q2 and Q7, related to aspects of respiration as an ongoing continuous process and the benefits of respiration, slightly lower success rates than for other questions were noted at 68% and 75%, respectively. However, other questions dedicated to the same aspects maintained a very high success rate, and Q2 and Q7 were still answered at quite a high rate compared to the other classes.

The *low achievers class* showed a very low success rate for all questions about respiration. The only question answered at a slightly higher rate was Q6, which was related to the aspect of respiration taking place in all living creatures; the success rate was 57%. However, Q13 was also dedicated to this aspect, and it had a low correct answer rate of 15%. Linking the success rate to Q6 and Q13, this class had a 9% chance of getting both questions right. The *low achievers class* tended to have an extremely low success rate with Q9, which was related to the aspect of the benefits of respiration; less than 4% chance to answer correctly. Q7, also dedicated to the benefits of respiration, had a 14% chance of being answered correctly. Other questions dedicated to the aspects of respiration as an ongoing continuous process and as occurring in all plant cells had less than a 30% chance of being answered correctly by the *low achievers class*.

The *ModPhotVaryingResp class* tended to have a correct scientific understanding of some aspects of the respiration processes but an incorrect understanding of others. This class showed a good scientific understanding that respiration takes place in all living creatures, with high success rates for Q6 and Q13. However, two other aspects, respiration as a process taking place in all plant cells and the benefits of respiration, tended to be poorly understood by the *ModPhotVaryingResp class*. Q5, related to the aspect of respiration as a process taking place in all plant cells, had a 37% chance of being answered correctly. Q7 and Q9 on the benefits of respiration both had less than an 8% chance of being answered correctly. Three questions related to the aspect of respiration as an ongoing continuous process tended to be answered at different success rates. The *ModPhotVaryingResp class* had a 20% and 38% chance of answering Q2 and Q3 correctly, respectively. However, this class had a 99% chance of correctly answering Q8, which was dedicated to the same aspect (gas exchange and cellular respiration at different times of the day and under different lighting conditions). Nevertheless, although the general topic was the same, the formulation of this particular item (Q8) made it presumably easier to answer correctly compared to Q2 and Q3.

The *ModPhotLowResp class* tended to have a very low success rate for questions related to all aspects of respiration. This class had a 30% chance of correctly answering Q5, which was dedicated to the aspect of respiration as a process taking place in all plant cells. Q7 and Q9, which were related to the benefits of respiration to a plant, respectively had a 4% and 18% chance of being answered correctly. The aspect about respiration as an ongoing continuous process tended to be poorly understood by the *ModPhotLowResp class*; Q2, Q3 and Q8 had a 4%, 39% and 0% chance, respectively, of being answered correctly. Q6 and Q13, dedicated to the aspect of respiration in plants and animals, had an 83% and 27% chance of being answered correctly. Linking the success rate to Q6 and Q13, there was a 22% chance that both questions related to the aspect respiration as a process in plants and animals were answered correctly by the *ModPhotLowResp class*.

***Relationship between Latent Classes and Grade Levels***

**Table 4**

*Percentages and Standardised Residuals (Std. Res.) of the Most Likely Class Memberships by Grade Level*

| Class | 7th grade % (Std. Res.) | 8th grade % (Std. Res.) | 9th grade % (Std. Res.) | 10th grade % (Std. Res.) | 11th grade % (Std. Res.) |
|---|---|---|---|---|---|
| *High achievers class* | **1.7** | 11.2 | 8.6 | 8.9 | 11.8 |
| | **(-3.1)** | (1.0) | (0.1) | (0.3) | (1.5) |
| *ModPhotVaryingResp class* | 35.6 | 36.8 | 31.4 | 30.6 | 40.6 |
| | (0.5) | (0.6) | (-0.7) | (-1.1) | (1.7) |
| *Low achievers class* | **47.1** | 42.4 | 39.7 | 34.4 | 29.9 |
| | **(2.0)** | (0.9) | (0.6) | (-1.2) | (-1.7) |
| *ModPhotLowResp class* | 15.5 | **9.6** | 20.4 | **26.2** | 17.6 |
| | (-1.4) | **(-2.7)** | (0.0) | **(2.8)** | (-0.8) |

There was an overall small (effect size Phi = .185) but significant relationship between the latent classes and grade level, X2 (12, N = 1310) = 44.881, $p < .001$. There were individual differences in class membership within grade levels (Table 4). All grades contained all four classes. The largest percentage of students in almost all grades was in the *low achievers class*. Among the 11th graders, the largest proportion of these students belonged to the *ModPhotVaryingResp class*, followed by the *low achievers class*. In almost all grades, the percentage of students in the *high achievers class* was the smallest, except the 8th grade, where the smallest class was the *ModPhotLowResp class*, followed by the *high achievers class*. The second-most frequent class in all grades was the *ModPhotVaryingResp class*, except for the 11th grade. The third-most frequent class was the *ModPhotLowResp class*, except for the 8th grade.

