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# Visioning Transformative Science Education for Sustainability

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Abstract

This article explores how global citizenship can be seen in the practices of science education in the context of international education policy and Finnish school and teacher education, with a focus on scientific literacy and sustainability education for promoting a sustainable future. Possibilities of science education to promote sustainability are discussed through teaching examples based on socio-scientific approaches. In addition, transformative science education for sustainability is regarded through competence development taking into account different knowledge dimensions. Solving problems however requires not only knowledge but also communicative and strategic and speculative activity. Thus, education must emphasize the main visions of scientific literacy and transdisciplinary perspectives proposed in the literature, supporting students to understand society and everyday socio-scientific challenges from the local to global level and to deal with differing scientific results and uncertain information. Our article presents findings and conclusions that provide opportunities for further work and provide insights into science and educational sustainability practice.
*Keywords:* science education, education for sustainable development, socio-scientific issues approach, sustainability competencies, scientific literacy.

## Introduction

Science education is crucial in implementing sustainability and promoting citizens' understanding of sustainability issues. It also influences young people's willingness to choose science professions to meet sustainability challenges. Societies confront multifaceted socio-scientific issues. For example, solving questions about energy, water, waste, public health threats, food, transport and climate change in a sustainable way requires scientifically literate citizens and science professionals. In this sense, the science-technology-society (STS) movement (Aikenhead, 1994) aims to change science education from learning science concepts towards understanding the relationships between science, technology and society. Further, socio-scientific issues (SSI) based approaches have been increasingly applied in teaching and learning processes (Chowdhury et al., 2020). SSI usually deals with value-laden, controversial and ill-structured situations and real-life problems involving moral reasoning and ethical perspectives. Students participate, for example, in decision making related to current social issues in a relevant context (Chowdhury et al., 2020). In accordance with the goals of science education, this supports students' scientific literacy and ability to participate in socio-scientific discourse (Hofstein et al., 2011) and promotes citizenry (Chowdhury et al., 2020). In this respect, the pedagogical approaches used in SSI are similar to those highlighted in Education for Sustainable Development (ESD) (Laurie et al., 2016; Lozano et al., 2017).

According to UNESCO (2020), ESD increases students' and the general public's awareness of the 17 Sustainable Development Goals (SDGs) and the understanding of their importance for individual and community life. Sustainable development competence should be developed through action-oriented transformative pedagogy (Rieckman, 2018). Using interactive, project-based, student-centred approaches based on a school-wide ESD programme, students can live what they have learned and learn to change their behaviour (UNESCO, 2020). Competence in sustainable development covers the knowledge, skills and attitudes needed to successfully perform tasks and solve problems in relation to real life (Wiek et al., 2011a). Key competencies to be taught are (Wiek et al., 2011a, 2016): interpersonal (or collaboration) competence, systems thinking competence, futures thinking (or anticipatory) competence, strategic thinking (or action-oriented) competence and values thinking (or normative) competence. According to Wiek et al. (2011b, 2016), interpersonal competence means that a student knows how to initiate, facilitate and support various forms of collaboration, for example, teamwork and stakeholder engagement in sustainability issues. A student masters systems thinking when they are able to analyse local, regional and global sustainability problems in different fields. They master future thinking when they know how to foresee problems of sustainability, create and form sustainable and desirable visions of the future, and examine alternative development paths in the light of evidence. The student possesses strategic thinking when they know how to develop and test interventions and transition strategies that promote sustainable development taking into account undesired consequences and successive effects. A student's value thinking is valid when they know how to define, compare, apply, reconcile and discuss the values, principles and goals of sustainability, for example from the perspective of justice, equity and responsibility in various processes, including visioning and evaluation. The global well-being and survival of individuals and societies requires the inclusion of competencies related to empathy, solidarity and action in education (UNESCO, 2020).

The complexity of current challenges requires education that develops students' scientific thinking in order to implement sustainability initiatives. International organizations have drawn up several guidelines for environmental and sustainability education since the 1970s. Initially, the education guidelines emphasized understanding of environmental problems and practical skills. Later, the focus has shifted from local and regional ecological issues towards societal and global environmental issues and global citizenship (Jeronen, 2023). According to UNESCO (2014), global citizenship refers to a sense of belonging to a wider community and common humanity and emphasizes political, social, economic and cultural interdependence from the local to the global level.

The article examines the possibilities of science education to promote sustainability through scientific literacy (SL). Brickhouse (2007) highlights four dimensions related to SL: civic, personal, cultural and critical. Scientifically literate citizens understand the nature of symbolic systems of representation and expressions, are aware of their own socio-scientific ways of thinking, and know how to relate their actions to their own needs and those of society. The SSI approaches we present have been found to promote students' activities towards sustainability.

## Three Visions of Scientific Literacy and Teaching Examples

Scientific literacy (SL) is a socially shaped, context- and time-dependent concept (Laugksch, 2000; Wickman et al., 2012), which emerged in the 1950s and has been used to define goals for science education worldwide (Bybee, 1995, 1997; Roberts & Bybee, 2014). The three visions of SL proposed in the literature (Sjöström & Eilks, 2018; Sjöström et al., 2020; Valladares, 2021) (hereafter Vision/s) are rather abstract, but they offer a broad view of science education and its different orientations and goals (Wei & Lin, 2022). Vision I emphasizes learning concepts and the acquisition of scientific content knowledge for a future career in science (Roberts, 2011). Vision II focuses on societal contexts connecting science and students' everyday experiences to ensure citizens are empowered to participate in action and able to make informed decisions (Haglund & Hultén, 2017). Vision III expands the conceptual dimension (Siarova et al., 2019). It is agency-oriented and includes competencies related to the development of participation, such as communication and decision making. It emphasizes social participation and advocates a politicized approach to science education (Sjöström & Eilks, 2018). Vision III strives for dialogic emancipation, the cultivation of critical global citizenship and the advocacy of social-ecological justice, where contentious and relevant issues guide the curriculum (Valladares, 2021). According to Sjöström and Eilks (2018), Vision III has a strong connection to transformative learning and education for sustainable development (EfS) due to its actor orientation. In Visions II and III, the goals are to develop critical-democratic participation skills and foster sustainability (Sjöström et al., 2020).

