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Press

Science Education Centre, Institute of Ecology and Earth Sciences, Faculty of Science and Technology, University of Tartu, Estonia

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The thesis is based on the following original publications, which are referenced in the text by their Roman numbers:

I. Semilarski, H. & Laius, A. (2021). Exploring biological literacy: A systematic literature review of biological literacy, *European Journal of Educational Research, 10*(3), 1182–1197.

II. Semilarski, H., Laius, A., & Rannikmäe, M. (2019). Development of Estonian upper secondary school students' biological conceptual understanding and competences. *Journal of Baltic Science Education, 18*(6), 955–970.

III. Semilarski, H. & Laius, A. (2019). Latent profile analysis as a tool to describe students' achievement in entering medicine faculty. *International Journal of Environmental & Science Education, 14*(6), 345–360).

IV. Semilarski, H. & Laius, A. (2019). A complex instrument for measuring the components of gymnasium students' biological literacy. *EDULEARN19 Proceedings: 11th International Conference and New Learning Technologies, 1st–3rd July 2019.* Palma, Mallorca, SPAIN: iated.org/edulearn, 6285–6293.

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Paper I: designing the study; formulating the research questions; undertaking data collection and analysis; writing the paper as the main author.

Paper II: participating in designing the study; formulating the research questions; undertaking data collection and analysis; writing the paper as the main author.

Paper III: participating in designing the study; formulating the research questions; undertaking data collection and analysis, writing the paper as the main author.

Paper IV: designing the study; formulating the research questions; undertaking data collection and analysis; writing the paper as the main author.

OTHER PUBLICATIONS

The following publications are related to this thesis.

1. Post, A., Semilarski, H., & Laius, A. (2017). Assessing the biological literacy cognitive components of 10th and 11th grade students. *Estonian Journal of Education, 5*(1), 206–238.
2. Laius, A. & Semilarski, H. (2018). Gender differences of Estonian gymnasium students' biological cognitive skills within socio-scientific issue of lactose intolerance. *ERIDOB2018: XII Conference of European Researchers in Didactics of Biology*. Zaragoza, Spain.
3. Semilarski, H., Soobard, R., Semilarski, H., Laius, A. & Rannikmäe, M. (2020). Using genetic variation as a disciplinary core idea in science education. In: L. G. Gomez Chova, A. Lopez Martinez, I. Candel Torres (Ed.). *INTED2020 Proceedings* (5423–5429). Valencia, Spain: IATED Academy.
4. Semilarski, H. & Laius, A. (2020). Upper secondary school students' conceptual understanding of biological core concepts. In: L. G. Gomez Chova, A. Lopez Martinez, I. Candel Torres (Ed.). *INTED2020 Proceedings* (2886–2892). Valencia, Spain: IATED Academy.
5. Semilarski, H. & Laius, A. (2021). Content analysis of upper secondary school students' conceptual understanding of biological core concepts. *EDULEARN21: 13th annual International Conference on Education and New Learning Technologies 5th–6th of July 2021*. Spain: EDULEARN.

1. INTRODUCTION

Being literate is seen as a fundamental personal competence (Olson, 2009), equipping people with the needed knowledge, skills, attitudes, and values to interact effectively within society (Theodotou, 2017). Competence is seen as the ability to do something successfully or efficiently (OED, 2020); knowledge has been considered rather subject specific in the context of science competences (Pedaste et al., 2020). While many studies have sought to investigate science, or scientific literacy (Eijck & Roth, 2010; Garthwaite et al., 2014; Holbrook & Rannikmäe, 2009; Klucevsek, 2017; Lederman et al., 2013; Mun et al., 2015; Smith et al., 2012), few articles have specifically referred to biology, or biological literacy (Mertens & Hendrix, 1982; Riddle, 1954; Uno & Bybee, 1994).

Nevertheless, biological literacy is seen as crucial for students as future citizens in making decisions in their everyday lives (Suwono et al., 2017); for example, deciding whether to become a gene donor; determining a healthy diet, selecting suitable medical treatment, or determining ways to protect oneself from Covid-19. It is therefore not surprising that, in recent decades, advances in biology have been increasingly portrayed in the literature (Narguizian, 2019; Weber, 2017; Wright, 2005).

An early description of biological literacy was put forward by Uno and Bybee (1994) and they argued that biological literacy, as a subset of scientific literacy, was not a single endpoint that could be attained within one biology course but was an ever-extending continuum over which a person's competence developed throughout their life. Despite the importance of issues having a biological component in today's society, much less attention has been placed on biological literacy in academic circles than on the enhancement of the more general and overarching scientific literacy (ibid.). Unfortunately, the precise meaning of biological literacy remains ambiguously defined (Birzina, 2011; Dorfner et al., 2018).

Discipline-based education research (DBER) is an emerging interdisciplinary field interested in understanding and improving discipline-specific teaching and learning as a rising, interdisciplinary field aimed at understanding and improving discipline-specific teaching and learning (Dolan et al., 2018). The number of science, technology, engineering and mathematics (STEM) faculty members involved in DBER has grown rapidly in recent years (ibid.). Biology education researchers are part of this growing field (Singer et al., 2013).

Biology as a school subject today encompasses an extensive array of new developments and methods when compared with the previous century (Labov et al., 2010; Winterbottom, 2020). Winterbottom (2020) emphasises the importance of biology education and recommends paying more attention to the inclusion of advances in biology research within biology education, even encompassing meaningful elements in basic and general secondary education. In fact, the goal of biology education is to enhance biological literacy (Nwagbo & Adam, 2012); for example, to support students in developing confidence as biological researchers – increase their self-perception (Ainscough et al., 2016).

While the acquisition of biological concepts has constantly been an essential feature of biology education (Jumanovich, 2021), Reiss (2020) indicates that today's biology education has been fundamentally changing from a conceptualisation based on a very descriptive portrayals of living things to placing more emphasis on conceptualising the function of biological processes. However, with the rapid advances in life sciences, the concern is that school biology education cannot keep pace with such advances (Reiss, 2020).

The goal of biology education is the development of biological literacy, especially engaging students in experiencing a range of practical and interactive activities to develop a caring mentality and critical analytical skills, and thus preparing students to put forward and develop the potential to undertake action (Reiss, 2006). This draws attention to the growing demands for an increasing enhancement of biological literacy (Adnan et al., 2021) and recognising that biology education in the 21st century needs to be forward looking and constantly updated to meet the needs of students as future members of a changing society (McComas et al., 2018).

In line with promoting biological literacy, the Estonian Curriculum (2014) sets a goal of biology learning in schools to enable a comprehensive overview of the diversity, as well as the structures and functions of organisms covering a broad scientific world view, seeking to solve biological problems in everyday life and making decisions for coping within a rapidly changing natural and social environment. However, one concern is that little attention has been paid to whether these aims have been achieved, especially at the upper school level, where career choices should be made, and acquisition of biological competence is crucial to meet 21st century challenges (Anakara, 2021; Wulandari et al., 2019). Unfortunately, in upper secondary science education, learning coherent interlinked concepts (an abstract idea according to OED, 2020) is often problematic (Ummels et al., 2015). Nearly 10 years ago, the Vision and Change national report (American Association for the Advancement of Science (AAAS, 2011) called for the life sciences community to improve undergraduate biology education by organising instruction around five core concepts that every undergraduate biology major ought to know upon graduating: (1) evolution; (2) structure and function; (3) information flow, exchange, and storage; (4) pathways and transformations of energy and matter; and (5) systems (Branchaw et al., 2020). These core concepts are mirrored in the big ideas outlined by the Next Generation Science Standards (NGSS, 2013) and core concepts are used to guide biology education (Brownell et al., 2014). Within such a frame, the biology curriculum can be expected to stipulate a new focus on real-life societal problems using the gained biological concepts and hence seek to enable students to enhance their biological literacy. However, evaluating (the making of a judgement about the value of something; assessment according to OED, 2020), or assessing (the action of assessing someone or something according to OED, 2020) a person's literacy is a complex undertaking, relying on detailed and context-bound analysis (Lind, 2008).

The curriculum builds on a range of topics that form the basis for developing the students' core concepts in biology and indicates that the biological conceptualisations included comprise three cognitive components, including explanation, decision-making and problem-solving skills (Estonian Curriculum, 2011).

With changes in the conceptualisation of biology education, concerns arise about how the suitability of the curriculum can be evaluated, and student achievement assessed. Where test scores have determined the level of academic achievement, studies, such as those by Illingworth et al. (2012), Post et al. (2017) and Weber (2014), have sought to measure attributes associated with biological literacy. However, a concern is that the instruments have used only partial indicators to measure biological literacy. This refers to the need for studies to investigate the development and validation of assessment instruments measuring student conceptual learning gains, as suggested by Smith et al. (2008) and Summers et al. (2018).

Assessment can be used for a variety of purposes and there is a need to monitor systems with a platform for improving teaching and learning (Suurtamm et al., 2016) that can give an indication of biological literacy measured using different forms of assessment: examinations, tests, questionnaires, and teacher assessments (Murchan & Shiel, 2017). Many students perceive biology as challenging, often dull and feeding a belief that it requires extensive background knowledge (Burke de Silva, 2008) and that the inclusion of self-diagnostic components, such as self-perception of learning as an assessment indicator (Choi et al., 2011), can potentially help students in their biology learning (Harrison, 2010).

Students' perception of their learning and actual performance has been researched in many psychology studies (Ehrlinger et al., 2008; Hacker et al., 2000) and specifically in biology studies (Bowers et al., 2005; Ziegler & Montplaisir, 2014). Students who lack an accurate self-perception of their learning tend to draw incorrect conclusions, and cannot recognise their faults (Kruger & Dunning, 1999). Problems emphasised in the following thesis are shown in Figure 1.

The research aims were to measure the Estonian upper secondary school students' (1) biological content knowledge (in studies 2 and 3) and (2) cognitive skills – explaining and using biological knowledge, problem-solving and decision-making in biological contexts (in studies 1 and 3), and also (3) self-perceptions of students' biology learning (in study 3). These cognitive and affective components were selected for assessment to address the learning goals of the Estonian Curriculum and the needs for a future Estonian labour force according to the opinions of Estonian stakeholders, which were revealed in previous research (Laius et al., 2016; Post et al., 2017).

The biological content knowledge was assessed based on Bloom's taxonomy (Bloom, 1956; Anderson & Krathwohl, 2001) approach to learning as a hierarchical process. Bloom's taxonomy has been used by biologists to develop higher-order cognitive tasks as well as assessing learning outcomes (Bissell & Lemons, 2006; Cleveland et al., 2017; Crowe et al., 2017).

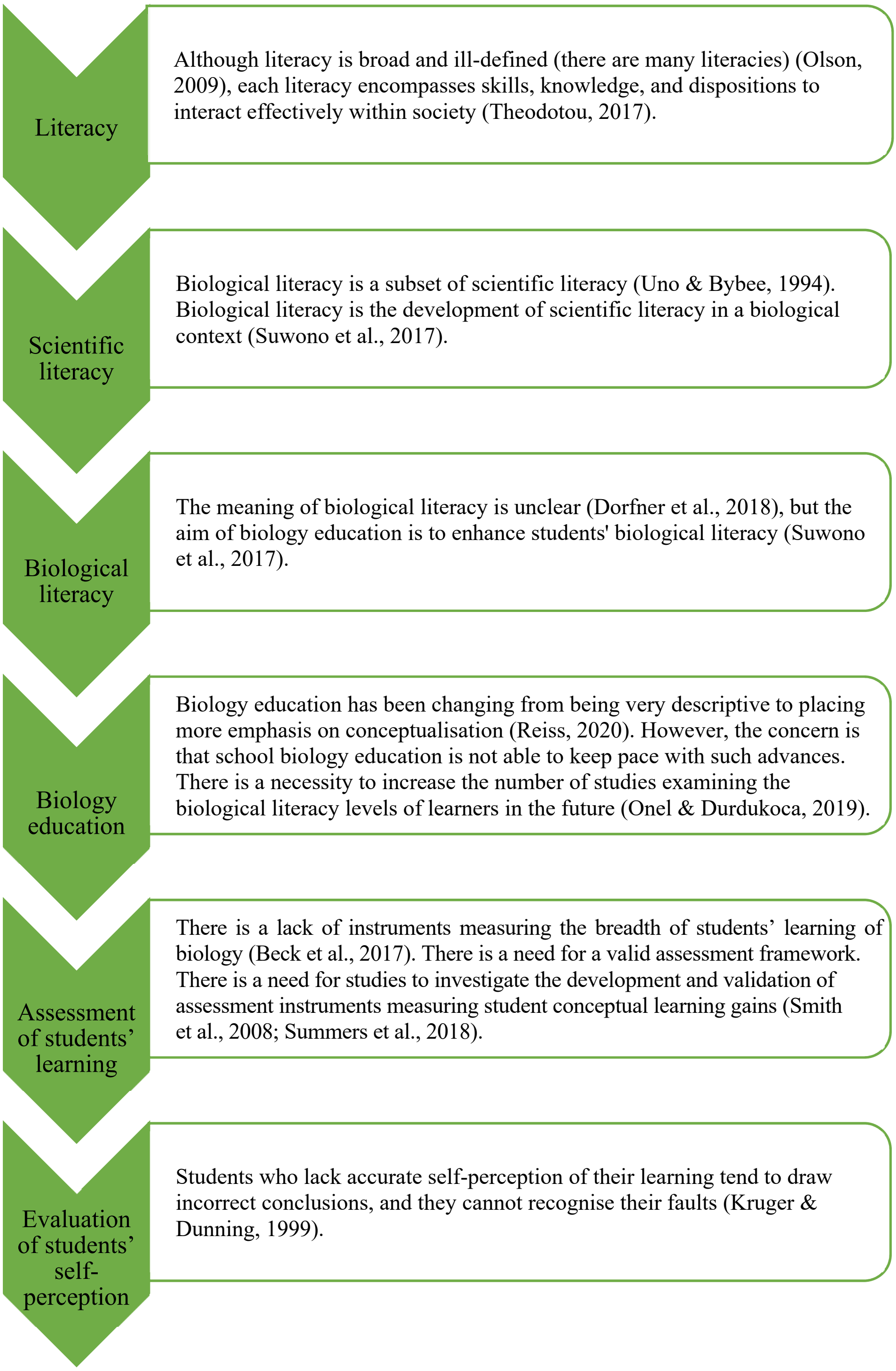

Figure 1. *Problems emphasised in the thesis*

Based on the aims, the following research questions were posed:

1. How has biological literacy been conceptualised in the literature, especially in relation to biological literacy as determined by competences associated with biology knowledge, cognitive skills, and self-perceptions?
2. How and to what degree have the cognitive skills of Estonian upper secondary school students in the context of biology been assessed?
3. In what manner and to what degree has the biological knowledge of Estonian upper secondary school students been assessed?
4. Which self-perceptions do upper secondary Estonian students hold in relation to their biological competence?