Based on the standardised residuals, the frequency of the *high achievers class* was smaller than expected in the 7th grade (standardised residual = -3.1). In addition, the frequency of the *low achievers class* was higher than expected (standardised residual = 2) in the 7th grade. The frequency of the *ModPhotLowResp class* was smaller than expected in the 8th grade (standardised residual = -2.7) but higher than expected in the 10th grade (standardised residual = 2.8).

**Discussion**

This study was conducted to reveal unobserved heterogeneity among 7th–11th graders' knowledge of various aspects of photosynthesis and respiration. Students' conceptual understanding of these phenomena was evaluated using a two-tier test that included 13 basic questions and explanations of different aspects of photosynthesis and respiration knowledge. The results showed a clear difference in the difficulty of the photosynthesis and respiration tasks. In all grade levels, from 7th to 11th, the students' success rates in the photosynthesis tasks were significantly higher than in the respiration tasks.

The LCA identified four unique latent classes, all of which had differing characteristics according to the conceptual understanding of photosynthesis and respiration. The *high achievers class* demonstrated a very high success rate in all questions. In contrast, the *low achievers class* showed a very low success rate for all questions. The other two classes were placed between these two. The *ModPhotVaryingResp class* and the *ModPhotLowResp class* indicated lower success rates than the *high achievers class* but higher success rates than the *low achievers class*. The success rate for photosynthesis-related questions was similar across both classes; however, there was a different success rate for respiration-related questions. The *ModPhotVaryingResp class* exhibited a higher success rate in respiration-related questions than that of the *ModPhotLowResp class*. The LCA also showed that photosynthesis questions were better understood than respiration questions.

Considering the poor scores for the respiration questions, it could be argued that most students did not understand the basic idea of cellular respiration. The possibility of answering the questions correctly was quite small for three of the four identified latent classes, which consisted of more than 90% of the students. The results showed that even though some of the students tended to have a correct scientific understanding overall, this proportion made up only less than one-tenth of the study population. In contrast, two-fifths of students were assigned to the latent class that had a mostly incorrect understanding of all investigated aspects of photosynthesis and respiration.

The *ModPhotVaryingResp* and the *ModPhotLowResp classes* comprised more than half of the study population. These two latent classes showed similar success rates across a portion of the test questions. Most of the students belonging to the *ModPhotVaryingResp class* or the *ModPhotLowResp* *class* had a correct conceptual understanding of two aspects—photosynthesis as a process during light conditions and photosynthesis inhibitors. By contrast, the aspects of respiration as a process taking place in all plant cells and the benefits of respiration tended to be misunderstood by the students belonging to the *ModPhotVaryingResp class* and the *ModPhotLowResp class*. However, responses to other questions measuring understanding of different aspects differed between the *ModPhotVaryingResp class* and the *ModPhotLowResp class*. Even though the aspect regarding respiration as a process taking place in plants and animals tended to be correctly understood by the *ModPhotVaryingResp class*, understanding of this aspect among the *ModPhotLowResp clas*s varied depending on the formulation of the question. While the aspect of respiration as an ongoing continuous process tended to be poorly understood by the *ModPhotLowResp class*, the understanding of the *ModPhotVaryingResp clas*s varied depending on the formulation of the questions. Finally, understanding of the benefits of photosynthesis varied depending on the formulation of the questions for both latent classes.

The results showed that most students could answer some questions correctly but failed to answer others, even if the questions were dedicated to the same aspect of photosynthesis or respiration. Analysis of the questions' structures revealed that students correctly answered the questions that asked about a certain aspect in a direct way (see appendix  for question structure). For example, for Q8 ('When do green plants respire?'), the *ModPhotVaryingResp class* tended to answer correctly. However, Q2 and Q3, dedicated to the same aspect, were formulated in a different way, requiring students to use critical thinking and apply their knowledge (Q2: 'Which gas is taken in by green plants in large amounts when there is no light energy at all?' and Q3: 'Which gas is given off by green plants in large amounts when there is no light energy at all?'). The success rates for these questions were low among the *ModPhotVaryingResp class*. Hence, we hypothesise that this tendency to answer direct questions correctly but more complicated questions incorrectly may indicate rote memorisation. This is in alignment with several previous studies showing that rote memorisation of given information alone is insufficient for conceptual understanding (Grove & Bretz, 2012; Schönborn & Anderson, 2008). Indeed, rote learning could even lead to misconceptions, despite many students believing that it is the only way to learn science (Cavallo et al., 2003).

Some aspects were understood worse than others, with the benefit of respiration being the worst understood aspect overall. There may be several reasons for this. First, the tendency to not understand the main benefit of respiration as the release of energy may be related to misconceptions about energy in general. A possible cause of this misconception may be difficulties in understanding the relationship between 'energy' and 'food' concepts (Balci et al., 2006). Second, concepts of ‘respiration’ and ‘breathing’ are often used simultaneously, without understanding that they are different, though closely related, processes. Teachers often use them simultaneously, too, which could easily lead students to adopt this misconception (Seymour & Longden, 1991). Furthermore, the majority of students interpreted respiration as a gas exchange process only, and some pre-service teachers have the same misconception as well (Susanti, 2017). In our study, the largest proportion of students tended to state that respiration only takes place in leaf cells. The source of this misconception could be the Lithuanian biology textbook typically used in schools. In this book, an illustration of the respiration process depicts a leaf, not the whole plant. This is in alignment with prior research that found that how concepts are presented in textbooks could be a source of misconceptions (Barrass, 1984; King, 2010; Widiyatmoko & Shimizu, 2018).