Visions I-III shape the content and culture of science education in different ways. For example, both Visions II and III emphasize relevance (Valladares, 2021). The difference is that the former emphasizes the importance of everyday life relevance and the latter the importance of critical citizenship and sustainability (Sjöström & Eilks, 2018). Although the Visions differ in content and purpose, they are dependent on and enhance each other and overlap to some degree (Liu, 2013). According to Liu (2013), they are intertwined with the conceptual, socio-scientific curriculum and critique traditions of science education mentioned by Andersson (2007), thus affecting the development of the science curriculum and the organization of teaching and learning (Siarova et al., 2019).

So, what should be taken into account in teaching based on these Visions? Broderick (2023) argues that science education based on Visions I–III is pivotal for developing students' interest, knowledge and skills in science. In addition to content knowledge (Shulman, 1986), it is necessary to promote understanding of the nature of science by examining cultural, political, and economic issues (Zeidler et al., 2011). The interpretation and evaluation of scientific information presented in the media fosters students' inquiry skills (Vision I) (Siarova et al., 2019); discussing social issues develops their critical thinking and communication skills (Visions II and III) (Vieira & Tenreiro-Vieira, 2016); and students' decision-making and participation skills develop when they examine controversial real-life issues (Vision III) (Broderick, 2023).

Visions II and III and the aims of EfS include similar ideas. The aim of EfS is to foster informed, empowered and responsible global citizens who are equipped to tackle the complex challenges of the 21st century in a way that promotes the well-being of people and the planet and brings prosperity to all (Fry & Egel, 2021). EfS's holistic approach to learning addresses both academic knowledge and emphasizes environmental, social and economic sustainability (Boeve-de Pauw et al., 2022). EfS includes several similar ideas as Visions II and III, for example, health and well-being (Vision II), empowerment (Vision II), agency (Vision III), global citizenship (Vision III) and social equity (Vision III) (Kioupi & Voulvoulis, 2019).

The Finnish compulsory school curriculum highlights the learning of transversal competencies (Lavonen, 2021). The term 'transversal competencies' refers to competencies related to attitudes and values (knowing how to be) and procedures (know-how). They can be transferred from one professional field to another (Torres-Coronas et al., 2014). The curriculum also emphasizes the use of inquiry when studying situations related to life, living and society (Vision I and II). In the Finnish school context, STS and SSI approaches have been used, for example, in the following examples to promote Visions I and II but also Vision III. An STS learning project on electricity implemented among fifth graders has been found to strengthen learners' understanding of electricity scientifically (Vision I), but also in relation to societal and environmental phenomena (Vision II and III) (Havu-Nuutinen & Keinonen, 2009). The first lesson dealt with the history of electricity, life today, and life before electricity. Pupils dramatized electrical safety situations and discussed which components are needed to get an incandescent bulb to light up and how electricity is obtained from the grid. Electrical energy was also discussed: its production, distribution and consumption, as well as how it can be conserved. Pupils dramatized open and closed circuits by role playing different circuit components. They did practical experiments on the conduction of electricity by connecting light bulbs in parallel and in series. Pupils visited a university physics research department and conducted hands-on experiments in the lab. The pupils were given a research puzzle to investigate – how does the electrical current change in different circuits? They also visited a local peat-burning power plant to answer the question 'How is electricity produced (its source and phases of production) in a power station?'.

In another STS approach example, fifth graders studied the structure and functions of the biological systems of the human body (Vision I) in the context of physical exercise (Vision II) (Havu-Nuutinen & Keinonen, 2010). Before the learning project, pupils were asked to draw what they think is included in the human body. The pupils also read a short article on children's physical exercise and, in pairs, made a mind map of the effects of physical exercise on the human being. The first unit started with a drama presented by student teachers. The drama discussed the importance of exercise and the most useful forms of exercise. Next, the student teachers showed pupils an X-ray of a human hand and discussed with them physical systems and technological devices related to the skeleton, joints and muscles and physical exercise. The science content included the structure and functions of the skeleton, joints and muscles. Technology and societal issues such as physical exercise today were discussed. Throughout the week, the pupils undertook the task of monitoring their individual physical activity, following the provided guidelines On the following week, the pupils carried out breathing and blood circulation tests. They measured the pulse, blood pressure, respiratory rate and lung volume. Finally, ways to take care of blood circulation and the lungs were discussed. The student teachers drew a digestive tract on a T-shirt and discussed with the pupils what happens to the banana that a student teacher had just eaten. The pupils then built a digestive tract using available materials: balloons, rubber bands, string, thread, and cardboard. Finally, the learning was tested in a small team competition. The pupils also reflected on their own group work.

In Visions I–III, argumentation and socio-scientific reasoning are the key competencies (UNESCO, 2016). Teaching-learning modules to promote these competencies have been developed and tested in several EU-funded science education projects, such as PROFILES and MultiCO (http://www.profiles-project.eu/; https://uefconnect.uef.fi/en/group/multico). PROFILES focused on a three-stage model of learning: scenario (context), inquiry, and decision making (conclusion). MultiCO focused on career awareness. In the developed learning modules, pupils had opportunities to engage in discussion as part of their science lessons, develop their scientific inquiry skills (Vision I), design scientific inquiries, and link science with their everyday life (Vision II and III). Pupils also evaluated scientific information from various sources (Vision II and III). Particularly in the MultiCO study modules, pupils also had opportunities to learn about careers in science (Vision III).

## Teaching and Learning Sustainability

For promoting sustainability, education plays a key role in changing the values and structures of society and individuals (UNESCO, 2019). The most important educational goal is SDG 4, which emphasizes the opportunity for all citizens to participate in basic education, lifelong learning and quality education at all educational levels (UNESCO, 2016). At all educational levels, the purpose of teaching is to teach understanding. This requires teachers to organize the subject matter to create thought-provoking activities that challenge students to extend and apply their prior knowledge.

During the last three decades there has been a constant debate about the role of education in teaching sustainability. Despite the different trends in environmental education and sustainability education (Table 1) there is a common understanding that in order to promote sustainability the goals of education must include cognitive, psychomotor and affective dimensions. As many professional skills, especially sustainability skills, are related to personal development and growth, teaching and learning must touch heads, hands and hearts to achieve transformative learning (Sipos et al., 2008).