2. THEORETICAL BACKROUND

2.1 Biological literacy

Literacy means competence in a particular field and is defined as the cognitive competence needed in daily life, like establishing causal relationships between phenomena and problem-solving (Onel & Durdukoca, 2019). According to Keen (1992), competence refers to the ability to operate in everchanging environments, deal with abstract work processes, handle decisions and responsibilities, work in groups, and understand dynamic systems similar to the essence of literacy in a specific field.

Framework Competences Democratic Culture (2018) indicates competences broken down as KSAV (knowledge, skills, attitudes and values), where these descriptors can be used as tools for curriculum planning, teaching, learning, and assessment:

- Values: dignity, cultural diversity, democracy.
- Attitudes: respect, openness, civic mindedness, responsibility, self-efficacy, tolerance of ambiguity.
- Skills: autonomous learning skills, analytical and critical thinking skills, listening and observing, empathy, adaptability, communication and plurilingual skills, cooperation, conflict resolution.
- Knowledge and critical understanding of communication, self, the world.

Framework Competences Democratic Culture (2018)

The main goal of science education is to enhance scientific literacy (Birzina, 2011; DeBoer, 2010; Holbrook & Rannikmäe, 2007). The concept of scientific literacy refers to scientific ideas and concepts within and across various scientific disciplines and scientific practices (Shwartz et al., 2006). To acquire the components of scientific literacy, Shwartz et al. (2006) indicated that it is necessary to investigate the various scientific disciplines.

Bybee (2008) claimed that the education community ought to respond to challenges; for example, help citizens develop better knowledge and appreciation of resources and the multitude of environmental issues. Educators are expected to take up the challenge to fill the void in student biological literacy (Jones, 1989).

Uno and Bybee (1994) defined biological literacy as a subset of scientific literacy, each having in common four levels – nominal, functional, structural, and multidimensional. Biological literacy is seen as a subset of scientific literacy having mostly the same characteristics but focuses on biological knowledge (Post et al., 2017).

Even so, biological literacy can be interdisciplinary and hence biological situations embrace more than biological knowledge and core concepts that use biological terms, biological scientific language, and specific investigative methodologies/processes etc. The integrative biological situations involve wider aspects such as nature of biology including understanding science, technological ideas, etc. Thus, biological literacy largely focuses on biology compared to scientific literacy (Reiss & Kampourakis, 2018). Kloser (2012) suggests that the nature of biology does play a more significant role in biology education. Examples of the nature of biology (NOB) include the following aspects: explanation of natural phenomena, understanding natural laws and solving practical problems from a biological perspective, and using biological knowledge when solving problems (Zhou, 2019). The NOB and the nature of science share many common aspects, with the focus of biology creating unique philosophical, methodological, and ethical premises on which biology should be understood (Kloser, 2012).

Biological literacy is addressed in the literature from different perspectives (Demastes & Wandersee, 1992; Mertens & Hendrix, 1982; Uno & Bybee, 1994; Weber, 2017; Wright, 2005; Zangori & Koontz, 2017). Mertens and Hendrix (1982) have described biological literacy as biological knowledge, and use of scientific methods, problem-solving and responsible decision-making. Uno and Bybee (1994) first described biological literacy through the identification of biologically literate students who are identified as understanding scientific knowledge, the methods and processes of scientific inquiry and appreciate values of science. Based on such an identification, they put forward four hierarchical dimensions of biological literacy (nominal, functional, structural, multidimensional) (Uno & Bybee, 1994).

Wright (2005) has also described biological literacy by considering biologically literate individuals: these are individuals who can ask and answer different biologically relevant questions. In this article, he addressed the importance of promoting biological literacy through developing assessment strategies. These instruments should measure the skills that help students ask biologically relevant questions, for example, critical thinking, data analysis, effective communication, critical collecting of information.

According to the American Association for the Advancement of Science (AAAS) in 2011, all sub-dimensions of scientific literacy have their own core concepts and methods; for example, biological core concepts and methods are specific to biological literacy, chemical core concepts describe chemistry literacy, and so on. Core concepts in biology have been investigated in the later papers. Weber (2017) described the meaning of biological literacy based on core concepts (AAAS, 2011), indicating that core concepts have changed over time. For example, decades ago, four core principles were envisaged: information, organisms, evolution, and energy flow (Demastes & Wandersee, 1992). Weber (2017) emphasised in her study three core concepts from five (Structure and Function; Pathways and Transformations of Energy and Matter; Systems – she did not include Evolution; Information Flow, Exchange, and Storage). Also, she did not include other aspects, such as skills or attitudes of biological literacy in her study (ibid.) but outlined five core concepts intended to guide undergraduate biology education: 1) evolution; 2) structure and function; 3) information flow, exchange, and storage; 4) pathways and transformations of energy and matter; and

5) systems (AAAS, 2011). Zangori and Koontz (2017) included new aspects of being biologically literate in their study; for example, understanding socio-ecological issues and the connection between processes and systems that leads to responsible environmental decision-making.

2.2 Biology Education

Biology is an important subject in school curricula (Vázquez, 2006). Modern biology education is an interdisciplinary field of education (Nagle, 2013) that is connected and interrelated with different disciplines, such as computer science (e.g., biometric analysis), chemistry (e.g., digestion, biochemistry), technology (e.g., biotechnology), etc. This interdisciplinary biology is seen as important to enable the solving of complex problems associated with health (diet), or medicine (vaccination). Therefore, biology education is also interrelated with other educational areas, such as health education, even though very few high school biology topics deal with health in the context of 21st century issues (Jacque et al., 2016). This has been changed with the Covid-19 pandemic causing many issues including in terms of people's behaviour during 'lockdown' which has drawn attention to establishing competence in simple hygiene measures that can be expected to facilitate the protection of everyone's health.

Today, 21st century biological knowledge is based on advancements in biology (Woese, 2004) and through these advancements, 21st century biology education can be expected to be both frequently updated and forward-looking, meeting the needs of students as future members of society (McComas et al., 2018). As biological 'facts' are constantly changing, biological research yields new insights, eventually impacting known biological knowledge (Antezana et al., 2009). New knowledge, for example, regarding the discovery of novel structural and functional nucleic acids (Sukowati et al., 2021) and developments in biology are expected to reach biology education at every school level to make biology lessons more contemporary. Biology as an interdisciplinary field can be expected to play an important role in improving the teaching and learning of biology (Stagg, 2008).

Lo et al. (2019) claim that biology education research is a growing field. Biology educational research requires an in-depth understanding of knowledge and practices (Gül & Sözbilir, 2016). Just as science educators have a major role in affecting students' understanding of what science is (Nurse, 2016), so too biology education also needs to be relevant to students facilitating their interest in biology, furthering their understanding of biological topics associated with their everyday lives, and thereby furthering their potential career choices within the field of biology (Mutanen & Uitto, 2020).

Cognitive component

Mertens and Hendrix (1982), Uno and Bybee (1994) and Rita Hoots (1999) have defined biological literacy through biological knowledge. In later articles, core concepts are emphasised (Post et al., 2017; Uno, 2009) and the importance of people understanding core concepts in biology (Begley, 2012; Illingworth et al., 2012). Understanding scientific knowledge is one important part of scientific literacy (Klymkowsky, 2005) and this can be applied also to biological literacy (Uno & Bybee, 1994).

Besides knowledge, biology education encompasses biological skills, such as cognitive skills or abilities. Cognitive skills refer to the use of mental activities; for example, analysing, understanding, learning, and reasoning. Uno and Bybee (1994) referred to these as scientific abilities, and Kampa and Köller (2016) later named them cognitive abilities. In this study they are referred to as cognitive skills. Mertens and Hendrix (1982) identified that problem-solving and responsible decision-making are parts of biological literacy. Vickers et al. (2003) considered the ability to solve problems a core cognitive component of biological literacy.

Critical thinking and scientific thinking skills have been included in biology education by Hoots (1999) and Uno and Bybee (1994). Later, Post et al. (2017) added problem-solving, decision-making and also scientific creativity as further important cognitive skills within biology education. Hu et al. (2013) went further and indicated that enhancing students' scientific creativity is critical for every aspect of thinking and learning. Unsurprisingly, Kampa and Köller (2016) identified a strong relationship between general cognitive abilities and academic achievement.

Cognitive ability also encompasses the use of scientific methods. In fact, Mertens and Hendrix (1982) have defined biological literacy through scientific methods. However, for Lederman (2018) scientific inquiry is broader than science methods and extends cognitive ability beyond simple references to process skills (observing, inferring, classifying, predicting, measuring, questioning, interpreting, analysing data).

Affective component

According to Uno and Bybee (1994), the affective component of biological literacy included that a student following a biology course should value life and biology. The affective component centres on reactions to teachers, school, or the subject (Fredricks et al., 2016). Gardner et al. (2016) indicated that biological literacy consists of a set of affective dimensions (attitudes, interests, perceptions, beliefs, etc.). Simpson and Oliver (1990) indicated that attitudes describe emotional tendencies towards different situations with people involved.

Barr (2007) indicated that the term environmental values is defined as underlying orientations held by individuals toward the physical environment.

Sustainability

For decades already one of the worldwide aims for the future has been the construction of a sustainable society (Gladwin et al., 1995; Global Sustainable Development Report, 2019). A sustainable society is reached through sustainable development, and includes social, cultural and environmental situations (Kopnina, 2012). Ecological issues are also very important in biology education (Jeronen et al., 2016).

Uno and Bybee (1994) indicated the impact of people on the biosphere. Biological literacy through studying biology as a school subject should develop a critical awareness of human relationships with nature (Oliveira et al., 2019). Narguizian (2019) addressed that all educators should help students in understanding the human-Earth relationship.

Interdisciplinarity

The diversity within biology is reflected in its many different subfields, which have developed into separate biological sciences and their goal is to develop field-based literacies; for example, environmental, ecological, health and genetic literacies (Jacque et al., 2016; Kaye & Korf, 2013; Krakow et al., 2017; Voithofer, 2012). All are related to biology education. Biotechnology is an innovative field that is growing in popularity (Lazaros & Embree, 2016). Nagle (2013) discussed in her study the nature of modern biology. She stressed that educators must provide students with opportunities to engage in studying interdisciplinary scientific questions or problems, for example, to use overarching themes, problems, or socio-scientific issues.

Nature of biology

One of the developing parts of biology education is the nature of biology that focuses on the uncertainty and renewing essence of biology as a science. Kloser (2012) argued that biology has many unique methods and has even stated that biology is a leading science of the 21st century with its new discoveries and new frontiers raising new ethical questions and causing new public debates. The nature of biology has been investigated by many studies (Adegboye et al., 2017; Kloser, 2012). Kloser (2012) argued that the discipline-specific nature of biology can be integrated into biology education to enhance what is currently taught about the general nature of science. Also, he emphasised that this would improve biology education's ability to focus on biology.

Biology-related career awareness

It is plausible that several individuals well-suited to a biology-related career may miss an opportunity due to lack of awareness or lack of accurate information; for example, about genetics (Gerard et al., 2019). Teachers themselves should be familiar with new biology-based career choices and the competences that are needed for them (Šorgo & Špernjak, 2020).

2.3 Biology Education in Estonia

Estonia introduced a new curriculum at the upper secondary school level (grades 10–12) in 2011 and its implementation became compulsory from September 2013 (Estonian Government, 2014). Within this the stated aims of learning biology are as follows:

- To gain a comprehensive overview of the basic principles of life diversity, the structure and function of organisms, heredity, evolution and ecology, and environmental protection and applied biology through problem-solving.
- To explain biological theories, practical outputs, future trends, and related applications and careers.
- To obtain a systematic overview of wildlife and its most important process and use correct biological vocabulary.
- To use various sources of information, including electronic sources, and evaluate critically the information they contain.
- To apply a scientific method in solving biological issues.
- To make competent decisions related to everyday life based on scientific, economic, and ethical moral views, considering legislation.
- To acquire an overview of careers related to biology and apply the knowledge and skills gained in career planning.

(Estonian Government, 2014).

The reason this thesis focused on cognitive and affective dimensions of biology education can be drawn from the Estonian Curriculum.

Core topics of biology

Brownell et al. (2014) outlined a set of statements that were more specific interpretations of each of the core concepts within the three major subdisciplines of biology: molecular/cellular/developmental biology, physiology, and ecology/evolution. The body of biological knowledge focuses on seven core topics, including core concepts that are used to guide biology education.

Evolution. The well-known quote of Theodosius Dobzhansky stresses the importance of evolution: "*Nothing in biology makes sense except in the light of evolution*" as the fundamental basis for the evolutionary development of life. Evolution as a school subject is regarded as a complex and scientifically complicated topic (Hermann, 2013; Nehm & Schonfeld, 2007; Van Dijk & Reydon, 2010). Decades of research have revealed that many students regularly misunderstand the meaning of evolution and how it occurs (Short & Hawley, 2014; Shtulman & Calabi, 2013; Sinatra et al., 2008; Sinatra et al., 2003). Research has shown students poorly understand topics on evolution (Morabito et al., 2010). Sager (2008) stated that due to the controversial nature of evolution, educational organisations have felt the need to explicitly state their support for the teaching of evolution. Evolution is key to understanding many other core topics, for example, heredity, and ecology (Tansey et al., 2013).

Cell theory. Learning cell biology is an essential topic in biology education as the basis for understanding the structure and functions of biological organisms. Unfortunately, many students have misconceptions about cellular processes (Yeong, 2015); for example, upper school students have problems with the topic of cell division (Lukša et al., 2016). The study by Lewis et al. (2010) revealed that students have a lack of understanding about the genetic relationship between cells.

Inheritance. Genetics is identified as a core topic in biology (Johansen et al., 2018). Kılıç and Sağlam (2014) have investigated students' understanding of genetics. Heredity is an important core topic in biology. There have been studies about how students understand heredity; for example, Kılıç and Sağlam (2014), researched secondary school students' understanding of fundamental topics in genetics.

Metabolism is a topic used to describe chemical reactions in cells and in organisms in which students have a lack of understanding of the energy transfer in photosynthesis and respiration (Lin & Hu, 2003; Parker et al., 2012; Wilson et al., 2006).

Ecology is also a core topic in biology. Students at upper secondary school level have a lack of understanding and misconceptions concerning fundamental topics of ecology; for example, about the greenhouse effect, and energy flow (Summers et al., 2018; Toman, 2018).

Molecules and structures are seen as one of the most important core topics as a basis for the understanding of biology (Weber, 2017).

Human anatomy and physiology are seen as a core topic in biology because regulatory mechanisms in humans are identified as one of the key topics in the upper secondary biology syllabus (Estonian Government, 2014). Students have difficulties identifying patterns in the body (Reiss & Tunnicliffe, 2001).

Conceptual understanding of biological knowledge

A concept, as defined by Koniceck-Moran & Keeley (2015), is a set of meanings that possess relationships and patterns observed. A framework for assessing core concepts of biology has been indicated by Branchaw et al., 2020, Brownell et al., 2014, and Quinn et al., 2011. Sawyer (2008) indicated that conceptual understanding takes place when facts and procedures are applied in real-life situations. However, conceptual understanding requires the ability to create a network of knowledge, skills and values, ideally in an interdisciplinary perspective, to transfer and apply biological knowledge and skills in diverse contexts as explained by Koniceck-Moran and Keeley (2015).