Many students had high achievement in many of the tasks of the test, but only a small number of students understood all the fundamental aspects related to photosynthesis and plant respiration. The largest portion of students did not understand the benefits of respiration and photosynthesis for the ecosystem and for plants themselves. In addition, some students did not have a clear understanding of respiration as a process taking place in plants and animals. Briefly, the largest portion of students did not seem to understand the crucial role played by photosynthesis in the ecosystem and in plants themselves with regard to nourishment and oxygen supply. This is in alignment with Tekkaya and Yenilmez (2006), who found that 8th graders responded correctly to only about half of test questions, indicating a low level of conceptual understanding of photosynthesis and respiration.

All four latent classes were found for all grade levels (7–11), but the distribution of latent classes among the grades differed. Only a few 7th graders belonged to the *high achievers class*. The majority of students of all grades belonged to the *low achievers class,* except 11th graders, where the majority of the students belonged to the *ModPhotVaryingResp class*. The smallest latent class was the *high achievers class* among all grades, except grade 8, where the smallest latent class was the *ModPhotLowResp class*. According to the findings, students’ understanding of photosynthesis and respiration improved with additional years of schooling. Surprisingly, the number of students in the *high achievers class* did not significantly increase after the 8th grade. This finding requires research into what happens after the 8th grade that prevents students from moving towards a better conceptual understanding of photosynthesis and respiration.

### *Pedagogical Implications*

Our findings could be useful for teachers and researchers in indicating which aspects are more complicated and require particular attention in teaching and in creating teaching interventions. In addition, teachers should consider the unobserved heterogeneity among students that exists in their classrooms. Students belonging to different latent classes have various levels of understanding of a topic and should be taught according to these levels. A personalised learning approach could be used to meet students' different needs (Shemshack & Spector, 2020). Furthermore, it is a valuable tool for ensuring a desirable conceptual understanding (Srisawasdi & Panjaburee, 2017). In biology, most school and even university assessment tasks check only factual knowledge and not conceptual understanding (Wood, 2002). Therefore, teachers should create new assessment tasks that require critical thinking and knowledge application, even when fact-oriented courses are still widely in use (Wood, 2009).

Biology is a discipline that requires a systemic understanding of how various levels of systems are related (Momsen et al., 2022; Verhoeff et al., 2018). These levels range from the smallest ones, such as molecules and cells, to the largest ones, such as populations and ecosystems. Nevertheless, when teaching biology, a systemic understanding is often ignored, and the main goal is memorisation (Plate, 2010). This does not allow a proper understanding of ecological problems, such as climate change, species extinction and air, water and soil pollution (Simon, 2006). In teaching, more attention should be paid to the interconnectedness of biological phenomena. This could help foster a generation that can better deal with environmental issues.

### *Limitations*

The results outlined in this study are constrained by factors that must be taken into consideration when generalising and interpreting them. In the study population, there was an imbalance between the different age groups. In addition, since a greater number of schools were contacted than agreed to participate, it is impossible to know whether there were systematic reasons for participation that could have influenced the results. Third, only some of the photosynthesis and respiration questions had the same wording. Thus, other factors aside from the biological topic could have influenced students' success rates. Fourth, the subscale for respiration had very low reliability among the 7th graders. This must be taken into account when interpreting the results. Fifth, scientific knowledge about complex phenomena such as photosynthesis and respiration consist of many parts, and the different aspects of the conceptual knowledge may be differently emphasised during the many years when these topics are taught. Even high proficiency in some of these aspects does not mean that the student can correctly answer questions dealing with some other aspect of the knowledge. Finally, the study was limited to one country, and it is important to repeat the study elsewhere.

### *Conclusions and Future Studies*

This study revealed that students have different levels of conceptual understanding of various aspects of fundamental biological concepts, such as photosynthesis and respiration, with the majority of students having a very poor understanding. The findings increase our understanding of the heterogeneity of students and provide insight into the exact differences in students' understanding. The study contributes to a growing body of empirical research indicating that a systemic and holistic understanding is crucial for grasping biological phenomena; however, an approach enabling this is not widely implemented by schools. A deeper scientific understanding of conceptual development over time and during the school years will require longitudinal studies (e.g. analysis of latent transition as in Schneider & Hardy, 2013). In the future, research should be extended to verify and possibly expand the results. Finally, providing opportunities for students to develop their conceptual understanding is an important next step. These can be implemented while creating and testing learning interventions intended to overcome common misunderstandings and to support groups of students belonging to different latent classes.