**Table 1**
*Concepts of Environmental Education and Sustainability Education (Jeronen, 2023).*

| Concepts | Educational view |
|---|---|
| Environmental education (EE) | In the beginning, the view emphasized environmental awareness and the protection of ecological systems (Taylor et al., 2019) as well as biophysical knowledge of the environment and related problems and increasing motivation to act to solve problems (Stapp, 1969).<br>Today, this holistic view includes aspects of the ecological, socio-economic and political environment and the connections between them emphasizing value education and the active participation of the individual (Tilbury, 1995/2006). |
| Education for sustainable development (EfSD, ESD) | The future-oriented view that emphasizes the social and economic aspects of sustainability (Taylor et al., 2019) and strives for it by increasing students' cognitive, social, emotional and action learning of sustainability at all levels of education (Fien, 2001; Taylor et al., 2019; Tilbury, 1995/2006). |
| Education for sustainability (EfS) | Like ESD, but the view emphasizes more social factors and active citizenship (Taylor et al., 2019). |
| Sustainability education (SE) | Like ESD, but the view emphasizes humanistic and ecological values and understands and appreciates a transformative way of thinking and strives for sustainability with the aim of maintaining ecological, social and economic well-being by recognizing their interdependence (Sterling, 2001, 2003, 2004, 2008). |
| Environmental and sustainability education (ESE) | The view emphasizes achieving a sustainable and equal world through environmental education, sustainability education and peace education. The goal is social and environmental well-being (Cincera et al., 2022; Simms et al., 2020). |
| Transformative sustainability education (TSE) | The view aims to change socio-ecological worldview and values, perceptions and actions regarding sustainability (Sterling, 2010-2011; Sterling et al., 2013; Sterling et al., 2018). |

In order to achieve transformative learning, similarly to ESD (UNESCO, 2019), Vision III pays attention to:

- student's individual change processes and how they happen
- critical thinking skills of students
- action learning and
- socio-emotional learning alongside cognitive learning.

Also EfS and transformative science education have a strong connection; issues of sustainability are often strongly integrated into science education. Similarly to EfS, transformative science education realizes Vision III. In transformative science education, contexts can be real-life (Vision II and III) or future oriented (Vision III). Recently, the term future-oriented science education has also been used (e.g., Laherto & Rasa, 2022). When the issues under consideration in science education focus on the future, possible future paths can be discussed. These cases offer the possibility to move from transformative knowledge to speculative knowledge (Stengers, 2011).

A transformative perspective on the promotion of sustainable change was seen, for example, in the Landscape learning module (NEED Project, ) implemented in a Finnish primary school (Age 10-11) (Kärkkäinen et al., 2017). This socio-scientific issues based inquiry learning module is a combination of EfS and science education. The intervention was carried out in school and in a nature park (out-of-school context). The primary school pupils studied landscape related issues through historical pictures showing the changes in the landscape. They also conducted several inquiry-based investigations. The pupils' landscape representations were recorded both before and after the intervention. It was found that socio-scientific issues based inquiry learning in varied learning environments noticeably enriched the pupils' representations and led to a multifaceted, holistic understanding of the landscape.

## Transformative Education

In order to make changes, students and societies need to understand global problems and know how to deal with them. According to Morrison (2016), transformative education can be used to steer students and societies towards social justice and democratic ideals. Transformative learning supports students' development of abilities needed in the future, such as responsiveness and responsibility, as well as students' learning and critical examination of phenomena and events (Howard, 2018). Transformative education is useful when developing students' awareness of themselves and their environment (Leal Filho et al., 2018; Mezirov, 1996, 2000). Transformative learning is a learning process in which the student interprets his or her previous experiences and points of view in order to form new or modified understanding to guide their future activities. It is based on an emancipatory approach (Sjöström & Eilks, 2018), where the student expands their awareness through critical reflection (Dirkx, 1998). This leads to a deep structural change in the student's thoughts, feelings and action, whereby the way of seeing the world and oneself as a part of it changes dramatically and permanently (Mezirov, 1996, 2000; Sterling, 2010). When the new interpretation is later used to guide decision making or action, learning takes place. Emotional and spiritual meanings that students attach to their everyday experiences are important in transformative sustainable development learning (Boyd, 2003).

A transformative perspective is valuable in science education. Especially, it is important in order to promote students' deep engagement and understanding with respect to values, attitudes and awareness (Pugh et al., 2009). The didactic approach of transdisciplinary education notably contributes to the implementation of Visions II and III. According to Kubisch et al. (2022), all three Visions are predictors of transformative engagement in climate action if they are preceded by a transformative learning process. Today's science education is meant to foster changes in values, attitudes and behaviours at individual and societal levels towards supporting sustainable development (Sjöström & Eilks, 2018; Valladares, 2021). Beyond SL visions I and II, which relate to scientific knowledge and processes for later application and understanding of the usefulness of scientific knowledge in life and society (Sjöström & Eilks, 2018), Vision III is assumed to contribute to transformative engagement by means of engaging teaching methods and knowing-in-action (Aikenhead, 2007; Liu, 2013).

Transformative education is a promising didactic concept working toward the aims of Vision III, which can be described as science for transformation (Sjöström & Eilks, 2018). Transformative education is considered to be a frame enabling students' active, situational, emotional, social, and self-regulated learning (Riemeier, 2007) as well as identification and pursuit of (scientific) issues within students' lifeworld (Pedaste et al., 2015). Active engagement in a research process as well as exchange of different perspectives and forms of knowledge between students and scientific experts are assumed to contribute to transformative learning (Mezirow, 2003), which enables change in habitual thought patterns, norms, values and, finally, behaviours (Klein, 2018; Mitchell et al., 2015).