Sabina Leonelli (2009) has defined conceptual understanding of biological knowledge as the ability to use biological knowledge to understand biological phenomena. Conceptual understanding is a relevant field in science education today, as routine memorisation and traditional methods of teaching are considered insufficient for real-world learning and application (Gunel et al., 2009; Jensen et al., 2014; Zacharia et al., 2016). Biological conceptual understanding is important for students when meeting new challenges (Wulandari et al., 2019) and for use in different situations.

Badie (2016) indicates that by learning and acquiring knowledge in the framework of constructivism, a human being attempts to provide a way to determine the truth values of non-logical parts through her/his conceptions.

1. Understanding as a conceptualisation focuses on the domain of conceptualisation.

2. Understanding as an interpretation focuses on the domain of interpretation.

(Badie, 2016)

Conceptual understanding of biological knowledge can be assessed using concept inventories that are typically multiple choice questionnaires based on student thinking; that is, the distractors (incorrect answers) correspond to common and persistent misconceptions shared by many students (Chapagne Queloz et al., 2017).

Cognitive skills in biology learning

According to the Structure of Observed Learning Outcomes (SOLO), the sequence "pre-structured knowledge → uni-structured knowledge → multi-structured knowledge → related knowledge → extended abstracts" represents a flow from shallow understanding to deep understanding (Biggs,1982).

Biological explanation

Biological explanation as a term is widely used by biology education researchers (Burston, 2017; Scalise & Clarke-Midura, 2018; Serban, 2017). Kampourakis and Niebert (2018) indicated that two types of biological explanations can be distinguished:

1. Developmental and evolutionary explanations for the origin of biological phenomena.

2. Causes of effects and the processes through which these effects are brought about.

Explaining the origin of biological phenomena is a central goal in biology education, and therefore it is important for students to understand the structure of these explanations (causes and processes), as well as the pluralism that characterises them (traits are the outcomes of both evolution and development) (Kampourakis & Niebert, 2018).

Problem-solving

The ability to solve issues is critically important in almost every subject both in and out of school (Csapò & Funke, 2017). Consequently, one major purpose of biology education is to build up and develop problem-solving skills in students. People often must deal with unpredictable situations where they need to resolve issues. Problem-solving is a part of scientific literacy (Roberts, 2007; Roberts & Bybee, 2014). Developing problem-solving skills in students is important in order to allow them to solve everyday problems effectively and professionally (Şenocak et al., 2007). Problem-solving skills in students at secondary school level have been investigated in several studies (Basu et al., 2017; Dahlberg et al., 2019).

Decision-making

Decision-making is a demanding thinking process that is needed in every field of personal life; for example, in work and in making health-related decisions (Colakkadioglu & Celik, 2016). As a part of the Estonian Curriculum, students are expected to utilise their newly acquired knowledge (including that gained through the learning of biology) to make informed decisions concerning socio-scientific issues (Estonian Curriculum, 2011).

Students' development of their reasoning in order to make justified decisions leans on their understanding of the related concepts (Zeidler et al., 2013). The need to pay more attention to decision-making is acclaimed in research (Millar et al., 1998; Zeidler, et al., 2005). Decision-making and reasoning skills are also valued by many Estonian stakeholders (Laius et al., 2016).

Hacker et al. (2008) add that in an exam, especially in a multiple choice test, students are being asked to make a choice among several alternatives, with such a selection also being a decision-making process.

Student self-perception of their knowledge, skills, and career awareness

Students who lack inappropriate self-perception of their knowledge tend to draw incorrect conclusions and lack the ability to recognise their faults (Kruger & Dunning, 1999). Students' perception of their knowledge and actual knowledge or performance have been researched in many psychology studies (Ehrlilinger et al., 2008; Hacker et al., 2000), as well as in biology (Bowers et al., 2005; Ziegler & Montplaisir, 2014).

Ziegler and Montplaisir (2014) have raised concerns about the effectiveness of evaluating the relationship between student perception of knowledge and actual knowledge through comparison of knowledge surveys and examinations.

2.4 Assessment of student learning

Broadfoot and Black (2004) indicate that assessment is seen as very important, and it is seen as the most important tool that educators can use to influence and improve the teaching process, but there is a lack of valid and reliable assessment tools (Broadfoot & Black, 2004). The main purpose of assessment is to verify educational systems (Long et al., 2011). Assessment can improve learning outcomes as well as measure its effects (William, 2018).

The terms *assessment* and *evaluation* have been widely used. Taras (2005) discussed in her paper the differences between these two and based on that, *assessment* refers to judgements of student work, and *evaluation* refers to student judgements of some topic.

Determining improvements in subject learning in students is the most common use of assessments (Murchan & Shiel, 2017). Multiple choice questions (MCQ) are frequently used to assess student knowledge in the field of medical and other sciences (Ahmed, 2020) as an objective and reliable tool to assess the learning performance of students (Ingale et al., 2017).

As academic achievement plays a major role in life, higher achievement in any subject is important for students to prepare for further education, as well as for life in our changing world (Mullis et al., 2012). An item's difficulty can be subjective, and one which should be assessed by the item's developers (Li & Belkin, 2008).

Assessment tools to measure students' understanding of disciplinary concepts need to be valid and reliable (Downing & Haladyna, 2006). Learning outcomes include knowledge, skills, or attitudes that students ought to develop as a result of their learning (Biggs & Tang, 2011).

To measure student achievements, a meaningful taxonomy is needed for developing items (Krajcik, 2011). One taxonomy that is considered appropriate to assess the quality of student cognitive responses is the taxonomy developed by Biggs and Collis in 1982 known as the taxonomy of The Structure of Observed Learning Outcomes (SOLO) (Mindayani et al., 2019). The other well-known taxonomy for assessment of student knowledge is Bloom's taxonomy (Bloom, 1956).

Classical Test Theory and Item Response Theory

To address measurement and test development: classical test theory (CTT) and item response theory (IRT) are used. Classical test theory (CTT) is an approach to measurement that considers the relationship between the expected score (or "true" score) and the observed score on any given assessment. The word 'classical' is used in the sense that the theory is considered to be the first practical application of mathematics to describe this relationship (Hauenstein & Embretson, 2018). IRT is a general statistical theory describing how performance relates to the abilities measured by the items used in the test (Hambleton & Jones, 1993). As a result, IRT enables us to determine which items are most suitable to measure latent traits and can increase the reliability and validity of the scale as a whole (Nima et al., 2020).

Fan (1998) indicated the major limitations: the person statistic (i.e., observed score) is (item) sample dependent; the item statistics (i.e., item difficulty and item discrimination) are sample dependent, while IRT, on the other hand, is more theory grounded and models the probabilistic distribution of examinees' success at the item level.

IRT has been used in validating assessment tools (Summers et al., 2018). According to De Beer (2004), each IRT model predicts the probability that a certain student will give a certain answer. The purpose of these models is to explain probabilities in an examinee's responses to test items as a way of relating to his/her probable ability.

The Rasch model provides detailed methodology that can evaluate the psychometric properties at item level (Messick, 1994). The Rasch model can help test developers to improve the reliability, validity, and efficiency of educational instruments (Bond, 2003).

According to IRT models, the probability of a correct answer makes use of two logistic functions. The one-parameter logistic (1PL) model attempts to address the probability of a correct answer by allowing each question to have an independent difficulty variable. The two-parameter logistic (2PL) model allows for different discrimination parameters per item and assumes that the guessing parameter is equal to zero.

Instruments developed by biology educators have measured one or some biology education components; for example, cognitive components (Köksal & Köksal, 2012; Post et al., 2017), reading skills (Brill et al., 2004), nature of science (Köksal & Köksal, 2012), and core concepts (Begley, 2012; Fiedler et al., 2019; Weber, 2014). Also, concept inventories have been developed for gauging student conceptual understanding (Klymkowsky et al., 2010; Smith et al., 2018).

The SOLO taxonomy

The SOLO taxonomy model means the classifying of learning outcomes in terms of their complexity, enabling examiners to assess the work of students in terms of its quality that can be used not only in assessment but in designing the curriculum in terms of the level of learning outcomes intended (Biggs, 1996). The Structure of Observed Learning Outcomes (SOLO) taxonomy has the following five levels:

1. *Pre-structural (e.g., fail, misses point);*
2. *Uni-structural (e.g., identify, name);*
3. *Multi-structural (e.g., combine, list);*
4. *Rational (e.g., analyse, apply, argue, justify, compare);*
5. *Extended abstract (e.g., create, formulate, generate, hypothesise, theorise).*

This study did not use the first level as it was not present in student responses.

Academic success should be measured not just in terms of what students can remember, but what students are able to do with their knowledge (Crowe et al., 2017). Crow and Crow (1965) have defined achievement as the extent to which a learner is profiting from instruction in a given area of learning, while Biggs (1982), forsaking the emphasis on the teacher and instruction, and placing emphasis on students' learning, sees academic achievement as an outcome of learning which is expressed by the extent to which instructional objectives have been met.

Bloom's taxonomy

Educational psychologist Benjamin Bloom devised a taxonomy to promote higher forms of thinking in education in 1956. Based on his study, three domains of learning were identified, which are cognitive (mental skills), affective (growth in feelings) and psychomotor (manual or physical skills) (Anderson & Krathwohl, 2001; Bloom et al., 1956; Harrow, 1972). Biological literacy should enhance higher-level thinking skills; for example, problem-solving and decision-making skills in students (Roberts, 2001).

Bloom's Taxonomy (Bloom et al., 1956; Anderson & Krathwohl, 2001) has been widely used by biologists to develop higher-order cognitive questions (Bissell & Lemons, 2006; Cleveland et al., 2017). Crowe et al. (2017) developed the blooming biology tool, which can be used to assess the level of questions on biology-related topics according to Bloom's taxonomy.

Multiple choice questions (MCQs) are frequently used to assess student knowledge in medical and other sciences (Ahmed, 2020) as an objective and reliable tool to evaluate the learning performance of students (Ingale et al., 2017). Properly constructed MCQs can assess higher cognitive processing in students according to Bloom's Taxonomy, such as interpretation, synthesis, and application of knowledge, instead of just testing the recall of isolated facts (Carneson et al., 2011).

3. RESEARCH METHODOLOGY

This dissertation focuses on the conceptualisation of biological literacy and assessment of biology learning outcomes in Estonian upper secondary school students, based on two stages, as illustrated in Figure 2: Stage I; a conceptualisation of biological literacy in biology education from a cognitive perspective, and Stage II; an assessment of biology learning. While biological literacy is meant to be a goal of biology education as indicated in the literature, Stage II is divided into three separate sub-studies according to the cognitive or affective component of biological literacy (Figure 2).

Study 1. Assessment of grade 10 and grade 12 students' cognitive skills in biology learning in terms of understanding biological concepts, giving biological explanations, problem-solving and decision-making abilities. An 8-item instrument was used, and the responses of students were categorised based on the SOLO taxonomy (Table 2, Paper II). This instrument was designed to reflect the Estonian biology curriculum in terms of cognitive skills.

Study 2. Assessment of upper school graduates' conceptual understanding of core concepts in biology, covering the main topics (later addressed as core topics) addressed in the Estonian biology syllabus (Table 3, Paper III).

Study 3. Investigation of students' biology learning towards (a) cognitive skills, (b) biological content knowledge and (c) the self-perception of their biology learning and career preferences (Table 4, Paper IV).

A detailed overview of the methodology of the study is illustrated in Table 1.

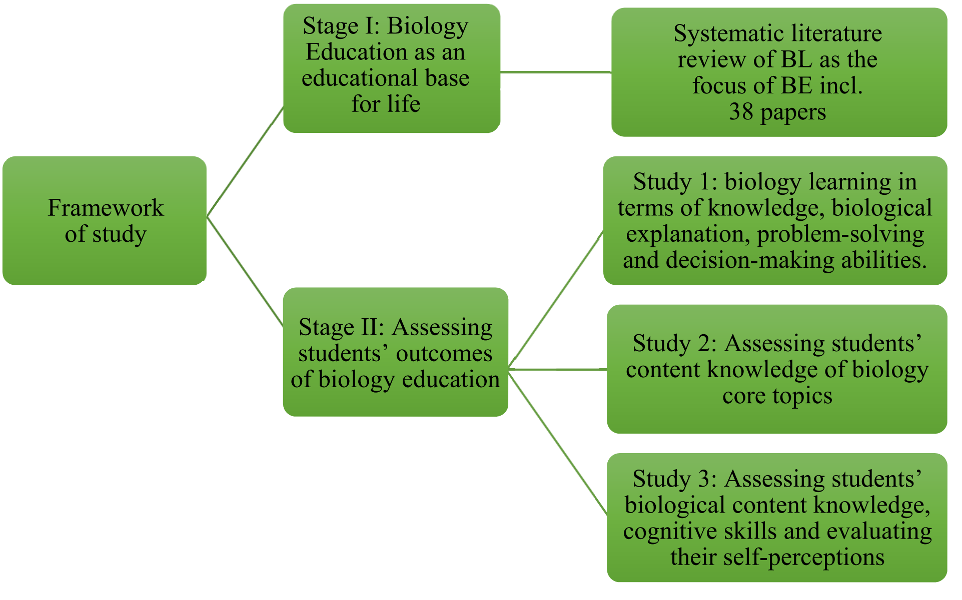

Figure 2. *Research division according to the assessment framework*

Note. Biological Literacy (BL), Biology Education (BE).

Biological content knowledge, cognitive skills and students' self-perceptions were amplified and measured in this study

Table 1. *An overview of the methodology of the study*

Stage	Study	Samples	Instruments	Design of data collection	Data Analysis	Interrater reliability	Papers
Stage I	–	38 papers	–	Systematic literature review	Following guide from Aguinis et al. (2018).	The weighted kappa	Paper I
Stage II	**Study 1**	967 Grade 10 students	Biology context-based test, with 8 cognitive tasks.	Longitudinal study	Normality test, Mann-Whitney *U* test, CFA.	EFA, CFA	Paper II
	Study 2	Upper secondary graduate students, varies 218–278 per year	50 multiple choice items covering 7 main topics.	Empirical study	EFA, CFA.	EFA, CFA	Paper III
	Study 3	130 students Grade 11	Combination of instruments used in Study 1 and Study 2. Plus, added tasks, that measured students' self-perception.	Empirical study, 2019.	Bivariate 2-tailed correlation test.	EFA, CFA	Paper IV

Note. Explorative Factor Analysis (EFA), Confirmative Factor Analysis (CFA).

3.1 Stage I: Conducting a systematic literature review of biological literacy

To conceptualise the meaning of biological literacy, a systematic literature review was conducted in April 2020 and updated in December 2020 using an electronic EBSCO host database. To gain an overview of worldwide views on biological literacy, the use of the guide for this systematic literature review (Aguinis et al., 2018) sought to gain an appreciation of the emphases placed on the development of biological literacy.