## References

Akçay, S. (2017) Prospective elementary science teachers' understanding of photosynthesis and cellular respiration in the context of multiple biological levels as nested systems. *Journal of Biological Education*, *51*(1), 52-65. https://doi.org/10.1080/00219266.2016.1170067

Al Khawaldeh, S. A., & Al Olaimat, A. M. (2010). The contribution of conceptual change texts accompanied by concept mapping to eleventh-grade students understanding of cellular respiration concepts. *Journal of Science Education and Technology*, *19*, 115–125. https://doi.org/10.1007/s10956-009-9185-z

Alparslan, C., Tekkaya, C. & Geban, Ö. (2003) Using the conceptual change instruction to improve learning. *Journal of Biological Education*, *37*(3), 133-137. https://doi.org/10.1080/00219266.2003.9655868

Australian Curriculum, Assessment and Reporting Authority (ACARA) (2016). *Senior secondary curriculum*. Sydney. https://www.australiancurriculum.edu.au/senior-secondary-curriculum/science/earth-and-environmental-science/?unit=Unit+2&cd=ACSES053&searchTerm=renewable+energy#dimension-content

Authors, 2013 (blinded for review)

Authors, 2015 (blinded for review)

Authors, 2015 (blinded for review)

Authors, 2018 (blinded for review)

Authors, 2023 (blinded for review)

Balci, S., Cakiroglu, J., & Tekkaya, C. (2006). Engagement, exploration, explanation, extension and evaluation (5E) learning cycle and conceptual change text as learning tools. *Biochemistry and Molecular Biology Education*, *34*(3), 199–203. https://doi.org/10.1002/bmb.2006.49403403199

Barrass, R. (1984). Some misconceptions and misunderstandings perpetuated by teachers and textbooks of biology. *Journal of Biological Education*, *18*(3), 201-206. https://doi.org/10.1080/00219266.1984.9654636

Barrutia, O., & Ramón Díez, J. (2019). 7 to 13-year-old students' conceptual understanding of plant nutrition: should we be concerned about elementary teachers' instruction? *Journal of Biological Education*, *55*(2), 196-216. https://doi.org/10.1080/00219266.2019.1679655

Brown, M. H., & Schwartz, R. S. (2009). Connecting photosynthesis and cellular respiration: Preservice teachers' conceptions. *Journal of Research in Science Teaching*, *46*(7), 791-812. https://doi.org/10.1002/tea.20287

Çakir, Ö. S., Geban, Ö. & Yürük, N. (2002). Effectiveness of conceptual change text-oriented instruction on students' understanding of cellular respiration concepts. *Biochemistry and Molecular Biology Education*, *30*, 239–243. https://doi.org/10.1002/bmb.2002.494030040095

Cakiroglu, J., & Boone, W. J. (2002). Preservice elementary teachers' self-efficacy beliefs and their conceptions of photosynthesis and inheritance. *Journal of Elementary Science Education*, *14*(1), 1-14. https://doi.org/10.1007/BF03174733

Cavallo, A. M., Rozman, M., Blickenstaff, J., & Walker, N. (2003). Learning, reasoning, motivation, and epistemological beliefs. *Journal of College Science Teaching*, *33*(3), 18-23. https://www.researchgate.net/publication/285323458_Learning_reasoning_motivation_and_epistemological_beliefs

Çokadar, H. (2012). Photosynthesis and respiration processes: Prospective teachers' conception levels. *Education and Science*, *37*(164), 82–94. https://www.researchgate.net/publication/285932059_Photosynthesis_and_Respiration_Processes_Prospective_Teachers'_Conception_Levels

Department for Education (2015). *National curriculum in England: science programmes of study*. Manchester. https://www.gov.uk/government/publications/national-curriculum-in-england-science-programmes-of-study/national-curriculum-in-england-science-programmes-of-study

Edelsbrunner, P. A., Schalk, L., Schumacher, R., & Stern, E. (2018). Variable control and conceptual change: A large-scale quantitative study in elementary school. *Learning and Individual Differences*, *66*, 38-53,. https://doi.org/10.1016/j.lindif.2018.02.003

Eisen, Y., & Stavy, R. (1993). How to make the learning of photosynthesis more relevant. *International Journal of Science Education*, *15*(2), 117-125.

Fan, L. C., Salleh, S., & Laxman, K. (2018). Embedding video technology in enhancing the understanding of the biology concept of breathing: A Brunei perspective. *E-Learning and Digital Media*, *15*(5), 217–234. https://doi.org/10.1177/2042753018797260

Finnish National Agency for Education. (2017). *National Core Curriculum for Basic Education for Adults*. Helsinki. https://www.oph.fi/en/statistics-and-publications/publications/national-core-curriculum-basic-education-adults-2017

Finnish National Agency for Education. (2019). *National core curriculum for general upper secondary education 2019*. Helsinki. https://verkkokauppa.oph.fi/EN/page/product/national-core-curriculum-for-general-upper-secondary-education-2019/2763815

Goodsell, D. S., Franzen, M. A. & Herman, T. (2018). From Atoms to Cells: Usimg Meso scale landscapesto vconstruct Visual Narratives, *Journal of molecular biology*, 430, (21), 3954–3968.