Barelli (2022) studied a future-oriented activity in which students were required to choose an urgent problem of their interest, imagine possible and desirable scenarios based on a simulation, and identify the sequence of actions to be undertaken to reach the preferable future. She discusses how the future-oriented activity led students (i) to imagine sustainable scenarios for the school of the future in which dynamic equilibrium between opposite tensions is achieved without any of them being eliminated and (ii) to recognize themselves as agents of transformation in a public, professional, and personal dimension. The structure of the future-oriented activity was designed to cause students to reflect on their role as agents of change who are able to impact the present in light of their desires for the future. In the future stories elaborated by the students, researchers identified three dimensions of agency: the public (establishing a relationship with institutions), the professional (involving relationships with colleagues), and the personal (carried out in individual routines). Future thinking activities are able to implement the goals of transformative science education for sustainability education (Laherto & Rasa, 2022). They can provide functional and student-centred pedagogy that aims for responsibility and facilitates change in both the student and society (Lotz-Sisitka et al., 2015).

## Visioning Transformative Science Education to Promote Sustainability

At the core of sustainable development, transformative action is crucial (UNESCO, 2019). The objectives of science education are to develop people's sustainability competence, environmental awareness, and increase participation and cooperation (Glavič, 2020). The focus in science education is on supporting students to become scientifically literate citizens who are able to participate in socio-scientific discourse (Hofstein et al., 2011), including sustainability issues. Particularly, SSI approaches seek to promote goals in science education related to general interest and public understanding with particular reference to: individual empowerment; intellectual capabilities such as critical thinking, logical reasoning/analytical skills, creative problem solving and decision making; national and global citizenship; socially responsible action by individuals and communities; communication skills in a variety of forms; and providing a skilled workforce for business and industry (Aikenhead, 1994, 2005; Holbrook & Rannikmäe, 2007; Rannikmäe, 2002). These objectives and features are essential for transformative science education.

Ratinen & Linnanen (2022) have studied how learning sustainability competences can be promoted in science education. They found that while the association between Finns' environmental awareness and their structural skills for making a more sustainable future is quite clear, there is a partly contradictory relation between Finns' personal dynamic skills and their environmental awareness. Structural skills refer to students' ability to organize present-day reality. Dynamic skills, on the other hand, help students navigate between local details and the global picture, between the future, the present and the past, and from the individual to the collective dimension (Levrini et al., 2021). Ratinen and Linnanen (2022) state that when emphasizing future skills in science teaching, attention should thus be paid to ways to improve individuals' abilities to assess environmental issues from a more sustainable future perspective.

Different levels of knowledge (factual, conceptual, procedural, and metacognitive) are important to include in teaching and learning processes in all science subjects (Aksela et al., 2012; Anderson et al., 2001). Factual knowledge includes the basic elements that students must know to be acquainted with a discipline or solve problems in it. Conceptual knowledge consists of the relationships between the basic elements of the structures that enable them to function together. Procedural knowledge is information about how something is done. Metacognitive knowledge involves knowledge about cognition in general as well as awareness of and knowledge about one's own cognition (Anderson et al., 2001; Krathwohl, 2002.) According to Pintrich (2002), metacognition contains three types of knowledge: strategic knowledge, cognitive task knowledge, and self-knowledge. Strategic knowledge includes knowledge of general learning, thinking and problem-solving strategies. Cognitive task knowledge includes the knowledge that tasks can be of different levels of difficulty and require different cognitive strategies. Self-knowledge includes knowledge of one's own strengths and weaknesses.

Climate change is considered by many researchers to be the most important topic of all to be taught in schools (Howlett et al., 2016; Leal Filho et al., 2018; Lehtonen et al., 2018) followed, in order of importance, by loss of global biodiversity (Leal Filho et al., 2018; Papenfuss et al., 2019) and 'a socially just world' (Moore, 2005). In Finnish school education, factual knowledge concerning climate change includes, for example, knowledge about greenhouse gases, the average carbon footprint of citizens, and greenhouse emissions producers (Yli-Panula et al., 2020). Species knowledge and identification skills form the basis for students' understanding of biodiversity and interest in environmental issues and sustainable development (Palmberg et al., 2016). Conceptual knowledge concerns knowledge of principles such as the carbon cycle and planetarity related theories (Yli-Panula et al., 2020) as well as ecological key concepts and processes that support students to see more complex relationships in natural and human systems (Palmberg et al., 2017). Procedural knowledge is covered by subject-specific information, skills, techniques and knowledge of the use of methods. This kind of information is required, among other things, for the utilization of map programs and related descriptors in regional climate change or biodiversity research. Metacognitive knowledge, on the other hand, helps the student to process new information also with respect to him- or herself as a learner and a person (Yli-Panula et al., 2020).

Sustainable development with its various dimensions is considered a core concept by many education researchers (Glavič, 2020; Howlett et al., 2016; Papenfuss et al., 2019). We suggest that the ecological dimension could be taught in science education in terms of environmental protection, the social and cultural dimension in terms of the promotion and preservation of culture, and the economic dimension in terms of sustainable and fair socio-economic development. Deep understanding of the above topics requires metacognitive knowledge including meaningful knowledge of cognition in general and awareness and knowledge of one's own knowledge, which includes strategic knowledge; cognitive task knowledge, including relevant contextual and conditional knowledge; and self-knowledge (Zohar, 2023). Individual reflection on one's own beliefs with the help of critical thinking promotes students' learning processes. The students' change process can be supported using a framework of learning experiences (learning to know – cognitive domain, learning to do – conative domain, learning living together – social domain, and learning to be – emotional domain) (UNECE, 2012).

Transformative teaching methods as student-centred methods have many positive effects both on students' personal growth and learning in general and also in science subjects. For example, problem-oriented and problem-based methods can improve student learning also when students work together using information and communication technology (Glavič, 2020). Online working can be used to enhance communication and cooperation between teachers and students and to motivate students (Ahmed et al., 2021). Cooperative learning helps students make their own thinking visible (Duschl, 2008). Service learning can increase students' self-confidence and strengthen motivation, responsibility for studying, and develop more positive relationships with other students and teachers and with the environment and the community (Turner & Fulmer, 2013). This is part of place-based pedagogy, where local environmental and community issues and problems are included in the studied theme to support learning (Grünewald, 2003). Case study methods, games and role-plays can support the structural change of students' thoughts, feelings, actions and consciousness, permanently changing the way in which they see and are in the world (Sterling, 2010). All active teaching-learning processes improve knowledge recall (Cooper et al., 2000) and develop motivation and higher level learning (Kern & Carpenter, 1986) as well as practical skills (Kent et al., 1997). They can also strengthen connections between cognitive and affective domains and develop social skills (Kent et al., 1997).