Data collection

The sample of articles was limited to academic articles in the EBSCO database.

After meeting the inclusion and exclusion criteria, 38 articles were used in this systematic literature review (flowchart of the search and screening process can be seen in Figure 3).

The search was limited to articles from academic journals and resulted in 505 articles. Additional records from the references in the searched articles were added (2). After removing the duplication of articles and articles published in foreign languages, the number of articles used in this study was reduced to 74. Based on duplications 12 more screened articles were excluded – 62 article abstracts were assessed for eligibility. Based on the abstracts 12 articles were not focused on biological literacy and they were excluded. The full texts of 50 articles were analysed based on whether the concept of biological literacy was defined, and 12 in total were excluded because they did not include biological literacy.

The EBSCO database was selected because it includes information from many relevant databases (e.g., ERIC, Science Direct, Academic Search Complete), and therefore is seen as giving a very broad overview of existing literature within different fields of study.

The keywords used for the search were: *"biological literacy" OR "biology literacy"*. The inclusion criteria were as follows:

- Focusing on conceptualising biological literacy and its aspects.
- Published in the English language.
- Published in a peer-reviewed academic journal.

The full texts were searched, allowing the EBSCO host service to search for related words.

Examples of items in a systematic review protocol were chosen based on preferred reporting items for a systematic literature review (Moher et al., 2015).

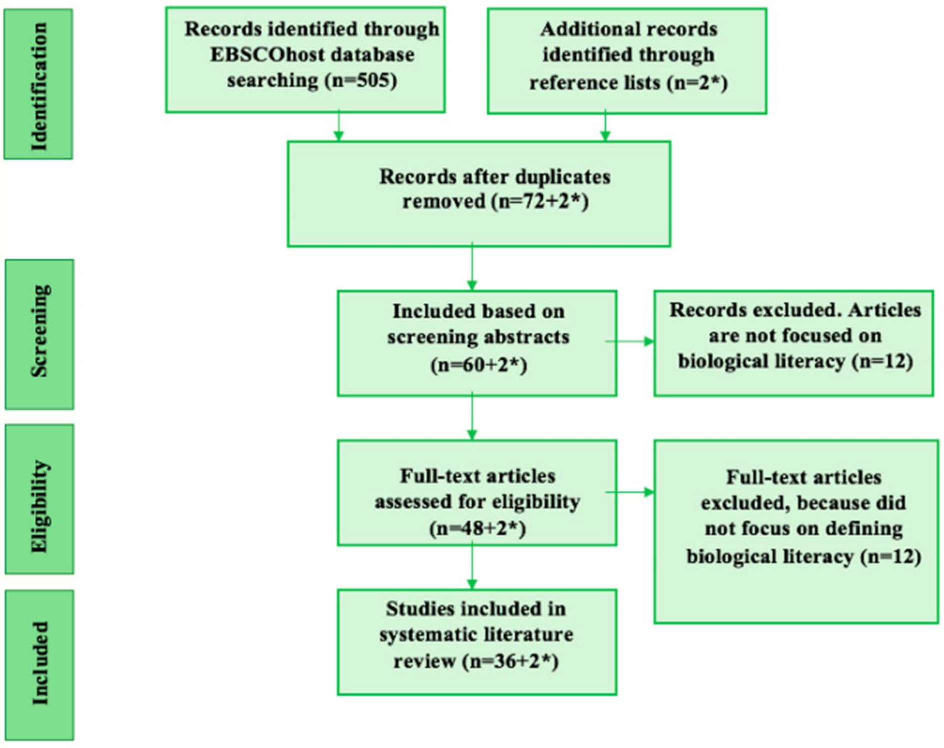

Figure 3. *Flowchart of the search and screening process for the systematic literature review*

Note. Two articles (*) were identified from the reference lists of the articles initially found and then these articles were treated as articles found in the EBSCO host database search. The flow of information through the different phases of systematic review by Moher et al. (2009) was used (Paper I).

Independent coders read through the abstract, or if needed, the full text to classify each article. They helped to calibrate the source selection process to see if the chosen articles were about biological literacy. The inclusion criteria were as follows: (1) focusing on defining biological literacy and its aspects; (2) published in the Estonian or English language; (3) published in a peer-reviewed academic journal.

The search was limited to articles from academic journals that resulted in 505 articles. Additional records from the references in the searched articles were added (2). After removing the duplication of articles and articles published in foreign languages, the number of articles used in this study was reduced to 74. Based on duplications 12 more screened articles were excluded, and 62 article abstracts were assessed for eligibility. Based on the abstracts 12 articles did not focus on biological literacy and were excluded. The full texts were analysed in the remaining 50 articles, based on whether the concept of biological literacy was defined. Twelve full text articles were excluded because they did not define biological literacy.

Data Analysis

The screening of titles and abstracts of articles was undertaken by two biology education researchers. They separately assessed every inclusion and exclusion criterion on the scale 0–2, where: 0 means there is not enough evidence to decide; 1 means the criterion is not met, nor its exclusion criterion; and 2 means all 3 inclusion criteria are met. The differences in decisions were discussed until a consensus agreement was reached.

In the case of 0, the article was further assessed based on the full text to make the final decision about inclusion. The weighted kappa for inter-rater agreement of the final decisions on the inclusion of the articles was substantial ($k = 0.73$, $p < .0001$) (Landis & Koch, 1997). There was a statistically significant agreement between the researchers.

The chosen articles were analysed based on how they conceptualised the meaning of biological literacy. The outlined aspects of biological literacy were added to the table (Paper I, Appendix).

Validity

To establish the validity of the systematic literature review, three independent biology educators evaluated the selection of articles from the review ($k = 0.73$, $p < .0001$) and validated the dimensions associated with the theoretical model for biological literacy by analysing the dimensions and determined whether they were sufficient for the stakeholders' needs. (Paper I)

3.2 Stage II: Assessing biology learning

Biological content knowledge and cognitive skills in upper secondary school students were assessed through Study 1 and Study 2.

Samples

Study 1

The stratified sample for Study 1 (Paper II) was obtained from 42 out of 151 schools forming the total list of Estonian upper secondary schools (Estonian statistics, 2019). The schools were selected by identifying every third school in an alphabetical list of schools from each of three groups (schools from the Capital city; schools from cities with at least two upper secondary schools; schools from rural areas). Criteria for the representativeness of the sample formation was described within the LoteGym project by Rannikmäe et al. (2017). The sample consisted of 503 female and 464 male grade 10 students and 489 female and 313 male grade 12 students.

The stratified sample for this research involved a total of 1769 students.

Study 2

The participants (Table 3, Paper III) consisted of upper secondary graduate students, varying in age from 18 to 25 who took an entrance test for biology in the years 2015–2018. In total the number of participants was 1017.

Study 3

The sample of students tested was formed from 130 17–19-year-old upper secondary students Table 4, Paper IV). The sample was collected from one specific school where students were taught by the same biology teacher and student participation in this study was voluntary**.**

Data collection

Study 1

For data collection, headmasters from every participating school signed an agreement/consent form with the Estonian Ministry of Education and Research. To ensure anonymity, school codes were assigned and used for the study. This context-based assessment instrument was used in the LoteGym study as one-quarter of the scientific literacy test that focused on biology knowledge (Soobard & Rannikmäe, 2015).

Study 2

The sample was collected over four years (2015–2018). The data for the study (Paper III) was obtained from students taking the medicine entrance test in biology. The students had 120 minutes to answer 50 multiple choice questions.

Study 3

The sample for the third study was chosen from schools that participated in the LoteGym project (Soobard & Rannikmäe, 2015). Schools with average results were chosen. The data for Study 3 (Paper IV) was collected through paper-and-pencil testing where students had exactly 120 minutes to complete the test.

Instruments

In the sub-studies of Stage 2, three different instruments were used in coherence with the research questions.

Study 1

The instrument used for Study 1 is one-quarter of the scientific literacy test that focused on biology knowledge and cognitive skills. This part of the instrument is based on a socio-scientific contextual situation of lactose intolerance. This instrument focuses on assessing students' cognitive skills according to SOLO levels as detailed in Table 2 (Paper II). A context-based assessment instrument on lactose intolerance consisting of 8 items was utilised from the LoteGym project team (Laius et al., 2016), the test in which test items were developed is based on the SOLO taxonomy levels as detailed in (Table 2). Categorisation of test items was undertaken, based on the LoteGym project test and this test was piloted and validated (Soobard, 2015).

The students' cognitive skills in the context of biology were assessed, utilising paper-and-pencil tests compiled according to the Structure of Observed Learning Outcomes (SOLO) taxonomy (Biggs, 1999). This kind of assessment was needed to ensure that the upper secondary school students are engaged in a biology curriculum that was coherent and prepared them for their next steps in life, whether they went on to study biology at university, utilised biology in a related career, or used their biology knowledge as non-scientist citizens.

Table 2. *Levels of SOLO taxonomy, keywords, and number of test items at each level*

Level	Biggs (1982)	Keywords	Items	Aspect assessed
Uni-structural	One obvious piece of information	Terminology	1, 7	Understanding biological concepts
Multi-structural	Use of two or more discrete and separate pieces of information	Combine	2, 6	Giving biological explanation
Relational	Use two or more pieces of information, each directly related to an integrated under-standing	Analyse, justify, apply, relate, solve problems	3, 8	Problem-solving
Extended abstract	Use abstract general principle or hypothesis	Generalise, having an insight	5, 4	Decision-making

Study 2

The 2nd instrument consisted of 50 MCQ items for each year group and were focused on 7 core concepts of biology determined by the Estonian national curriculum and biology syllabus (2014). The total item bank consists of 116 items with the assumption that every year part (approx. 20%) of the questions could be rotated, and one concept was covered by 7–8 questions in the line of the Bloom's taxonomy, including the items on different cognitive levels, demanding approx. 50% of lower order (recalling and understanding) and approx. 50% of higher-order thinking skills (application, analysis, synthesis, evaluation) as has been determined by the National Examination and Qualification Centre (REKK, 2002).

A multiple choice test was used because they were seen as having many advantages; for example, they are easy to score, allow more content to be covered, and offer better objectivity in grading; they are good for students also for learning (Butler, 2018; Pan & Rickard, 2018). Multiple choice questions are frequently used to assess student knowledge in the field of medical and other life sciences (Ahmed, 2020) as an objective and reliable tool to assess the learning performance of students (Ingale et al., 2017). Properly constructed multiple choice questions can assess higher cognitive processing in students using Bloom's taxonomy, such as interpretation, synthesis, and application of knowledge, instead of just testing the recall of isolated facts (Carneson et al., 2011).

The items were especially developed for the biology entrance tests in 2015–2018.

The core concepts included were deemed appropriate by biology education experts using the following criteria (Paper III; Semilarski & Laius, 2020):

1. Items (Table 3) were set, based on the existing Estonian Biology Curriculum (questions covered the topics included in Estonian Curriculum).
2. The 50 multiple choice items measured all 7 core concepts of biology (Paper III).
3. Items enabled easy scoring and appropriate objectivity (Butler, 2018).
4. Items enabled assessment of learning associated with application skills, analysis skills, etc. (Paper II).
5. Items were valid – measures many outcomes (e.g., topics) of biology curriculum (expert opinion described in the following paragraph).

Table 3. *Core concepts used in entrance tests in biology according to the item bank (2015–2018)*

Assessed core concept	Item numbers
Molecules and structures	1 – 19
Metabolism	20 – 37
Cell and cell theory	38 – 55
Human anatomy and physiology	56 – 78
Heredity	79 – 99
Evolution	100 – 109
Ecology	110 – 116

Study 3

The students' self-perceptions of learning biology were determined by conducting a 47-item pencil-and-paper questionnaire. The instrument combined the items from three previously used and validated instruments for assessing the biological cognitive components of the biological literacy of upper secondary students consisting of 47 items, divided into three sections (Paper, IV). The instrument's first section included 8 tasks from Study 1, the second section 25 tasks from Study 2 and the third section included 14 items from the LoteGym project self-perception questionnaire (Table 4).

Table 4. *The combined instrument used in Study 3*

	Assessed aspect	No. of items
Section 1	Biological understanding and cognitive skills according to the SOLO levels	8
Section 2	Understanding of core concepts according to Bloom's taxonomy	25
	Evaluated aspect	
Section 3	Self-perception	14

Data analysis

Study 1

Descriptive statistical methods were used to calculate means and standard deviations, noting that according to the normality test, the values for Skewness and Kurtosis fell within the acceptable level of +2 to –2, (George & Mallery, 2010). Cohen's *d* was used to calculate the effect size (magnitude of a phenomenon) using IBM SPSS Statistics 25 (Lakens, 2013). The Mann-Whitney *U* test was used to compare the results of the grade 10 and grade 12 students. To compare differences that come from the same population (Leech et al., 2005), the Mann-Whitney *U* test as a nonparametric independent *t*-test was used.

Study 2

Data analysis was carried out using the Mplus program to undertake the validation of the results. Mplus was used to investigate the instrument based on IRT (Item Response Theory, Rasch measurement) and 1PL modelling was used. As a result, a dataset was generated with 116 items consisting of variables with values 0 (incorrect answer) or 1 (correct answer).

Factor analyses were conducted to group similar items and to describe the validity of the instrument. IRT was used to describe the validity and to analyse items in the item bank.

Latent profile analysis, as a person-oriented mixture modelling analysis (Williams & Kibowski, 2016), was performed using the Mplus 8.7 program to distinguish biology entrance test results in the students' profiles based on the achievement levels of the test. That can be described through examination of the distributions of groups and determining the meaningfulness of those distributions (Ferguson et al., 2020).

To find the best model with the best number of students' profiles, procedures by Ram and Grimm (2009) were followed by choosing the optimal model based on a combination of model results, theory and fit statistics.

Models with different numbers of profiles (1–5) were compared, based on the following fit indices: Bayesian Information Criteria (BIC) and Akaike Information Criteria (AIC). Lower values in these indices refer to a better model (Masyn, 2013; Muthén, 2004). The accuracy of the models was evaluated by determining entropy values, those near 1 indicating that the individuals were grouped with high confidence and the separation between the profiles was adequate (Muthén, 2004; Tein et al., 2013), high entropy may indicate more classification uncertainty (Ferguson et al., 2020).

However, entropy as a statistical measure of uncertainty can still be useful in supporting LPA model retention as high entropy may indicate more classification uncertainty (Masyn, 2013).

An adjusted Lo–Mendell–Rubin likelihood ratio test (A-LMRT) was used to ensure that the model with k-1 profiles was not more appropriate than the model with k profiles (Yungtai et al., 2001).

In total, 116 different items were used in the biology entrance test over the 4 years. Table 5 shows the model fit statistics for the students' achievement profiles. Students' achievement profiles from each year are shown in Paper III.