Grove, N. P., & Bretz, S. L. (2012). A continuum of learning: From rote memorization to meaningful learning in organic chemistry. *Chemistry Education Research and Practice, 13*(3), 201-208. https://doi.org/10.1039/C1RP90069B

Halim, A. S., Finkenstaedt-Quinn, S. A., Olsen, L. J., Gere, A. R., & Shultz, G. V. (2018). Identifying and remediating student misconceptions in introductory biology via writing-to-learn assignments and peer review. *CBE—Life Sciences Education*, *17*(2), Article 28. https://doi.org/10.1187/cbe.17-10-0212

Haslam, F. & Treagust, D. F. (1987) Diagnosing secondary students' misconceptions of photosynthesis and respiration in plants using a two-tier multiple choice instrument. *Journal of Biological Education*, *21*(3), 203-211. https://doi.org/10.1080/00219266.1987.9654897

Hickendorff, M., Edelsbrunner, P. A., McMullen, J., Schneider, M., & Trezise, K. (2018). Informative Tools for Characterizing Individual Differences in Learning: Latent Class, Latent Profile, and Latent Transition Analysis. *Learning and Individual Differences,* 66. https://doi.org/10.17605/OSF.IO/JMTCV

Jancaríková, K. & Jancarík, A. (2022). How to teach photosynthesis? A review of academic research. *Sustainability*, *14*(20), Article 13529. https://doi.org/10.3390/su142013529

Janssen, P. J., Lambreva, M. D., Plumeré, N., Bartolucci, C., Antonacci, A., Buonasera, K., Frese, R. N., Scognamiglio, V., & Rea, G. (2014). Photosynthesis at the forefront of a sustainable life. *Frontiers in Chemistry*, *2*(36). https://doi.org/10.3389/fchem.2014.00036

Karakaya, F., Yilmaz, M., & Aka, E. I. (2021). Examination of Pre-Service Science Teachers' Conceptual Perceptions and Misconceptions about Photosynthesis. *Pedagogical Research*, *6*(4), Article em0104. https://doi.org/10.29333/pr/11216

King, C. J. H. (2010). An analysis of misconceptions in science textbooks: Earth science in England and Wales. *International Journal of Science Education*, *32*(5), 565-601. https://doi.org/10.1080/09500690902721681

Lin, C. Y. & Hu, R. (2003). Students' understanding of energy flow and matter cycling in the context of the food chain, photosynthesis, and respiration. *International Journal of Science Education*, *25*(12), 1529-1544. https://doi.org/10.1080/0950069032000052045

Lumpe, A. T., & Staver, J. R. (1995). Peer collaboration and concept development: Learning about photosynthesis. *Journal of Research in Science Teaching*, *32*(1), 71–98. https://doi.org/10.1002/tea.3660320108

Marmaroti, P., & Galanopoulou, D. (2006). Pupils' understanding of photosynthesis: A questionnaire for the simultaneous assessment of all aspects. *International Journal of Science Education*, *28*(4), 383–403. https://doi.org/10.1080/09500690500277805

Mikkilä-Erdmann, M. (2001). Improving conceptual change concerning photosynthesis through text design. *Learning and Instruction*, *11*(3), 241–257. https://doi.org/10.1016/S0959-4752(00)00041-4

Mintzes, J. J. & Wandersee, J. H. (2005). Research in science teaching and learning: A human constructivist view. In J. J. Mintzes, J. H. Wandersee & J. D. Novak (Eds.), *Teaching science for understanding: A human constructivist view* (pp. 59–92). Academic Press.

Momsen, J., Speth, E. B., Wyse, S., & Long, T. (2022). Using systems and systems thinking to unify biology education. *CBE—Life Sciences Education*, *21*(2). https://doi.org/10.1187/cbe.21-05-0118

Neto, M. C. L., Carvalho, F. E. L., Souza, G. M., & Silveira, J. A. G. (2021). Understanding photosynthesis in a spatial–temporal multiscale: The need for a systemic view. *Theoretical and Experimental Plant Physiology*, *33*, 113–124. https://doi.org/10.1007/s40626-021-00199-w

Nylund, K. L., Asparouhov, T., & Muthén, B. O. (2007). Deciding on the number of classes in latent class analysis and growth mixture modeling: A Monte Carlo simulation study. *Structural equation modeling: A multidisciplinary Journal*, *14*(4), 535-569. https://doi.org/10.1080/10705510701575396

Özay, E., & Öztaş, H. (2003). Secondary students' interpretations of photosynthesis and plant nutrition. *Journal of Biological Education*, *37*(2), 68–70. https://doi.org/10.1080/00219266.2003.9655853

Park, S., Suh, J. & Seo, K. (2018). Development and validation of measures of secondary science teachers' PCK for teaching photosynthesis. *Research in Science Education*, *48*, 549–573 .https://doi.org/10.1007/s11165-016-9578-y

Parker, J. M., Anderson, C. W., Heidemann, M., Merrill, J., Merritt, B., Richmond, G., & Urban-Lurain, M. (2012). Exploring undergraduates' understanding of photosynthesis using diagnostic question clusters. *CBE—Life Sciences Education*, *11*(1), 47-57. https://doi.org/10.1187/cbe.11-07-0054