For example, in the PROFILES (2019; http://www.profiles-project.eu/) 'Energy' learning module students considered what a sustainable future might entail. Through different learning methods (e.g., role play, inquiries, cooperation) and disciplines (e.g., physics, geography, English language) students learned concepts, scientific methods, collaboration and argumentation. Through role playing, students representing different EU Member States became familiarized with the countries' energy sources. In a fictive EU meeting they then jointly decided from the sustainability perspective which energy sources should be used in the different EU countries in the future.

In a study by Varis et al. (2018), a lower secondary school teacher integrated participation competence into physics studies. In the studying process, students (7th grade, age 13) exchanged knowledge and tools with others and produced a citizen's initiative leading to an action by the municipality: the painting of a pedestrian crossing. The students were keen to exercise participation in society and produce information through inquiries for their citizen initiative. After the intervention, most of the students expressed their willingness to participate in society and act as active citizens particularly in their local communities. Students perceived that they had learned and gained competences while participating, and stated that new knowledge regarding road safety in their community was the basis for their decisions making. The students had clearly encountered a transformation in their thinking.

Health literacy, as a part of SL, is the degree to which individuals have the capacity to obtain, process and understand basic health information and services needed to make appropriate health decisions. The SSI approach by way of the three-stage model, the stages being scenario, inquiry and decision making (Bolte et al., 2012), provides an excellent opportunity for schools for local co-operation with the community. Moreover, it offers the possibility to enhance pupils' health literacy. In a study by Kärkkäinen et al. (2018), a local pharmacy was used as an example of a community organization. At the beginning of the intervention, pupils were shown to have detailed knowledge about the proper use of medicines, but they did not refer to the role of the pharmacy as a source of medicinal knowledge, which, however, they did after the intervention. Pupils' perceptions were transformed regarding how to store and dispose of unnecessary medicines and their theoretical and practical knowledge of careers in pharmacy and medicine production were deepened.

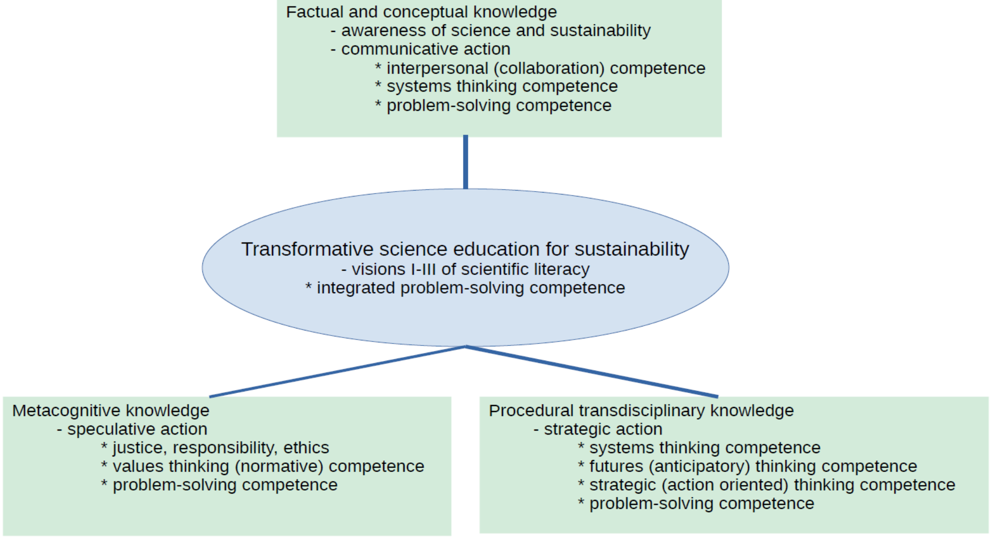
Most of the MultiCO project's career-based scenarios in science education focus on sustainability issues related to energy, water, waste, climate change, food, health and transport, as well as on career awareness and competences associated with a multitude of scientific careers and particularly on promoting collaboration, creativity and evidence-based reasoning (Keinonen et al., 2021). The aims of the MultiCO project realized through the career-based scenarios are strongly in line with the aims of EfS and quality education. Thus, MultiCO scenarios can be used to promote sustainability through science education.

Systems thinking is needed to understand that if natural life-sustaining systems collapse, human existence is also at risk. According to previous studies, a large proportion of student teachers have a relatively low level of systems thinking regarding, for example, biodiversity and ecological sustainability (Palmberg et al., 2017). Achieving a sustainable future requires an interconnected approach, creative thinking about human-environment interactions, and critical thinking when identifying, resolving, and reconciling conflicts between values, preferences, and beliefs related to environmental, social and economic systems (Remington-Doucette et al., 2013).

Stengers (2010) discusses two asymmetric branches of knowing – realist and speculative. The realist branch is so called because it verifies what is already the case. The speculative challenge concerns the difference that could be produced if scientific communities were to succeed in creating different allies than the traditional ones. Stengers (2010) proposes that a crucial speculative point is a culture of hesitation that enhances the distinction between obligations and rules or norms, or between essence and habits. The point is not to denounce habits and rules, but to amplify this distinction as important, as worth the positive attention of practitioners. Hesitation is what differentiates a practice from a normative or rule-following activity. This does not mean that practices are free from rules or norms. Only through hesitation can new knowledge be created. Speculative knowledge identifies uncertainties and alternative development paths. Speculative knowledge needs a transdisciplinary approach. Cooperation reveals uncertainties that cannot be identified within one discipline. As transdisciplinary knowledge is created in cooperation with re-searchers and practitioners, also speculative knowledge is created in cooperation, considering the uncertainties of the research objective and becoming sensitive to the challenges confronted in real life. In science education, we propose that the aim should be to create speculative knowledge by systematically implementing a future orientation in the teaching and learning process. Transformative science education can produce speculative knowledge when students seek solutions to future-oriented issues through hesitation. Arada et al. (2023) also highlights the role of science learning environments as well as the significance of teachers' pedagogical support.Transformative science education for sustainability can be summarized as follows in Figure 1.