Table 5. *Model fit statistics for students' achievement profiles*

Model fit statistics	1-profile model	2-profile model	3-profile model	4-profile model	5-profile model
Akaike (AIC)	*35354.316*	*34248.310*	***33550.469***	*33311.577*	*33227.855*
Bayesian (BIC)	*35774.703*	*35092.706*	***34818.876***	*35003.993*	*35344.281*
Lo-Mendell-Rubin adjusted LRT test	–	*1337.973 p=0.0000*	**930.427 p=0.3149**	*472.175 p=0.7525*	317.239 p=0.7612
Entropy	–	0.950	**0.930**	*0.944*	0.954
N for each profile	C1=277	C1=175, C2=102	**C1=121, C2=99, C3=57**	C1=39, C2=114, C3=66, C4=58	C1=62, C2=100, C3=35, C4=31, C5=49

Study 3

The dimensionality, reliability and difficulty of the instrument were measured with Rasch analysis using the Mplus program (Paper IV). Correlations between different instrument sections were analysed using a Bivariate 2-tailed correlation test of SPSS. Students' achievement levels were analysed using LPA with Mplus.

To increase the interpretation of the instrument outcomes, the statistical program Mplus (Version 7) (Muthén & Muthén, 1998–2015) was used for a confirmatory factor analysis (CFA). To evaluate the meaningfulness of the created models of Mplus, criteria for fit indexes, proposed by Bowen and Guo (2012) and Hair et al. (2013) were used based on the following criteria:

1. Root Mean Square Error of Approximation (RMSEA): Close fit: ≤ 0.05, reasonable fit: 0.05–0.08, poor fit: ≥ 0.10 (Bowen & Guo, 2012) and 0.03 < RMSEA < 0.08 (Hair et al., 2013)

2. Bentler's Comparative Fit Index (CFI): ≤ 0.95 (Bowen & Guo, 2012) and CFI ≥ 0.90 (Hair et al., 2013)
3. Tucker-Lewis Index (TLI): 0 ≤ 0.95 (Bowen & Guo, 2012) and TLI ≥ 0.90 (Hair et al., 2013).

As the chi-square fit statistic is affected by large samples (Schermelleh-Engel et al., 2003; Vandenberg, 2006), the ratio of the chi-square statistic to the respective degrees of freedom (χ^2/df) is preferred (Wheaton et al., 1977). A ratio of ≤ 2 indicates a superior fit between the hypothesised model and the sample data (Cole, 1987).

Validity and reliability

The validity and reliability of the three studies in Stage II were ensured as described in Table 6.

Study 1

Validation by the instrument's reliability was determined using Cronbach's α (0.69), which was taken to be sufficient even though the number of instrument tasks was small (Loewenthal, 1996; Taber, 2018). Cronbach's alpha of 0.60 or above was taken to indicate a significant correlation (Creswell, 2005), shown in Table 6.

Study 2

Experts were included for establishing the validity of the test. The reliability of the instruments was determined to be acceptable (Cronbach's α 0.80–0.86). The validity of the instruments for 4 years and the used methodology was determined as shown in Table 6. Items in the tests varied over the years. All seven independent experts were the same during all validations.

Study 3

The instrument was validated by three independent biology education experts and the reliability coefficient Cronbach's Alpha was 0.85 (Paper IV).

Table 6. *The validity and reliability of instruments used for assessment studies*

Study (year)	**Validity**	**Validation method**	**Reliability** ***Cronbach α***
Study 1	Content validity	Expert method: One biology researcher, one expert biology teacher, two biology education researchers. In total four independent experts in the field of biology education.	.69
	Construct validity	Analysis of Estonian upper secondary school biology syllabus to ensure that tasks are valid in terms of expected learning outcomes by experts. CFA.	
Study 2	Content validity Construct validity	Expert opinion method: two biologists, three biology teachers, two educational researchers. In total seven independent experts in the field of science education. Analysis of Estonian upper secondary school biology curriculum to ensure that items are valid in terms of expected learning outcomes. CFA, IRT.	
2015			.80
2016			.86
2017			.84
2018			.87
Study 3	Content validity	Expert method: One biology researcher, one expert biology teacher, one biology education researchers. In total four independent experts in the field of biology education.	.85
	Construct validity	Expert analysis of Estonian upper secondary school biology syllabus to ensure that tasks are valid in terms of expected learning outcomes. CFA.	

Ethical benchmarks of the study

The current research was conducted within the Estonian Code of Conduct for Research Integrity (2017). As the research activities to achieve the aims were set by the Estonian National Curriculum for Upper Secondary Schools (2011) no ethics committee approval was required.

The research participants were not subjected to damage in any way whatsoever. Consent was obtained from the participants prior to the study. The privacy of the research participants was ensured (codes were used instead of names). Confidentiality of the research data was ensured. The anonymity of the individuals and schools participating in the research was ensured. The data collected from this doctoral study is in the possession of the University of Tartu. To ensure the participants' confidentiality, the data were encoded, and no personal information was shared.

4. RESULTS AND ANALYSIS

Table 7 shows the findings from the systematic literature review (SLR) of biological literacy from a worldwide perspective (elaborated in Paper I).

Stage I

To gain an indication of the emphasis in biology education worldwide, this study was carried out to determine the different views put forward in the international literature related to the conceptualisation of biological literacy.

Results of Stage I

Table 7. *The findings from the literature review on conceptualising biological literacy (BL)*

Findings	Purpose
The concept of biological literacy covers the following components: • Cognitive component: cognitive skills; conceptual understanding; biological inquiry as a dimension. • Affective components of biological literacy: values; attitudes; bioethics. • Biology-related career awareness. • Sustainability as a component of BL. • Interdisciplinarity of biology. • Nature of biology as a component of BL.	Systematic literature analysis of biological literacy from a worldwide perspective.

The findings indicated (in Table 7) an increased use of the term biological literacy in academic articles, although a modern widely accepted meaning of biological literacy has not been defined (Paper I).

The results of the systematic literature analysis (Table 8) can be summed up with the following definition: Biological literacy is an interdisciplinary concept, including biological knowledge and core concepts, the nature of biology, and includes socio-scientific issues focused on biological issues, positive values and attitudes towards biology, biology-related career awareness that together enhances students' cognitive skills (e.g., problem-solving, decision-making, socio-scientific reasoning skills reasoning), enabling citizens to cope scientifically creatively and make theoretically justified bioethical choices about their health and towards the environment in their lives (Paper I).

Table 8. *The findings from the literature review of articles including biological literacy (Paper I, Appendix)*

Dimensions of biological literacy	Components of biological literacy	Articles included in the SLR from earlier to latest
Cognitive dimension	Biological knowledge, conceptual understanding, core concepts	Mertens & Hendrix, 1982; Demastes & Wandersee, 1992; Uno & Bybee, 1994; McInerney, 1996; Uno, 2009; Hartley et al., 2012; Begley, 2012; Illingworth et al., 2012; Köksal & Köksal, 2012; May et al., 2013; Weber, 2014; Kampa & Köller, 2016; Weber, 2017; Post et al., 2017; Suwono et al., 2017; Halmo et al., 2018; Fiedler et al., 2019.
	Cognitive skills	Mertens & Hendrix, 1982; Uno & Bybee, 1994; Lemons, 1994; Hoots, 1999; Roberts, 2001; Wright, 2005; Klymkowsky et al., 2008; Uno, 2009; Köksal & Köksal, 2012; Davenport et al., 2015; Kampa & Köller, 2016; Post et al., 2017; Suwono et al., 2017; Zangori & Koontz, 2017.
	Biological inquiry	Mertens & Hendrix, 1982; Uno & Bybee, 1994; Köksal & Köksal, 2012; Kampa & Köller, 2016; Suwono et al., 2017; Lederman, 2018.
Affective dimension	Values, attitudes, beliefs, bioethics	Riddle 1954; Mertens & Hendrix, 1982; Uno & Bybee, 1994; Gardner et al., 2016; Buma, 2018.
Sustain-ability	Human relationship with nature	Lemons, 1994; Zangori & Koontz, 2017; Narguzian, 2019; Oliveira et al., 2019.
Inter-disciplinarity	Environmental, ecological, health, genetic and literacies, biotechnology	Lemons, 1994; McInerney, 1996.
Nature of biology	Biology of science	Hoots, 1999; Narguzian, 2019.
Biology-related career awareness	career choices and the competences that are needed for them	Gerard et al., 2019; Šorgo & Špernjak, 2020.

Results from Stage II

Table 9 shows the results of assessing the different aspects of biology learning elaborated in Papers II, III and IV. Study 1 and Study 2 seek to answer the following research questions: (1) How have the cognitive skills of Estonian upper secondary school students been assessed in the context of biology and to what degree? and (2) In what manner and to what degree has the biological knowledge of Estonian upper secondary school students been assessed? Study 3 investigates (3) What self-perceptions do Estonian upper secondary school students hold in relation to their biological competence and their expectations to undertake a biology-related career?

Results from Study 1

The results of Study 1 about assessments of biology learning in terms of cognitive skills in secondary students (their understanding of biological concepts, and biological explanation, problem-solving and decision-making abilities) were obtained using a context-based 8-task instrument (Paper II) and to indicate the quality of this instrument, a CFA was carried out to ensure a quality fit (Table 10).

Table 9. *An overview of the results from Stage II*

Results of the study	Purpose
• The CFA showed that the test was unidimensional. • The indexes showed a good model fit. • The grade 12 students did not show statistically better results in problem-solving compared with t he results from 3 years previously. • There were more students in grade 12 who obtained the highest score in the test (totally correct answers with correct explanations) than students in grade 10. • Students' conceptual understanding was sufficient, but more emphasis should be put on how to enhance their cognitive skills, especially their problem-solving skills. • Among the biological core concepts, metabolism appeared to be the most difficult topic of biology and the topics of ecology and evolution were the simplest for the students to answer.	To use SOLO levels to show students' performance growth in different competences limited to cognition. To use Bloom's taxonomy to assess the students' understanding of the core concepts of biology.
Students' opinions about their biological content knowledge and cognitive skills did not accord with their actual test results. In the case of complex tasks, they overestimated themselves.	Identifying correlations based on students' self-perception and achievement.

The instrument for Study 1 was shown to be unidimensional (Table 10), measuring the students' use of their knowledge in different tasks. The model fit statistics (Chi-square, RMSEA, CFI, and TLI) indicated that the model was statistically significant and had good quality indices.

Table 10. *Model fit statistics for the confirmatory factor analysis of student knowledge use in different tasks*

Model fit statistics	10th grade	12th grade
χ^2	87.201	28.826
df	20	20
χ^2/df	4.4	1.4
p	< .001	0.30
RMSEA	0.05	0.04
CFI	0.931	0.992
TLI	0.904	0.989

The respective degrees of freedom (χ^2/df) ratio were ≤ 2, which indicates a superior fit between the hypothesised model and the sample data (Cole, 1987). The RMSEA value ≤0.05 showed a close fit (Bowen & Guo, 2012), and CFI and TLI values ≥ 0.90 also indicated a good fit (Hair et al., 2013).

The students' performance growth from the 10th grade to the 12th grade within biological competence in terms of cognitive skills was also analysed in Study 1. This was determined according to the SOLO levels as shown in Table 11. The Mann-Whitney *U* test was used to compare the grade 10 and grade 12 student results.

Table 11. *Student biology competence in terms of cognitive skills based on the SOLO taxonomy*

Measured SOLO level	Task	Grade	Mean score of tasks (SD)	Percentage of correct answers (%)	Mann-Whitney U Test	*p*	Effect size (Cohen's *d*)
Unistructural Understanding of biological concepts	1	10	1.66 (0.99)	55.5	212609.0	<.001**	.978***
		12	2.44 (0.54)	81.3			
	7	10	2.35 (1.05)	78.4	377164.5	.215	.090
		12	2.44 (0.95)	81.5			
Multistructural Giving biological explanation	2	10	1.68 (0.88)	56.0	382002.0	.562	.079
		12	1.75 (0.89)	58.3			
	6	10	1.98 (0.69)	66.0	342711.5	<.001**	.265***
		12	2.15 (0.59)	71.7			
Relational Problem-solving	3	10	1.65 (0.96)	55.1	356190.5	<.001**	.187
		12	1.82 (0.85)	60.7			
	8	10	1.48 (0.76)	49.3	372873.0	.081	.136
		12	1.58 (0.71)	52.7			
Extended Abstract Decision-making	4	10	1.12 (0.84)	37.3	311140.5	<.001**	.354***
		12	1.43 (0.85)	47.7			
	5	10	1.13 (0.80)	37.6	349033.5	<.001**	.188
		12	1.28 (0.80)	42.7			

Note. *Significant at the .05 level (two-tailed) **Significant at the .01 level (two-tailed) ***Cohen's d > .2 shows that the difference is scientifically meaningful.

Table 11 indicates that the increase in biology competence in the students was statistically most significant at the lower level of understanding biological core concepts. During upper secondary school, the students gained significantly better results at the level of decision-making (tasks 4 and 5), while students in the 10th grade had the lowest results in these tasks. No significant development was found in tasks 2, 7 and 8. The difficulties of the tasks affected the rate of increase, as some tasks (2, 7) had already relatively higher mean scores in the 10th grade. Table 11 also shows that grade 12 students did not indicate statistically significantly higher results in problem-solving (task 8) than grade 10 students, as this task needed divergent thinking skills that evidently were not effectively improved in biology lessons. But because of the large sample size, Cohen's d was considered, and the results indicated that only the increase in the results of tasks 1, 6 and 4 (understanding biological concepts, giving biological explanations and decision-making) were scientifically meaningful but the other differences, especially in problem-solving tasks, were not pedagogically significant.

Results from Study 2

The analysis of biology entrance test results (Paper III) showed that the mean results of the students vary highly (respectively 24% to 88%). The mean results were expressed in percentages of the maximum possible outcome and the students' results are illustrated as achievement levels in Table 12.

Table 12. *Task achievement levels in biology entrance tests for 2015–2018*

Achievement level	Year	Number of items	Mean results of items (SD)	Achievement level (%)
Advanced-performed tasks (Scores are equal to or higher than 80%)	2015	9	**0.86** (0.34)	86
	2016	8	**0.83** (0.37)	83
	2017	9	**0.85** (0.36)	85
	2018	1	**0.83** (0.45)	83
High-performed tasks (Scores 60% to less than 79%)	2015	17	**0.70** (0.46)	70
	2016	19	**0.70** (0.45)	70
	2017	19	**0.69** (0.46)	69
	2018	15	**0.68** (0.46)	68
Intermediate-performed tasks (Scores 40% to less than 59%)	2015	15	**0.52** (0.50)	52
	2016	14	**0.48** (0.50)	50
	2017	14	**0.49** (0.50)	49
	2018	24	**0.48** (0.50)	48
Low-performed tasks (Scores 0% to less than 39%)	2015	9	**0.30** (0.45)	30
	2016	9	**0.30** (0.46)	30
	2017	8	**0.31** (0.46)	31
	2018	10	**0.32** (0.46)	32

To standardise the test items used to assess biological content knowledge, IRT (Item Response Theory) was used. Altogether this related to 116 different items (Appendix 1). Based on the results of IRT a lot of items were excluded from the item bank.