Partosa, J. D., Clores, M. A., Conde, M. A. A., Prudente, M. S., Goingo, L. T., & Reganit, A. R. (2013). Secondary in-service teachers and pre-service teachers conceptual understanding of photosynthesis: A cross regional study. *US-China Education Review*, *3*(8), 636-645. https://doi.org/ n497qg0xjy/1267259

Pettersson, A., Tibell, L. A. E. & Löfgren, R. (2021). *The brain needs nutrition: pupils´connention between organizational levels. Nordic Studies in Science Education*, *17*(1), 48–63. https://doi.org/10.5617/nordina.7930

Plate, R. (2010). Assessing individuals' understanding of nonlinear causal structures in complex systems. *System Dynamics Review*, *26* (1), 19–33. https://doi.org/10.1002/sdr.432

Rakhmankulova, Z. F. (2019). Physiological Aspects of Photosynthesis–Respiration Interrelations. *Russian Journal of Plant Physiology*, *66*(3), 365–374. https://doi.org/10.1134/S1021443719030117

Roth, K. (1990). Developing meaningful conceptual understanding in science. In B. Jones & L. Idol (Eds.), *Dimensions of thinking and cognitive instruction* (pp. 139–175). Erlbaum.

Rybarczyk, B. J., Baines, A. T., McVey, M., Thompson, J. T., & Wilkins, H. (2007). A case-based approach increases student learning outcomes and comprehension of cellular respiration concepts. *Biochemistry and Molecular Biology Education*, *35*(3), 181-186. https://doi.org/10.1002/bmb.40

Schneider, M., & Hardy, I. (2013). Profiles of inconsistent knowledge in children's pathways of conceptual change. *Developmental Psychology*, *49*(9), 1639–1649. https://doi.org/10.1037/a0030976

Schönborn, K. J., & Anderson, T. R. (2008). Bridging the educational research-teaching practice gap. *Biochemistry and Molecular Biology Education*, *36*(5), 372-379. https://doi.org/10.1002/bmb.20230

Seymour, J., & Longden, B. (1991). Respiration—that's breathing isn't it? *Journal of Biological Education*, *25*(3), 177–183. https://doi.org/10.1080/00219266.1991.9655203

Shemshack, A., Spector, J. M. (2020). A systematic literature review of personalized learning terms. *Smart Learning Environments*, *7*, Article 33. https://doi.org/10.1186/s40561-020-00140-9

Simon, S. (2006). Systemic educational approaches to environmental issues: The contribution of ecological art. *Systemic Practice and Action Research*, *19*, 143–157. https://doi.org/10.1007/s11213-006-9008-6

Sinatra, G., & Mason, L. (2008). Beyond knowledge: Learner characteristics influencing conceptual change. In S. Vosniadou (Ed.), *International handbook on conceptual change research* (pp. 560–582). Routledge.

Skribe-Dimec, D., & Strgar, J. (2017). Scientific conceptions of photosynthesis among primary school pupils and student teachers of biology. *CEPS Journal*, *7*(1), 49-68. https://doi.org/10.26529/cepsj.14

Songer, C. J., & Mintzes, J. J. (1994). Understanding cellular respiration: An analysis of conceptual change in college biology. *Journal of Research in Science Teaching*, *31*(6), 621-637. https://doi.org/10.1002/tea.3660310605

Srisawasdi, N., & Panjaburee, P. (2017, November). A development of supervised-online personal learning environment: Examining factors affecting self-directed learning and conceptual understanding progression [Paper presentation]. 6th IIAI International Congress on Advanced Applied Informatics (IIAI-AAI) 2017, Hamamatsu, Japan. https://doi.org/10.1109/IIAI-AAI.2017.67.

Susanti, R. (2017). Misconception of biology education student of teacher training and education of Sriwijaya University to the concept of photosynthesis and respiration. *Journal of Physics: Conference Series*, *1022*(1), Article 012056. https://doi.org/10.1088/1742-6596/1022/1/012056

Svandova, K. (2014). Secondary school students' misconceptions about photosynthesis and plant respiration: Preliminary results. *Eurasia Journal of Mathematics, Science and Technology Education, 10*(1), 59-67. https://doi.org/10.12973/eurasia.2014.1018a

Tekkaya, C., & Yenilmez, A. (2006). Relationships among measures of learning orientation, reasoning ability, and conceptual understanding of photosynthesis and respiration in plants for grade 8 males and females. *Journal of Elementary Science Education*, *18*(1), 1–14. https://doi.org/10.1007/BF03170650

TIMSS & PIRLS International Study Center (2015). *The Science Curriculum in Primary and Lower Secondary Grades*. Chestnut Hill, MA. https://timssandpirls.bc.edu/timss2015/encyclopedia/countries/united-states/the-science-curriculum-in-primary-and-lower-secondary-grades/

Treagust, D. (1986). Evaluating students' misconceptions by means of diagnostic multiple choice items. *Research in Science Education*, *16*, 199–207. https://doi.org/10.1007/BF02356835