**Figure 1**

*Transformative science education for sustainability (Anderson et al., 2001; Krathwohl, 2002; Laherto & Rasa, 2022; Rieckman, 2018; Sjöström & Eilks, 2018; Sjöström et al., 2020; Stengers, 2010; Wiek et al., 2011b, 2016; Zohar, 2023).*




Awareness of environmental and science issues is the basis for transformative science education promoting sustainability. This awareness consists of sensitivity towards the environment and factual and conceptual knowledge of sustainability and science. Communicative action is based on interpersonal competence, systems thinking competence, and problem-based competence. It involves the exchange of ideas and information between individuals and society. Developing and refining these competences can enhance one's ability to convey messages effectively, build positive relationships in personal and professional settings, and communicate in ways that address challenges and find solutions and encourage a collaborative approach to problem-solving. Procedural transdisciplinary knowledge is needed for knowing how to enable and make decisions in scientific inquiries, but also reasoned decisions on issues dealing with sustainability. Metacognitive knowledge is also important. Speculative action involves activities that are based on assumptions or uncertainties about the future. Citizens take risks or make decisions in the absence of complete information concerning local, national or global issues. In transformative science education for sustainability, Visions I-III are all present, which means that SSI approaches are used to solve both real-life and future life issues, making learning meaningful. Meaningful science also means the development of competences. The future perspective also brings to science education a hesitation aspect.

## Conclusions and Prospects

Scientific literacy has three Visions (Sjöström & Eilks, 2018; Sjöström et al., 2020; Valladares, 2021) that guide science education. Of these, Vision III is especially related to transformative learning and education for sustainability. The aim is to develop integrated problem-solving competences that are needed for citizenship. We consider that transformative science education to promote sustainability should include all three Visions.

Transformative science education for sustainability consists of awareness of the environment and science, knowledge of concepts and methods and how to work for sustainability, and metacognition allowing critical reflection and transformation of values, views, perceptions and behaviour. In a rapidly changing world, we need citizens who critically evaluate scientific information and who base their decisions on scientific information both in their private lives and their professional and societal action. Global citizenship can be seen as a process of continuous self-development (Levinson, 2010) where individuals act responsibly and actively participate in developing and implementing sustainable practices and preparing for the future (Vesterinen et al., 2016).

## References

Ahmed, S., Taqim, H. M., Farabi, Y. I., Sarker, M., & Ali, S. M., & Sankaranarayanan, B. (2021). Evaluation of flexible strategies to manage the COVID-19 pandemic in the education sector. *Global Journal of Flexible Systems Management, 22*, 81–105.

Aikenhead, G. (1994). What is STS in science teaching? In J. Solomon, & G. Aikenhead (Eds.), *STS education: International perspectives on reform* (pp. 47–59). New York: Teachers College Press.

Aikenhead, G. S. (2005). Research into STS Science Education. *Educación Química*, *16*, 384–397.

Aikenhead, G. (2007). Expanding the research agenda for scientific literacy. In C. Linder, L. Östman, & P.O. Wickman (Eds.), Promoting scientific literacy: Science education research in transaction, *Proceedings of the Linnaeus Tercentenary Symposium* (pp. 64–71). Sweden: Geotryckeriet.

Aksela, M., Tikkanen, G., & Kärnä, P. (2012). Mielekäs luonnontieteiden opetus: Miten tukea oppilaiden ajattelua ja ymmärtämistä? [ Meaningful science education: How to support students' thinking and understanding?] In Teoksessa P. Kärnä, L. Houtsonen & T. Tähkä (Eds.), *Luonnontieteiden opetuksen kehittämishaasteita* [ Development challenges in science education] (pp. 9–28). Koulutuksen seurantaraportit, 10. Helsinki: Opetushallitus.

Anderson, L. W., Krathwohl, D. R., Airasian, P. W., Cruickshank, K. A., Mayer, R. E., Pintrich, P. R., Raths, J., & Wittrock, M. C. (Eds.) (2001), *A taxonomy for learning, teaching and assessing: A revision of Bloom's taxonomy of educational objectives.* Abridged Edition. New York: Addison Wesley Longman.

Arada, K., Sanchez, A., & Bell, P. (2023). Youth as pattern makers for racial justice: How speculative design pedagogy in science can promote restorative futures through radical care practices. *Journal of the Learning Sciences, 32*(1), 76–109. https://doi.org/10.1080/10508406.2022.2154158

Barelli, E. (2022). Imagining the school of the future through computational simulations: scenarios' sustainability and agency as keywords. *Frontiers in Education*, *7*, 897582. doi: 10.3389/feduc.2022.897582

Bianchi, G., Pisiotis, U., & Cabrera Giraldez, M. (2022). GreenComp – The European sustainability competence framework. In M. Bacigalupo, & Y. Punie (Eds.), *Publications Office of the European Union*, Luxembourg. doi:10.2760/13286, JRC128040

Boeve-de Pauw, J., Olsson, D., Berglund, T., & Gericke, N. (2022). Teachers' ESD self-efficacy and practices: A longitudinal study on the impact of teacher professional development. *Environmental Education Research*, *28*(6), 867–885. doi: 10.1080/13504622.2022.2042206

Bolte, C., Holbrook, J., & Rauch, F. (2012). Inquiry-based science education in Europe: First examples and reflections from the Profiles project. Graz: University of Klagenfurt.

Boyd, R. D. (2003). *Personal transformations in small groups: A Jungian perspective,* Routledge.

Brickhouse, N. W. (2007) Scientific literates: What do they do? Who are they? *Proceedings of the Linnaeus Tercentenary 2007 Symposium Promoting Scientific Literacy: Science Education Research in Transaction*, May 28-29, 2007, Uppsala, Sweden.

Broderick, N. (2023). Exploring different visions of scientific literacy in Irish primary science education: core issues and future directions. *Irish Educational Studies*, 1-21. https://www-tandfonline com.ezproxy.uef.fi:2443/doi/full/10.1080/03323315.2023.2230191

Bybee, R. W. (1995). Achieving scientific literacy. *The Science Teacher*, *62*(7), 28. https://www.proquest.com/docview/214631067?pq- origsite=gscholar&fromopenview=true

Bybee, R. W. (1997). Achieving scientific literacy: From purposes to practices. Portsmouth, NH: Heinemann.