As the model fit statistics (Chi-square, RMSEA, CFI, and TLI) indicated in Table 13 showed that the models were statistically significant and had good quality indices, determined using an Exploratory Factor Analysis (EFA), the indexes optimal number of factors was chosen based on Preacher et al. (2013). Based on the EFA indexes, the best model to use on 2015 data was determined to be a 6-factor model, on 2016 data, a 7-factor model, on 2017 data, a 7-factor model, and on 2018 data, a 7-factor model. Based on this, a CFA was conducted, and the results are presented in Table 13.

The model fit statistics showed that the respective degrees of freedom (χ^2/df) ratio were ≤ 2, which indicates a superior fit between the hypothesised model and the sample data (Cole, 1987). The RMSEA value ≤ 0.05 showed a close fit (Bowen & Guo, 2012), and CFI and TLI values ≥ 0.90 also indicated a good fit (Hair et al., 2013).

In total, 116 different items were used in the medicine entrance biology test over the years. Table 13 shows the model fit statistics for the students' achievement profiles. Six factors were differentiated for 2015 and 7 factors for 2016–2018.

Table 13. *Model fit statistics for confirmatory factor analysis based on students' achievements in different tasks*

Model fit statistics	**2015 (6FA)**	**2016 (7FA)**	**2017 (7FA)**	**2018 (7FA)**
χ^2	1112.735	938.285	3564.568	815.126
df	940	896	1175	786
χ^2/df	1.2	1.5	2.0	1.6
p	< .001	0.2	< .001	0.1
RMSEA	0.03	≤0.05	0.00	≤0.05
CFI	0.852	0.977	0.765	0.846
TLI	0.807	0.968	0.743	0.852

As a result of Study 2, the students' achievement profiles were determined from each year (2015–2018) as shown in Paper III, Table 1.

To conduct the latent profile analysis, the test items ranked according to difficulty or percentages of correct answers and total outcome of LPA are presented in Figure 4. According to LPA, the students were grouped in 3 profiles:

1. High achievers (green line) – 57 (20.5%) students got mainly the highest scores in each item.
2. Unstable achievers (blue line) – 97 (35.9%) students got the best score in some items (in 14 items out of 50), also got the lowest scores in some items (in 14 items out of 50)
3. Low achievers (red line) – 123 (43.6%) students got mainly the lowest scores in each item.

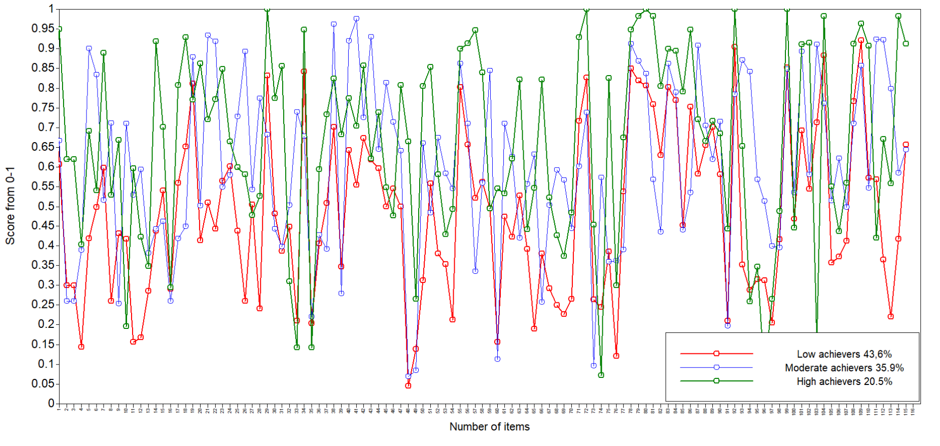

Figure 4. *Students' achievement level; 3-profile model*

Results from Study 3

The instrument for Study 3 was a combined test of three previously used instruments from the LoteGym project and the biology entrance test. The combined instrument was used to assess the biological cognitive components of biological literacy in upper secondary students and their self-perception towards biology. The instrument consisted of 47 items divided into three sections (Paper, IV), assessing biological content knowledge and cognitive skills, and evaluating the students' perceptions of their own abilities in biology. Test reliability according to Cronbach's α (.85) was high.

Results from section 1 (cognitive skills)

The mean percentage of the correct answers in the test of cognitive skills (shown in Table 14) was the highest in the students' understanding of biological knowledge (76%) and in giving biological explanations 58%, which indicated slightly above average results (over 50%). The mean percentage of correct answers for decision-making skills was 49% and for problem-solving skills only 35%.

Table 14. *Students' mean percentage per task and task descriptions of items (Paper IV)*

Level (Biggs, 1982)	Assessed aspect	Task description	Task No.	Mean score percentage (%) N=130	SD
Uni-structural	Under-standing biological concepts	The concept of lactose intolerance	1	84	.37
		The inheritance of triplets	7	67	.46
		Average		*76*	
Multi-structural	Giving biological explanation	Choice of suitable dairy products in case of lactose intolerance	2	63	.49
		Analysing the probability of osteo-porosis of lactose intolerant person	6	53	.35
		Average		*58*	
Relational	Problem-solving	Problem-solving	8	52	.38
		Changes of dairy products during fermentation	3	53	.31
		Average		*53*	
Extended abstract	Decision-making	Decision-making based on the evolutionary preferences of lactose tolerance	4	46	.28
		Diagnosing the lactose intolerance (integrative complex task)	5	32	.29
		Average		*39*	

Results from Study 3 (Paper IV) showed that students should enhance their cognitive skills, especially their problem-solving skills and decision-making skills. But compared with the results of the second section, measuring the students' biological content knowledge, the average results were higher in cognitive skills (Table 14, Table 15).

Results from section 2 (biological content knowledge)

The 2nd section of the instrument measured different core concepts of biology. All items (25) were categorised into groups based on the core concept measured (Table 14).

The analysis showed that the best mean percentage of correct answers was in the context of evolution (52%) followed by ecology (50%), cells (49%), human anatomy and physiology (47%), molecules and structures (31%), heredity (28%), and metabolism (19%) (Paper IV).

Table 15 indicates students' mean percentage scores for conceptual understanding of biological core concepts, showing the mean score percentage of each item and item descriptions of the 2nd section of the instrument.

Table 15. *Mean percentage scores on biological core concepts*

Core concept	Content of tasks	Mean score percentage (%)	SD
Cells and cell theory	Unicellular organisms	70	.46
	Cell theory	61	.49
	Cell division	49	.50
	Phases of mitosis	19	.40
	Structure of mitochondria	45	.50
	Average	**48.8**	
Molecules and structures	Complementarity of nucleotides	42	.50
	Peptides – molecules and structures	33	.47
	Chlorophyll and light absorption	24	.43
	Structure of DNA	6	.24
	Average	**26.3**	
Evolution	Struggle for existence	82	.39
	Natural selection	22	.42
	Average	**52**	
Ecology	Ecological effectiveness	76	.43
	Global warming in arctic ecosystems	51	.50
	Trophic levels and energy transfer	48	.50
	Food network	25	.44
	Average	**50**	
Metabolism	Enzymes	33	.47
	Anaerobic glycolysis	21	.41
	Metabolism of proteins	4	.21
	Average	**19.3**	
Heredity	Genetic variance	69	.47
	Number of chromosomes during the phases of meiosis	30	.46
	Division of chromosomes	10	.31
	DNA mass differences during meiosis	4	.21
	Average	**28.3**	
Human anatomy and physiology	Nucleotide order in human DNA – molecules and structures	63	.49
	The importance of lactase	55	.50
	Necessity of phosphorous	24	.43
	Average	**47.3**	

Students did not indicate high results in their knowledge of biological core concepts compared with the results of their biological cognitive skills compared with the results from Table 15 and 16 (Paper IV). This intercourse between biological knowledge and cognitive skills has changed since the previous studies in favour of skills during the operationalisation of the competence-based curriculum in Estonia.

Results from section 3 (self-perceptions of biology competence)

To evaluate the adequacy of students' self-perceptions of their biology competence, the correlations between different instrument sections were analysed using a bivariate 2-tailed correlation test. For this, the Spearman correlation coefficient (Spearman's rho) was calculated as indicated in Table 16.

Table 16. *The correlations between students' self-perception and biological competence (content knowledge and cognitive skills) (N=130)*

Self-perception statements	Level (Biggs, 1982)	Assessed aspect	Spearman's rho	p
Achievement of biology learning				
My understanding of biological knowledge is good	Uni-structural	1 – Understanding biological knowledge	–.171	.052
		7 – Understanding biological knowledge	.127	.149
I can make explanations from scientific information	Giving biological explanation	2 – Giving biological explanation, based on the given information from the text	.071	.425
		6 – Giving biological explanation	–.025	.776
I can solve scientific problems	Relational	3 – Problem-solving, analysing information from the table	.176*	.045
		8 – Problem-solving	–.120	.174
I can use socio-scientific reasoning in making decisions	Extended essay	4 – Decision-making	.552**	.000
Career-oriented statements				
I want to continue my studies in the field of biology			.338**	.000
I want to work in the biology-related field.			.402**	.000

Note. *Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

According to the correlation analysis, the students did not perceive their actual biological competence (knowledge and cognitive skills) adequately, except in scientific problem-solving and socio-scientific decision-making abilities. The students' willingness to continue their career in the field of biology was highly correlated with their biological competence.

5. DISCUSSION

As a result of the current thesis, a definition of biological literacy (BL) was developed to update the concept of BL based on a systematic literature review. Also, three instruments were developed and used to assess the students' biological content knowledge and cognitive skills and to evaluate their self-perception of biology learning.

5.1 Conceptualisation of biological literacy

This section focuses on discussing the results with respect to the first research question: *How are different views of biological literacy put forward in the literature and, what are the expectations of biology education in Estonia especially in relation to the cognitive dimension?*

The systematic literature review was conducted in the absence such a study, noting that literacy is seen as an important aspect of people's lives (Birzina, 2011; Dorfner et al., 2018, Paper I Olson, 2009; Theodotou, 2017). The concept "literacy" refers to the person's ability to read and understand knowledge on the field of study (Cope & Kalantzis, 2000). Onel and Durdukoca (2019) have indicated that there is a need to discuss biological literacy in addition to scientific literacy. A major intention of emphasising biological literacy is the need for citizens, who can cope with their everyday life in a rapidly changing world.

However, although Paper I indicated that the use of the term *biological literacy* has been increasing in the last decade; unfortunately, a clear definition of biological literacy has not been clearly identified and this is shown to be problematic (Birzina, 2011; Dorfner et al., 2018, Paper I). According to the meaning ascribed to literacy the following components of biological literacy were put forward and thus indicate important components of biology education.

The findings indicated the following components of biology education as important:

1. *Cognitive component:* Uno and Bybee (1944) referred to these as abilities while decades later Kampa and Köller (2016) used cognitive abilities to clarify this major component.
2. *Affective component*: Buma (2018) has described its meaning as attitudes, beliefs, values, and bioethics, seeing these as playing an increasing role in society and referring to their role in ensuring outcomes that involve changes in feelings, values, appreciation, interests, motivations, or attitudes that might result from learning experiences (Buma, 2018).
3. *Biology-related career awareness as a component of biological literacy:* The author of this study recommends that 21st century biology education should consider biology-related careers. Students should know careers that are related to biology and teachers should introduce these to them. Teachers themselves ought to be familiar with the new biology-based career choices.

In line with the above, the Estonian Curriculum (2014) intends the study of biology in schools to enable a comprehensive overview of the diversity as well as the structures and functions of organisms covering a wider scientific world view, seeking to solve biological problems in everyday life and making decisions for coping in the changing natural and social environment. However, there is a concern that little attention has been paid to whether these aims are being achieved, especially at the upper secondary school level, where career choices are being made and recognition of biological competences needs to be mastered to meet 21st century challenges (Anakara, 2021; Wulandari et al., 2019). Evaluating, or assessing a person's level of literacy is a complex undertaking, relying on detailed and context-bound analysis (Lind, 2008).

It is widely recognised today that rapid changes are occurring in the world and society. That is why being able to use biological content knowledge to solve problems, give explanations and make decisions are necessary skills in this rapidly changing world. This forms the rationale for ascertaining student performances as measured in this study.

The study by Chapagne Queloz et al. (2017) revealed several concepts that need to be deepened at the university level to promote biological literacy. As in this thesis, pre-university students (upper secondary school level) also participated in the previously mentioned study.

5.2 Students' biological content knowledge

To be biologically literate is essential for citizens, as nowadays biological knowledge is seen as crucial for future citizens in making decisions and solving problems in their everyday life (e.g., vaccination or becoming a gene donor). Uno and Bybee (1994) put forward the need to understand major concepts in biology. Begley (2012) concluded in her study that providing students with core concepts in biology can help them to process new information and competences can show them how practicing biologists study biology in the real world. Understanding and learning about biological concepts is important but students also need to learn how to use these concepts in different situations. Biological knowledge is needed to comprehend the core concepts of biology and to understand and apply these concepts in problem-solving.

Förtsch et al. (2018) analysed how the use of core concepts in biology lessons influenced the students' knowledge development. The findings of their study are interesting as they put forward the relationship between cognitive load and teaching based on core concepts in biology lessons. Student opinions about their biological content knowledge and cognitive skills did not accord with their actual test results, as they overestimated themselves. Modern biology teaching should not only focus on the core concepts of biology but also needs to enhance students' self-perception including positive attitudes toward biology as well as biology-related careers. The changes in biological knowledge should impact not only the students' knowledge but should also impact and lead to the ability to cope with changes, as there is need for people, who can use their knowledge in making justified decisions and solve problems in their everyday life.

Student understanding of core concepts was investigated in Study 2 and Study 3 (Paper III and Paper IV). The best mean percentage (Table 10 and Table 13) of correct answers was measured in the context of the topic of evolution; however, the mean score was low – slightly above 50 percent. Morabito et al. (2010) also indicated that student understanding of evolution is poor. The reason behind this could be that evolution is regarded as a difficult and scientifically complicated topic (Hermann, 2013; Nehm & Schonfeld, 2007; Van Dijk & Reydon, 2010).

Toman (2018) assessed students' conceptual understanding of ecology and the findings indicated that students in upper secondary school have a lack of understanding and hold misconceptions concerning fundamental concepts of ecology. The findings of this thesis indicated students' have a poor understanding of ecology. Therefore, more attention should be paid to ecology during teaching.

5.3 Students' cognitive skills when studying biology

The results of this study differed from the results of the study by Onel and Durdukoca (2019), which showed that students have a high level of biological literacy. The results of this research (Paper, II) indicated that decision-making and problem-solving skills were at a low achievement level (Table 12), meaning that students had a poor understanding of how to make effective decisions and reason them. Köksal and Köksal (2012) and Post et al. (2017) indicated in their research the same problem. This is especially concerning, as previous research by Laius et al. (2015) emphasised that the different Estonian stakeholders considered the development of decision-making and reasoning skills in graduating students as very important.