Urey, M. (2018). Defining the relationship between the perceptions and the misconceptions about photosynthesis topic of the preservice science teachers. *European Journal of Educational Research*, *7*(4), 813-826. https://doi.org/10.12973/eujer.7.4.813

Verhoeff, R. P., Knippels, M. C. P. J., Gilissen, M. G. R., & Boersma, K. T. (2018). The theoretical nature of systems thinking. Perspectives on systems thinking in biology education. *Frontiers in Education, 3*, Article 40. https://doi.org/10.3389/feduc.2018.00040

Vosniadou, S. (2012). Reframing the classical approach to conceptual change: Preconceptions, misconceptions and synthetic models. In B. J. Frazer, K. Tobin &C. J. McRobbie (Eds.), *Second International Handbook of Science Education. Springer International Handbook of Education* (pp. 119-130). Springer.

White, J. S., & Maskiewicz, A. C. (2014). Understanding cellular respiration in terms of matter & energy within ecosystems. *American Biology Teacher*, *76*(6), 408-414. https://doi.org/10.1525/abt.2014.76.6.9

Widiyatmoko, A., & Shimizu, K. (2018). Literature review of factors contributing to students' misconceptions in light and optical instruments. *International Journal of Environmental and Science Education*, *13*(10), 853-863. http://www.ijese.net/makale/2093.html

Wood, W. B. (2002). Advanced high school biology in an era of rapid change: A summary of the biology panel report from the NRC committee on programs for advanced study of mathematics and science in American high schools. *Cell Biology Education, 1*(4), 123-127. https://doi.org/10.1187/cbe.02-09-0038.

Wood, W. B. (2009). Science education. Revising the AP biology curriculum. *Science, 325*(5948), 1627-1628. https://doi.org/10.1126/science.1180821

Wurpts, I. C., & Geiser, C. (2014). Is adding more indicators to a latent class analysis beneficial or detrimental? Results of a Monte-Carlo study. *Frontiers in Psychology*, *5*, Article 920. https://doi.org/10.3389/fpsyg.2014.00920

Yenilmez, A., & Tekkaya, C. (2006). Enhancing students' understanding of photosynthesis and respiration in plant through conceptual change approach. *Journal of Science Education and Technology, 15*, 81-87. http://dx.doi.org/10.1007/s10956-006-0358-8

Yong, C. L., & Kee, C. Z. (2017). Utilizing concept cartoons to diagnose and remediate misconceptions related to photosynthesis among primary school students. In: M. Karpudewan, A. Md Zain, & A. Chandrasegaran (Eds.), *Overcoming students' misconceptions in science* (pp 9–27). Springer. https://doi.org/10.1007/978-981-10-3437-4_2

Appendix

Conceptual understanding test

**1. What kind of gas do green plants release the most in sunlight?**

A. Carbon dioxide gas

*B. Oxygen gas*

The reason for my answer is:

1. This gas is released in sunlight because green plants only respire during the daytime.

2. Green plants release this gas because in sunlight they do photosynthesis but do not respire.

*3. This gas, which is produced during photosynthesis, is produced in larger amounts than is necessary for the respiration of green plants and other processes, so the excess of this gas is released into the environment.*

4. This gas is waste, which is produced during photosynthesis, so green plants release this gas into the environment.

5__________________________________________________

**2. What kind of gas do green plants absorb from the environment in large quantities when there is an absence of light energy (in the dark)?**

A. Carbon dioxide gas

*B. Oxygen gas*

The reason for my answer is:

1. This gas is used for photosynthesis, which all stages takes place constantly in green plants.

2. This gas is used for photosynthesis, which all stages occur in green plants when there is an absence of sunlight energy.

3. This gas is used for respiration, which occurs in green plants only when there is an absence of sunlight energy for photosynthesis.

*4. This gas is used for respiration, which takes place constantly in green plants.*

5__________________________________________________

3. **What kind of gas do green plants release the most in the dark?**

*A. Carbon dioxide gas*

B. Oxygen gas

The reason for my answer is:

*1. Green plants do not start to photosynthesize when there is an absence of sunlight energy, but they continue to respire, therefore they release this gas.*

2. Green plants release this gas during photosynthesis, which all stages takes place in the absence of sunlight.

3. Green plants release this gas because they respire only in the absence of sunlight.

4. ____________________________________________________________

**4. What kind of gas do green plants absorb the most in the sunlight?**

A. Carbon dioxide gas

*B. Oxygen gas*

The reason for my answer is:

*1. Green plants absorb this gas in the sunlight and produce their food from this gas.*

2. Animals need this gas for respiration in the presence of sunlight.

3. ____________________________________________________________

**5. Plants respiration occurs in:**

A only in the roots' cells.

*B in all plants' cells.*

C only in the leaves' cells.

The reason for my answer is:

*1. All living cells need energy to live.*

2. Only leaves have special pores (stomates) needed for gas exchange.

3. Only roots have small pores to respire.

4. Only roots need energy to absorb water.

5 ___________________________________________________________________

**6. Respiration is:**

*A A chemical process which occurs in all living plant and animal cells.*

B A chemical process which occurs in plant cells, but not in animal cells.