Chowdhury, T. B. M., Holbrook, J., & Rannikmäe, M. (2020), Socio-scientific issues within science education and their role in promoting the desired citizenry, *Science Education International, 31*(2), 203–208. https://doi.org/10.33828/sei.v31.i2.10

Cooper, J. L., MacGregor, J., Smith, K. A., & Robinson, P. (2000). Implementing small-group Instruction: Insights from successful practitioners. *New Directions for Teaching and Learning, 81*, 63–76.

Dirkx, J. M. (1998). Transformative learning theory in the practice of adult education: An overview. *PAACE Journal of Lifelong Learning*, *7*, 1–14.

Duschl, R. A. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. *Review of Educational Research, 32,* 268–291. doi: 10.3102/0091732X07309371

Fien, J. (2001). *Education for sustainability: Reorientating Australian schools for a sustainable future*. Fitzroy, Victoria, Australia: TELA: Environment, Economy and Society: Australian Conservation Foundation.

Fry, L. W., & Egel, E. (2021). Global leadership for sustainability, *Sustainability, 13*(11), 6360. https://doi.org/10.3390/su13116360

Glavič, P. (2020). Identifying key issues of education for sustainable development. *Sustainability*, *12*(16), 6500. https://doi.org/10.3390/su12166500

Grűnewald, D. A. (2003). Foundations of place: A multidisciplinary framework for place-conscious education. *American Educational Research Journal*, *40*(3), 619–654. https://doi.org/10.3102/00028312040003619

Haglund, J., & Hultén, M. (2017). Tension between visions of science education: The case of energy quality in Swedish secondary science curricula. *Science & Education*, *26*, 323–344. https://link.springer.com/article/10.1007/s11191-017-9895-1

Havu-Nuutinen, S., & Keinonen, T. (2009). Learning electricity through STS-Learning environment. *The International Journal of Learning: Annual Review*, *16*(6), 177–188. doi:10.18848/1447-9494/CGP/v16i06/46353

Havu-Nuutinen, S., & Keinonen, T. (2010). The changes in pupils' conceptions of human body based on science, technology and society based teaching. *Journal of Baltic Science Education*, *9*(3), 212–223.

Hofstein, A., Eilks, I., & Bybee, R. (2011). Societal issues and their importance for contemporary science education - A pedagogical justification and the state-of-the-art in Israel, Germany, and the USA. *International Journal of Science and Mathematics Education*, *9*(6),1459–1483. doi: 10.1007/s10763-010-9273-9

Holbrook, J., & M. Rannikmäe (2007). Nature of science education for enhancing scientific literacy. *International Journal of Science Education, 29,* 1347–1362. https://doi.org/10.1080/09500690601007549

Howard, P. G. (2018). Twenty-first century learning as a radical re-thinking of education in the service of life. *Education Sciences*, *8*(4), 189. https://doi.org/10.3390/educsci8040189

Howlett, C., Ferreira, J., & Blomfield, J. (2016). Teaching sustainable development in higher education: Building critical, reflective thinkers through an interdisciplinary approach. *International Journal of Sustainability in Higher Education, 17*(3), 305–321. doi:10.1108/IJSHE-07-2014-0102

Jeronen, E. (2023). Sustainable education. In S. Idowu, R. Schmidpeter, N. Capaldi, L. Zu, M. Del Baldo, & R. Abreu (Eds.), *Encyclopedia of sustainable management*. Springer. https://doi.org/10.1007/978-3-031-25984-5_237"

Keinonen, T., Varis, K., Constantinou, C. P., Rannikmäe, M., Scheersoi, A., & Simon, S. (2021). Integrating sustainability issues through career-based scenarios in the MultiCO project. In E. Jeronen (Eds.), *Transitioning to quality education* (pp. 203–224), Basel.

Kent, M., Gilbertsson, D. D., & Hunt, C. O. (1997). Fieldwork in geography teaching: A critical review of the literature and approaches. *Journal of Geography in Higher Education, 21*, 313–332.

Kern, E., & Carpenter, J. (1986). Effect of field activities on student learning. *Journal of Geoscience Education*, *34*, 180–183.

Kioupi, V., & Voulvoulis, N. (2019). Education for sustainable development: A systemic framework for connecting the SDGs to educational outcomes. *Sustainability*, *11*(21), 6104. https://doi.org/10.3390/ su11216104

Klein, J. T. (2018). Learning in transdisciplinary collaborations: a conceptual vocabulary. In D. Fam, L. Neuhauser, & P. Gibbs (Eds.), *Transdisciplinary theory, practice and education: The art of collaborative research and collective learning* (pp.11–23). Cham: Springer International Publishing. doi: 10.1007/978-3-319-93743-4_2

Krathwohl, D. R. (2002). A revision of Bloom's taxonomy: An overview. *Theory into Practice*, *41*(4), 212–218.

Kubisch, S., Krimm, H., Liebhaber, N., Oberauer, K., Deisenrieder, V., Parth, S., Frick, M., Stötter, J., & Keller, L. (2022). Rethinking quality science education for climate action: Transdisciplinary education for transformative learning and engagement. *Frontiers in Education*, *7,* 838135. doi: 10.3389/feduc.2022.838135

Kärkkäinen, S., Keinonen, T., Kukkonen, J., Juntunen, S., & Ratinen, I. (2017). The effects of socio-scientific issue based inquiry learning on pupils' representations of landscape. *Environmental Education Research*, *23*(8), 1072–1087, doi: 10.1080/13504622.2016.1177711

Kärkkäinen, S., Kukkonen, J., Kontturi, S., & Keinonen, T. (2018). Promoting health literacy: sixth graders working in partnership with the local pharmacy. *Health Education, 118*(6), 470-482. doi:10.1108/HE-01-2018-0004

Laherto, A., & Rasa, T. (2022). Facilitating transformative science education through futures thinking. *On the Horizon, 30*(2), 96–103. https://doi.org/10.1108/OTH-09-2021-0114

Laurie, R., Nonoyama-Tarumi, Y., McKeown, R., & Hopkins, C. (2016). Contributions of education for sustainable development (ESD) to quality education: A synthesis of research. *Journal of Education for Sustainable Development, 10*(2), 226–242. 10.1177/0973408216661442