The results of Stage II, Study 2 showed that despite three years of upper secondary school biology studies, grade 10 and 12 students exhibited no gains in their cognitive skills in biology. Soobard and Rannikmäe (2015) had similar results when they measured the difference between 10th and 11th grade student scientific literacy.

Students received the highest points (level of achievement was 70%) for tasks that measured their understanding of biological knowledge. The results showed that the higher-level tasks according to the SOLO taxonomy were considerably more poorly answered (problem-solving and decision-making). It is necessary to develop student problem-solving skills. One way to do that is to increase biological knowledge to use in the problem-solving process (Greiff & Neubert, 2014).

5.4 Students' self-perception of biology

Firmansyah et al. (2018) indicated in their study that self-perception affects the outcomes of studying biology for students. Correlations were determined between students' self-perception and their achievement in biology. A statistically significant correlation was found between the students' decision-making and problem-solving skills. A statistically significant correlation was also found between students' actual biology competence and their desire to work in a biology-related field.

These results should be considered when developing the biology curriculum. Gardner et al. (2016) have investigated how a curriculum designed to increase the affective component of biological literacy increased students' self-perception; for example, students perceived that biology was more personally helpful to them as citizens, more intriguing to them, more enlightening, more relevant to "real-life" discussions, more worthwhile for them in seeking additional information, more gratifying to study, more understandable, more empowering, and that biology became more meaningful to them personally.

To validate the instruments used in this research it should be concluded that the instruments were of good quality, as the first instrument (used in Stage II, Study 1) was unidimensional, measuring students' use of their knowledge in different tasks. Based on the results of the 8 items, the instrument was unidimensional, and a CFA was carried out (Table 9).

In total, 116 different items were used over the years in the biology test to enter studies in medicine, which was used as the second instrument (in Stage II, Study 2). Table 12 shows the model fit statistics for the students' achievement profiles. Six factors were differentiated for 2015 and 7 factors for 2016–2018. The model fit statistics showed that the respective degrees of freedom (χ^2/df) ratio were ≤ 2, which indicates a superior fit between the hypothesised model and the sample data (Cole, 1987). The RMSEA value ≤ 0.05 showed a close fit (Bowen & Guo, 2012), and the CFI and TLI values ≥ 0.90 also indicated a good fit (Hair et al., 2013).

6. CONCLUSIONS

6.1 Conclusions

The aim of this dissertation was to contribute to a growing area of research by exploring the meaning behind biological literacy to explain and elucidate the meaning and components of Estonian biology education.

This research aimed to measure the biological content knowledge and cognitive skills of upper secondary school students. Also, the aim of this study is to determine self-perceptions held by Estonian upper school secondary students in relation to biological content knowledge and cognitive skills as key components of biological literacy and expectations for undertaking a biology-related cognitive skills assessment as components of biological literacy.

Based on the aim, the following research questions were posed:

1. How has biological literacy been conceptualised in the literature, especially in relation to biological literacy as determined by competences associated with biology knowledge, cognitive skills and self-perceptions?
2. How have the cognitive skills of Estonian upper secondary school students been assessed in the context of biology and to what degree?
3. In what manner and to what degree has the biological knowledge of Estonian upper secondary school students been assessed?
4. What self-perceptions do upper secondary Estonian students hold in relation to their biological competence?

To answer the research questions the following stages were carried out:

Stage I

The systematic literature review indicated six components (1) cognitive (cognitive skills, conceptual understanding, biological inquiry); (2) affective, from the systematic literature review; (3) sustainability; (4) interdisciplinarity; (5) career awareness; and (6) the nature of biology (NOB), from a literature review conducted to write a theoretical overview for this research (Paper I).

Stage II

Furthermore, data to assess the conceptual understanding and cognitive skills of upper secondary school students was collected by means of a paper-and-pencil test. Such a format can only cover selected components but not the whole framework of biological literacy.

Study 1 (Paper II) assessed the biological conceptual understanding and cognitive skills of grade 10 and grade 12 students. These two are important dimensions of biological literacy. After three years of secondary school biology studies, the students in grade 12 had significantly better results than they had in grade 10 in five out of the eight tasks. They indicated better results in understanding the scientific meaning of lactose intolerance. Grade 12 students did not show statistically better results in problem-solving.

Study 2 (Paper III) focused on evaluating biological conceptual understanding of students through core concepts in biology. The results showed that the mean results of the students' answers to questions vary greatly (respectively 24% to 88%). According to item difficulty (which was decided according to the mean score of the item), there were 4 different items: items performed at an advanced level, items performed at a high level, items performed at an intermediate level, and items performed at a low level. The results showed that we can differentiate students into profiles based on their level of achievement. The results of the examination met the requirements of the assessment system and was suitable to assess the candidates' biological knowledge. In all four years, the distribution of entrance examination scores followed a normal distribution and in accordance with the assessment regulation system, 15% of students achieved the highest score level and were successful in entering the faculty of medicine.

The aim of *Study 3* (Paper IV) was to use two different biological literacy assessment instruments combined, both were used accordingly in the second and third study. Overall, the complex instrument for measuring the biological content knowledge, conceptual understanding and cognitive skills of upper secondary school students and their self-perception about these competences is valid and reliable, and it can be suggested for use when measuring student cognitive competences in biological literacy. Among the biological core concepts, metabolism appeared to be the most difficult topic of biology and the topics of ecology and evolution were the simplest for the students to answer. This shows that the complexity of biological concepts can also influence the biological cognitive skills of students.

6.2 Recommendations

Theoretical recommendations

A recommendation from the current thesis for biology education research is that the developed model of biological literacy can be used as a framework of the dimensions of biological literacy.

Practical recommendations

Based on the empirical findings, different recommendations are apparent for teachers, and curriculum and learning material developers. The model of biological literacy should be explicit for teachers so that they understand the meaning behind the concept. Teachers should put more emphasis on the core concepts of biology, meaning that learners should understand and conceptualise different core concepts in biology. More collaboration between researchers, teachers, curriculum specialists, and assessment developers should be applied. There is a shortage of learning and teaching activities, as well as teaching materials which concern biological literacy.

Suggestions for future studies

This research has many questions in need of further investigation. It is recommended that further research is undertaken in the following areas: Research should focus on each of the branches of biological literacy in greater depth. Further data collection is required to include stakeholders besides students; for example, including teachers could enrich the data collected.

A study should be carried out, similar to that by Gardner et al. (2016), to explore how a curriculum designed to increase the affective components of biological has literacy increased students' self-perception.

6.3 Limitations

The second and fourth empirical sample included upper secondary school students (from grades 10 and 12). For the third study data was collected using a medicine faculty entrance exam in biology. The aim of the third study was to assess biological literacy after the students have graduated from upper secondary school. Unfortunately, from 2014, national exams in biology have been cancelled. That affected the sample and, why different samples were selected.

When conducting a study, it is important to have a sufficient sample size to conclude a valid research result. For the fourth study, the sample size was small because it was not part of the main study and based on that it was important to show the connection between the two different tests.

There was a lack of previous research studies on the topic – prior research studies that are relevant to biological literacy are limited.

Regarding the medical faculty entrance tests in biology, access to the respondents was limited. Interviews with the respondents were sought, but due to the addressed problem, these were not done. Despite the limitations, the findings are still reliable and valid because expert opinions were included, and test items were analysed for each year.

SUMMARY IN ESTONIAN

Bioloogiaalase kirjaoskuse kontseptualiseerimine ning gümnaasiumiastme õpilaste bioloogiahariduse kognitiivsete komponentide hindamine ning enesehinnangud bioloogias

Tänapäeval on bioloogia kiiresti arenev valdkond, mille olulised fundamentaalsed ja rakenduslikud teadussaavutused näiteks geneetikas või kliinilises meditsiinis on muutnud ühiskonda. Sellised teadussaavutused eeldavad ühiskonnaliikmete kõrget bioloogiaalast kirjaoskust, et kardinaalselt muutunud tingimustes igapäevaelus hakkama saada. Sellest tulenevalt on praeguse bioloogiahariduse peamiseks eesmärgiks suurendada õpilaste bioloogiaalast kirjaoskust, mis hõlmab bioloogiaalaseid teadmisi, kognitiivseid oskusi, hoiakuid, uskumusi ning väärtusi, sh. säästva arengu põhimõtete väärtustamist (Krell & Schmidt, 2020). Kuid bioloogia ainekavasid ei ole suudetud piisavalt kiiresti täiendada uute teadussaavutuste ja meetodite ning nn 21. sajandi kompetentsuste kujundamisega, et täita ühiskonna suurenevat nõudlust kõrge bioloogiaalase kirjaoskusega kodanike järele. Seetõttu on kooliharidusel ning bioloogiatundidel oluline roll õpilastes nende täiustunud ning uute bioloogiaalaste teadmiste ja oskuste arendamisel.

Bioloogiaalast kirjaoskust on siiani uuritud peamiselt loodusteadusliku kirjaoskuse kaudu (Eijck & Roth, 2010; Garthwaite et al., 2014; Holbrook & Rannikmäe, 2009; Klucevsek, 2017; Lederman et al., 2013; Mun et al., 2015; Smith et al., 2012). Samas on suuremat tähelepanu hakatud pöörama ka distsipliinipõhistele haridusuuringutele (Singer et al., 2013), mis rõhutavad vajadust uurida järjest keerukamaks kujunevaid distsipliine eraldi, et ühe distsipliini uurimisega rohkem süvitsi minna ning et õpitu ei jääks vaid pinnapealseks. Samas peab ka arvestama sellega, et bioloogia on ainulaadne eluga seotud teadusharu, millel on omapärased filosoofilised põhimõtted ja metoodika, mis pole sarnased teiste teadusharudega (Adegboye et al., 2017). Samas on bioloogia interdistsiplinaarne teadus ning seega on ka bioloogiaalane kirjaoskus loodusteadusliku ja tehnoloogiaalase kirjaoskuse komponent, millel on viimasega enamasti sarnased tunnused, kuid põhifookuses on bioloogiaalased teadmised, kognitiivsed oskused ja hoiakud.

Hetkel on loodusteaduslikus hariduses kolm arengusuunda: (a) jätkuvalt on kasvav rõhuasetus interdistsiplinaarsel loodusteaduslikul uurimisel; (b) loodusteadusliku hariduse liikumine globaliseerumise suunas ja (c) samas on suurenenud uuringute arv, mis on suunatud distsiplinaarsele ehk ainespetsiiflilisele lähenemisele haridusteaduses (Liu & Wang, 2019). Kindlal distsipliinil põhinev haridusteadus uurib konkreetsel erialal õpetamise ja õppimise põhilisi aspekte fokuseeritumalt ja süvitsi (Singer et al., 2013). Eelnimetatu on põhjus, miks antud doktoritöös on uuritud bioloogiaharidust ja bioloogiaalast kirjaoskust kui loodusteadusliku hariduse ja loodusteadusliku kirjaoskusega suuresti kattuvat, kuid siiski osaliselt eraldi seisvat osa, millel on bioloogiast kui eluteadusest tulenevaid erisusi ning bioloogiaalane kirjaoskus on viimasel ajal järjest rohkem kasutust leidnud termin bioloogiahariduses.

Käesoleva doktoritöö üheks eesmärgiks on uuendada ja täiendada bioloogiaalase kirjaoskuse kontseptsiooni ning hinnata gümnaasiumiõpilaste olulisemaid bioloogiaalaseid pädevusi, mille saavutamine on sätestatud 2011. aastal vastu võetud kompetentsipõhises gümnaasiumi riiklikus õppekavas, kuid mille rakendumise kohta pole piisavalt andmeid. Bioloogiahariduses on üheks probleemiks see, et erinevates uurimistöödes kasutatakse bioloogiaalase kirjaoskuse mõistet, viidates juba 1984.a. R. Bybee poolt sõnastatud kontseptsioonile või mõnele komponendile, ilma et seda mõistet oleks üheselt selgitatud (Dorfner et al., 2018). Antud probleem tekitab küsimuse, kuidas on saadud varasemates uuringutes hinnata bioloogiaalast kirjaoskust, mille sisu ei ole üheselt määratletud ega ka bioloogihariduse uuenedes täiendatud. Bioloogiaalase kirjaoskuse hindamise kohta on seni vähe uuringuid ning loetud kirjandusele põhinedes saab väita, et on kasutatud erinevaid instrumente bioloogiaalase kirjaoskuse komponentide hindamiseks (Illingworth et al., 2012; Post et al., 2017; Weber, 2014). Näitena saab tuua Indoneesia uuringu (Suwono et al., 2017), milles mõõdeti bioloogiaalast kirjaoskust 20 valikvastuselistega küsimuste testiga. Ka on Klymkowski (2005) välja toonud probleemi, et objektiivseid ja valideeritud bioloogiaalase kirjaoskuse hindamisvahendeid on siiani vähe.

Antud doktoritöö põhieesmärgiks on hinnata gümnaasiumiõpilaste bioloogiaalase kirjaoskuse põhikomponente ja selleks on vaja eespool toodud mõistet täiendada. See viib konkreetsema eesmärgi saavutamiseni ja erinevate seisukohtade ühtlustamiseni teoreetilise bioloogiaalase kirjaoskuse mudeli loomise abil. Käesolevas doktoritöös määratleti bioloogia-alane kirjaoskus loodusteadusliku kirjaoskuse alamkomponendina, keskendudes peamistele bioloogiaalastele teadmistele ja kognitiivsetele oskustele.

Bioloogiaalase kirjaoskuse teoreetilise mudeli loomiseks viidi läbi vastavasisuline teaduskirjanduse süstemaatiline analüüs. Analüüsi tulemustele vastavalt ja tuginedes gümnaasiumi riiklikule õppekavale valiti õpilaste hindamiseks kõige olulisemad bioloogia-alase kirjaoskuse komponendid: ainealased teadmised ning bioloogiaalased olulisemad kompetentsused ning nendevahelised seosed.

Bioloogias on gümnaasiumiastmes õppivatele õpilastele sageli problemaatiliseks erinevatest mõistetest ja protsessidest arusaamine ja bioloogiaalaste teadmiste rakendamine uutes situatsioonides. Viimast arvesse võttes on käesolevale doktoritööle seatud alljärgnevad eesmärgid:

1. Uuendada bioloogiaalase kirjaoskuse mõistet ning luua teooriast lähtuv bioloogiaalase kirjaoskuse mudel.
2. Hinnata õpilaste bioloogiaalase kirjaoskuse olulisemaid kognitiivseid komponente ja õpilaste enesehinnanguid.

Lähtuvalt uurimistööle seatud eesmärkidest püstitati neli uurimisküsimust:

1. Kuidas on bioloogia-alast kirjaoskust kirjanduses käsitletud, eriti seoses bioloogia-alase kirjaoskusega, mille määravad bioloogiateadmiste, kognitiivsete oskuste ja enesetajuga seotud pädevused?