C A chemical process which occurs in animal cells, but not in plant cells.

The reason for my answer is:

1. Only plant cells receive energy to live during the respiration process.

2. *All live plant and animal cells receive energy to live through the respiration process.*

3. Energy for life is necessary only for animal cells because they cannot perform photosynthesis.

4 ___________________________________________________________________

**7. Which of the following statements about green plant respiration is the most accurate?**

A It is a chemical process by which plants produce food from water and carbon dioxide.

*B It is a chemical process by which the energy stored in food is released using oxygen.*

C It is the exchange of carbon dioxide and oxygen gases through the plant stomates only.

D It is a process that does not occur in green plants when photosynthesis takes place.

The reason for my answer is:

1. Green plants never respire but only perform photosynthesis.

2. Green plants absorb carbon dioxide and release oxygen when they respire.

*3. Respiration provides energy for green plants to live.*

4. In green plants, respiration occurs only when there is an absence of sunlight.

5 ___________________________________________________________________

**8. When do green plants respire?**

A Only at night (in the dark, when there is an absence of sunlight)

B Only daytime (when there is sunlight energy)

*C All the time (whether there is light energy or not).*

The reason for my answer is:

1. Green plant cells can perform photosynthesis during the daytime when there is light energy, therefore they only respire at night when there is an absence of light energy.

*2. Green plants need energy to live, and respiration provides energy.*

3. Green plants do not respire; they only perform photosynthesis, which provides energy for the plants.

4 ____________________________________________________________________

**9. Which of the following equations best represents the respiratory process in plants?**

A Glucose + oxygen → energy + carbon dioxide + water.

*B Carbon dioxide + water → energy + glucose + oxygen.*

C Carbon dioxide + water $\xrightarrow{\text{light energy and chlorophyll}}$ oxygen + glucose.

D Glucose + oxygen → carbon dioxide + water.

The reason for my answer is:

1. During respiration in the sunlight, green plants produce glucose using carbon dioxide and water.

2. Green plants use carbon dioxide and water to produce energy, while glucose and oxygen waste are generated during this process.

3. During respiration, green plants absorb oxygen and release carbon dioxide and water.

*4. During respiration, green plants get energy from glucose by using oxygen.*

5 ____________________________________________________________________

**10. Which of the following equations best represents the overall process of photosynthesis?**

A Glucose + oxygen $\xrightarrow{\text{light energy and chlorophyll}}$ carbon dioxide + water.

*B Carbon dioxide + water* $\xrightarrow{\text{light energy and chlorophyll}}$ *glucose + oxygen*

C Carbon dioxide + water + energy → glucose + oxygen

The reason for my answer is:

1. In sunlight, a green pigment called chlorophyll binds to carbon dioxide to produce glucose and water.

*2. Plants, which contain chlorophyll, use sunlight energy to combine carbon dioxide and water to produce glucose and oxygen.*

3. The combination of glucose and oxygen under the action of chlorophyll and light energy forms carbon dioxide and water.

4______________________________________________________________

**11. Which of the following factors is least important for the process of photosynthesis?**

*A The amount of oxygen.*

B The amount of carbon dioxide.

C The amount of chlorophyll.

D The amount of light.

The reason for my answer is:

1. Photosynthesis can take place without sunlight's energy.

2. Non-green plants, such as fungi that do not contain chlorophyll or similar pigments, can also perform photosynthesis.

3. Photosynthesis cannot take place without carbon dioxide.

*4. Oxygen is not required for photosynthesis; it is a product of photosynthesis.*

5 ______________________________________________________________

**12. The most important benefit for green plants during photosynthesis is:**

A Removal of carbon dioxide from the air.

*B Conversion of light energy into chemical energy.*

C Production of energy.

The reason for my answer is:

1. Photosynthesis provides energy for plant growth.

*2. During photosynthesis, solar energy is converted into the energy of chemical bonds and stored in glucose molecules.*

3 Leaves absorb carbon dioxide through their stomates during photosynthesis.

4 ________________________________________________________________

**13. Which of the following comparisons of photosynthesis and respiration processes in green plants is correct?**

A Photosynthesis occurs only in green plants. Respiration occurs only in animals.

B Photosynthesis occurs in all plants. Respiration occurs only in all animals.

*C Photosynthesis starts in green plants in the presence of light energy. Respiration occurs in all plants and all animals at all times.*

D Photosynthesis strats in green plants in the presence of light energy. Respiration occurs in all plants only in the absence of light energy and always in animals.

The reason for my answer is:

1. Green plants perform photosynthesis and do not respire at all.

2. Green plants perform photosynthesis during the day and respire at night (when there is an absent of light energy).

*3. Respiration is a continuous process in all living organisms. Photosynthesis starts only when there is light energy.*

4. Plants respire when they cannot get enough energy from photosynthesis (e.g., at night); animals respire constantly because they cannot perform photosynthesis.

5 ________________________________________________________________