2. Kuidas ja mil määral on hinnatud Eesti gümnaasiumiõpilaste kognitiivseid oskuseid bioloogia kontekstis?
3. Kuidas ja mil määral on Eesti gümnaasiumiõpilaste bioloogia-alseid teadmisi hinnatud?
4. Milliseid enesehinnanguid omavad Eesti gümnaasiumiõpilased seoses oma bioloogia-alaste pädevustega?

Töö uudsus seisneb selles, et varasemalt puuduvad teaduskirjanduses süstemaatilised analüüsid bioloogiaalase kirjaoskuse kohta ning nii Eestis kui maailmas on tehtud vähe uuringuid gümnaasiumiõpilaste bioloogiaalase kirjaoskuse ja selle komponentide saavutustasemete kohta.

Doktoritöö koosneb kahest etapist. Esimese etapi eesmärgiks oli määratleda bioloogiaalase kirjaoskuse mõiste. Selleks koostati süstemaatiline kirjanduse analüüs bioloogiaalasest kirjaoskusest. Süstemaatilise kirjanduse analüüsi abil leiti 38 bioloogiaalast kirjaoskust käsitlevat artiklit, mille abil koostati uuendatud ja täiendatud teoorial põhinev bioloogiaalase kirjaoskuse mudel.

Bioloogiaalase kirjaoskuse mudelisse kuulub kuus alljärgnevat dimensiooni süstemaatilise kirjanduse analüüsi alusel:

1. Kognitiivne dimensioon (kognitiivsed oskused, kontseptuaalne arusaam ja bioloogia-alane uurimistöö).
2. Afektiivne dimensioon (hoiakud, suhtumine ja väärtused).
3. Jätkusuutlikkus (ökoloogiline, sotsiaalkultuuriline ja majanduslik aspekt).
4. Interdistsiplinaarsus (loodusainete õpetamine lõimituna teiste valdkondadega).
5. Teadlikkus bioloogiaalastest karjääridest (valmisolek end siduda edasistes õpingutes bioloogiaalase karjääriga).
6. Bioloogia kui teaduse olemus.

Doktoritöö teine etapp tugines kolmel uuringul, mis viidi läbi gümnaasiumiõpilaste bioloogiaalase kirjaoskuse kognitiivsete ja afektiivsete komponentide hindamiseks. Kõigis kolmes ala-uuringus hinnati gümnaasiumiõpilaste bioloogiaalase kirjaoskuse peamisi komponente, mis valiti vastavalt bioloogiaalase kirjaoskuse mudelile ning gümnaasiumi riiklikus õppekavas sätestatud kompetentsustele ning bioloogia ainekavas käsitletud teemadele. Andmeid koguti gümnaasiumiõpilastelt kirjalike testide abil, mis võimaldasid hinnata valitud bioloogiaalase kirjaoskuse komponente, kuid mitte bioloogiaalast kirjaoskust tervikuna. Teine etapp võimaldab anda vastused doktoritöö teisele ja kolmandale uurimisküsimusele.

Kolm ala-uuringut viidi läbi alljärgnevalt:

1. Gümnaasiumiõpilaste bioloogiaalaste kontseptuaalsete arusaamade ja kognitiivsete oskuste (kontseptuaalne arusaamine bioloogiaalastest põhimõistetest, kognitiivsed oskused: põhjendamisoskus, probleemi lahendamise ja otsuse tegemise oskus) hindamiseks viidi läbi longituuduuring, mis tugines kontekstipõhistele probleemülesannetele. Instrumendina kasutati longituuduuringu ühte osa, mis oli fokuseeritud bioloogiaalasele laktoositalumatuse kontekstile ja moodustas loodusteadusliku kirjaoskuse suuremahulisest testist, mis oli läbi viidud projekti LoteGüm raames (Soobard, 2015). Andmeid koguti 10. klassi õpilastelt (967 õpilast) ning saadud tulemusi võrreldi samade uuringus osalenud õpilaste tulemustega, kui nad olid jõudnud 12. klassi (802 õpilast). Tulemused näitasid, et kolme gümnaasiumiaasta jooksul nende tulemused paranesid viies ülesandes (ülesannete koguarv oli kaheksa). Õpilaste keskmised tulemused olid mõlemas uuritud klassis madalad. 12. klassi õpilased näitasid paremaid tulemusi bioloogiaalaseid teadmisi uurivates ülesannetes. Tulemuste muutus oli küll statistiliselt usaldusväärne, kuid suure valimi tõttu näitas *Coheni d*, et muutus ei ole pedagoogilises mõttes märkimisväärne. Õpilaste tulemused ei paranenud probleemi lahendamise ja põhjendamise ülesannetes. Seetõttu on oluline bioloogiatundides senisest enam tähelepanu pöörata õpilaste põhjendamisoskuse arendamisele.
2. Selleks, et hinnata õpilaste bioloogiaalaste teadmiste kognitiivseid tasemeid bioloogia ainekavas ettenähtud teemades (sh ökoloogia, rakuteooria, evolutsioon, pärilikkus, metabolism, molekulid ja struktuurid, inimese anatoomia ja füsioloogia), kasutati valikvastuselist 50 küsimusega kirjalikku bioloogia testi. Valimi moodustasid gümnaasiumi lõpetanud, kes tegid Tartu Ülikooli arstiteaduskonda sisseastumiseks erialakatse bioloogias. Põhiuuringusse kaasati sisseastujate tulemused aastatest 2015–2018, mis tegi valimi koguarvuks 1017 gümnaasiumi lõpetanut. Tulemused näitavad, et õpilaste tulemused erinesid suurel määral, kuid keskmised tulemused olid madalad ning seda eriti kõrgemat mõtlemisjärku eeldavate küsimuste osas.

Selleks, et näidata eespool nimetatud erinevate õpilaste bioloogiaalase kirjaoskuse komponentide tulemuste omavahelisi seoseid, koostati kolmas uuring, mille läbiviimiseks kasutati kombineeritud test, mis sisaldas nii kontekstipõhiseid probleemülesandeid kognitiivsete oskuste mõõtmiseks, ainealaste teadmiste erinevaid kognitiivseid mõtlemisoskuste tasandeid hindavaid ülesandeid kui ka õpilaste enesehinnanguid ja hoiakuid mõõtvaid küsimusi. Kolmandas uuringus osales 130 11. klassi õpilast. Saadud tulemustest selgub, et kui õpilased ei saanud bioloogiaalastest põhimõistetest ja protsessidest arusaamisel häid tulemusi, siis oli ka nende kognitiivsete oskuste tase madal. Madalate ainealaste ja kognitiivsete oskuste taga võib olla Eesti riiklik õppekava, mis rõhutab küll õpilaste erinevate kognitiivsete oskuste arendamist, kuid mida bioloogia peamiselt ainekeskne õppekava piisavalt ei toeta. Lisaks võib seda põhjendada ka asjaoluga, et gümnaasiumiõpilaste ainealaste teadmiste langus bioloogias algas pärast Bioloogia riigieksami kaotamist 2014. aastal.

Adnan ja tema kolleegid (2021) on välja toonud, et ühiskonnas on kasvamas nõudlus bioloogia-alase kirjaoskuse märkimisväärse arendamise järele. Antud doktoritöö tulemused näitavad, et koolibioloogia ei toeta bioloogiaalase kirjaoskuse arendamist piisavalt ning vajab uuendamist. Kuna seni puudus bioloogiaalase kirjaoskuse selge kontseptsioon (Dorfner et al., 2018), siis antud doktoritöö tulemusena valminud bioloogiaalase kirjaoskuse täiendatud kontseptsioon ja teoreetiline mudel on esialgseks võimaluseks selle probleemi lahendamisel, sest bioloogiaalase kirjaoskuse ja selle komponentide hindamine on eelduseks bioloogiaalase kirjaoskuse taseme tõstmiseks. Õpilased õpivad sageli motiveeritumalt seda, mida hinnatakse, kuid bioloogiaalane kirjaoskus on vältimatult vajalik tänapäeva üha keerukamates tingimustes. Seda selleks, et lahendada loovalt probleeme, võtta vastu põhjendatud otsuseid ning suhtuda teadmistepõhiselt ja vastutustundlikult loodusesse.

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APPENDICES

Appendix 1. *1-parameter IRT model results item specific parameters*

Item	Item nr. In LPA (Figure 4)	Core concept	Estimate	S. E	Est/S. E	p-value
MOL1	1	*Molecules and structures*	–0.046	0.088	–0.518	0.604
MOL2	2		0.806	0.028	28.863	0.000
MOL3	3		0.071	0.082	0.871	0.387
MOL4	4		0.069	0.079	0.869	0.385
MOL5	5		0.889	0.015	60.696	0.000
MOL6	6		0.946	0.007	129.905	0.000
MOL7	7		0.926	0.008	111.605	0.000
MOL8	8		0.151	0.077	1.967	0.049
MOL9	9		0.923	0.009	104.865	0.000
MOL10	10		0.051	0.076	0.664	0.507
MOL11	11		0.887	0.011	77.360	0.000
MOL12	12		0.901	0.012	76.042	0.000
MOL13	13		0.910	0.012	70.128	0.000
MOL14	14		0.044	0.079	0.553	0.580
MOL15	15		0.228	0.074	3.094	0.002
MOL16	16		0.115	0.076	1.508	0.132
MOL17	17		0.841	0.018	46.568	0.000
MOL18	18		0.123	0.076	1.612	0.107
MOL19	19		0.037	0.078	0.475	0.635
META1	20	*Meta-bolism*	0.097	0.092	1.058	0.290
META2	21		0.726	0.031	23.137	0.000
META3	22		0.955	0.008	123.580	0.000
META4	23		0.956	0.007	138.365	0.000
META5	24		0.740	0.030	24.311	0.000
META6	25		–0.011	0.078	–0.137	0.891
META7	26		0.918	0.009	106.251	0.000
META8	27		0.951	0.006	164.994	0.000
META9	28		–0.115	0.076	–1.514	0.130
META10	29		0.924	0.009	107.302	0.000
META11	30		0.075	0.089	0.840	0.401
META12	31		0.047	0.077	0.611	0.541
META13	32		0.753	0.028	27.025	0.000
META14	33		0.843	0.014	59.760	0.000
META15	34		0.913	0.011	81.187	0.000
META16	35		0.085	0.089	0.962	0.336
META17	36		0.858	0.019	44.137	0.000
META18	37		0.161	0.076	2.113	0.035

Item	**Item nr. In LPA (Figure 4)**	**Core concept**	**Estimate**	**S. E**	**Est/S. E**	**p-value**
CELL1	38	Cell and cell theory	0.144	0.076	1.902	0.057
CELL2	39		0.967	0.009	106.884	0.000
CELL3	40		0.657	0.032	20.433	0.000
CELL4	41		0.956	0.009	107.075	0.000
CELL5	42		0.958	0.008	124.055	0.000
CELL6	43		0.719	0.033	22.036	0.000
CELL7	44		0.933	0.010	96.833	0.000
CELL8	45		0.050	0.079	0.632	0.527
CELL9	46		0.908	0.010	93.408	0.000
CELL10	47		0.898	0.010	88.607	0.000
CELL11	48		0.095	0.078	1.222	0.222
CELL12	49		0.500	0.035	14.122	0.000
CELL13	50		–0.063	0.095	–0.662	0.508
CELL14	51		0.916	0.009	101.278	0.000
CELL15	52		0.293	0.070	4.165	0.000
CELL16	53		0.902	0.010	91.329	0.000
CELL17	54		0.879	0.012	71.968	0.000
CELL18	55		0.899	0.012	76.989	0.000
HUM1	56	*Human anatomy and physiology*	0.798	0.030	26.338	0.000
HUM2	57		0.796	0.030	26.880	0.000
HUM3	58		0.129	0.076	1.709	0.087
HUM4	59		0.729	0.031	23.526	0.000
HUM5	60		0.920	0.009	105.679	0.000
HUM6			0.131	0.086	1.522	0.128
HUM7	61		0.903	0.010	92.666	0.000
HUM8	62		0.881	0.011	79.658	0.000
HUM9	63		0.119	0.076	1.569	0.117
HUM10	64		0.869	0.013	68.870	0.000
HUM11	65		0.913	0.010	89.777	0.000
HUM12	67		0.249	0.073	3.403	0.001
HUM13	68		0.865	0.014	64.060	0.000
HUM14	69		0.893	0.012	74.861	0.000
HUM15	70		0.891	0.013	71.041	0.000
HUM16	71		0.881	0.013	65.844	0.000
HUM17	72		0.078	0.081	0.959	0.338
HUM18	73		0.237	0.088	2.695	0.007
HUM19	74		0.054	0.085	0.632	0.528
HUM20	75		0.886	0.014	61.922	0.000
HUM21	76		0.773	0.025	31.007	0.000
HUM22	77		0.873	0.017	51.414	0.000
HUM23	78		0.017	0.077	0.218	0.828

Item	Item nr. In LPA (Figure 4)	Core concept	Estimate	S. E	Est/S. E	p-value
HER1	79	*Heredity*	0.866	0.028	31.256	0.000
HER2	80		0.920	0.023	39.294	0.000
HER3	81		0.895	0.025	35.318	0.000
HER4	82		0.302	0.076	3.971	0.000
HER5	83		0.099	0.076	1.292	0.196
HER6	84		0.798	0.030	26.338	0.000
HER7	85		0.749	0.030	25.030	0.000
HER8	86		0.104	0.076	1.368	0.171
HER9	87		0.122	0.081	1.510	0.131
HER10	88		0.935	0.010	94.251	0.000
HER11	89		0.048	0.079	0.604	0.546
HER12	90		–0.009	0.079	–0.119	0.905
HER13	91		0.900	0.010	86.127	0.000
HER14	92		0.024	0.084	0.293	0.769
HER15	93		0.122	0.099	1.235	0.217
HER16	94		0.936	0.007	125.572	0.000
HER17	95		0.917	0.009	99.117	0.000
HER18	96		0.862	0.014	62.614	0.000
HER19	97		0.857	0.016	53.360	0.000
HER20	98		0.866	0.016	53.752	0.000
HER21	99		0.067	0.076	0.883	0.377
ECO1	100	*Ecology*	0.850	0.027	31.794	0.000
ECO2	101		0.127	0.076	1.666	0.096
ECO3	102		0.812	0.030	27.272	0.000
ECO4	103		0.794	0.027	28.953	0.000
ECO5	104		0.905	0.009	96.641	0.000
ECO6	105		0.227	0.093	2.450	0.014
ECO7	106		0.872	0.013	69.664	0.000
ECO8	107		0.896	0.011	84.842	0.000
ECO9	108		0.057	0.077	0.746	0.456
ECO10	109		0.164	0.084	1.961	0.050
EVO1	110	*Evolution*	0.098	0.106	0.929	0.353
EVO2	111		0.197	0.076	2.597	0.009
EVO3	112		0.934	0.008	115.293	0.000
EVO4	113		0.956	0.006	159.784	0.000
EVO5	114		0.918	0.009	100.967	0.000
EVO6	115		0.836	0.021	40.431	0.000
EVO7	116		0.115	0.080	1.441	0.149

Note. Two articles (*)

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