Lavonen, J. (2021). How the Finnish compulsory school science curriculum emphasizes scientific literacy, *9*(2), 26-46 https://doi.org/10.12697/eha.2021.9.2.02b

Leal Filho, W., Raath, S., Lazzarini, B., Vargas, V. R., de Souza, L., Anholon, R., Quelhas, O. L. G., Haddad, R., Klavins, M., & Orlovic, V. L. I. (2018). The role of transformation in learning and education for sustainability. *Journal of Cleaner Production, 199*, 286–295. https://doi.org/10.1016/j.jclepro.2018.07.017

Lehtonen, A., Salonen, A., Cantell, H., & Riuttanen, L. (2018). A pedagogy of interconnectedness for encountering climate change as a wicked sustainability problem. *Journal of Cleaner Production, 199,* 860e867. https://doi.org/10.1016/j.jclepro.2018.07.186

Levinson, R. (2010). Science education and democratic participation: An uneasy congruence? *Studies in Science Education, 46*(1), 69–119. https://doi.org/10.1080/03057260903562433

Levrini, O., Tasquier, G., Barelli, E., Laherto, A., Palmgren, E., Branchetti, L., & Wilson, C. (2021). Recognition and operationalization of Future-Scaffolding Skills: Results from an empirical study of a teaching–learning module on climate change and futures thinking. *Science Education, 105,* 281–308. doi: 10.1002/sce.21612

Liu, X. (2013). Expanding notions of scientific literacy: A reconceptualization of aims of science education in the knowledge society. In N. Mansour, & R. Wegerif (Eds.), *Science Education for diversity theory and practice* (pp. 23−39), Springer.

Lotz-Sisitka, H., Wals, A. E., Kronlid, D., & McGarry, D. (2015). Transformative, transgressive social learning: Rethinking higher education pedagogy in times of systemic global dysfunction. *Current Opinion in Environmental Sustainability*, *16*, 73–80.

Lozano, R., Merrill, M. Y., Sammalisto, K., Ceulemans, K., & Lozano, F. J. (2017). Connecting competences and pedagogical approaches for sustainable development in higher education: A literature review and framework proposal. *Sustainability, 9*, 1889, 1– 15. doi:10.3390/su9101889

Mezirow, J. (1996). Contemporary paradigms of learning. *Adult Education Quarterly*, *46*(3), 158–173.

Mezirow, J. (2000). A guide to transformative and emancipatory learning, critical reflection In Mezirow, J. *(Ed.), How critical reflection triggers transformative learning.* USA: Jossey-Bass.

Mezirow, J. (2003). Transformative learning as discourse. *Journal of Transformative Education, 1,* 58–63. doi: 10.1177/1541344603252172

Mitchell, C., Cordell, D., & Fam, D. (2015). Beginning at the end: the outcome spaces framework to guide purposive transdisciplinary research. *Futures,* 65, 86–96. doi: 10.1016/j.futures.2014.10.007

Moore, J. (2005). Is higher education ready for transformative learning? A question explored in the study of sustainability, *Journal of Transformative Education*, *3*, 76–91. http://www.doi.org/10.1177/ 1541344604270862

Morrison, P. (2016). School home interactive curriculum development: Teachers and families in partnership. In K. González, & R. Frumkin (Eds.), *Handbook of Research on effective communication in culturally diverse classrooms* (pp. 129–152). Hershey, USA: IGI Global.

Palmberg, I., Hofman-Bergholm, M., Jeronen, E., & Yli-Panula, E. (2017). Systems thinking for understanding sustainability Nordic student teachers' views on the relationship between species identification, biodiversity and sustainable development. *Education Sciences*, *7,* 1-18; doi:10.3390/educsci7030072

Papenfuss, J., Merritt, E., Manuel-Navarrete, D., Cloutier, S., & Eckard, B. (2019). Interacting pedagogies: A review and framework for sustainability education. *Journal of Sustainability Education*, *20*, 1–19. http://susted.com/wordpress/wp-content/uploads/2019/04/Papenfuss-JSE-April-2019-General-Issue-PDF.pdf

Pedaste, M., Mäeots, M., Siiman, L. A., De Jong, T., Van Riesen, S. A., Kamp, E. T., ... & Tsourlidaki, E. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational research review, 14*, 47–61. https://doi.org/10.1016/ j.edurev.2015.02.003

Pintrich, P. R. (2002). The role of metacognitive knowledge in learning, teaching, and assessing. *Theory into Practice*, *41*(4), 219–225.

Pugh, K., Linnenbrink-Garcia, L., Koskey, K. L. K., Stewart, V. C., & Manzey, C. (2009). Motivation, learning, and transformative experience: A study of deep engagement in science. *Science Education*, *94,* 1–28.

Rannikmäe, M. (2002). Science teachers change towards STL teaching. *Journal of Baltic Science Education*, *2*, 75–81.

Ratinen, I., & Linnanen, L. (2022). Exploring systems thinking competence of Finns in fostering sustainable transformation. *World*, 3, 287–298. https://doi.org/ 10.3390/world3020015

Remington-Doucette, S. M., Connell, K. Y. H., Armstrong, C. M., & Musgrove, S. L. (2013). Assessing sustainability education in a transdisciplinary undergraduate course focused on real-world problem solving: A case for disciplinary grounding. *International Journal of Sustainability in Higher Education, 14*(4), 404–433. https://doi.org/10.1108/IJSHE-01-2012-0001.

Rieckman, M. (2018). Learning to transform the world: key competencies in Education for Sustainable Development. In A. Leicht, J. Heiss, & W. J. Byun, (Eds.), Issues and trends in education for sustainable development (pp. 39-59). UNESCO. Paris, France. https://unesdoc.unesco.org/ark:/48223/pf0000261802

Riemeier, T. (2007). Moderater Konstruktivismus. In D. Krűger, & H. Vogt (Eds.), Theorien in der biologiedidaktischen Forschung. Ein Handbuch für Lehramtsstudenten und Doktoranden [Theories in biology didactic research. A handbook for student teachers and doctoral students] (pp. 69–79), Springer.

Roberts, D. A. (2011). Competing visions on scientific literacy. The influence of science curriculum policy image. In C. Linder, L. Östman, D. A. Roberts, P-O. Wickman, G.

Ericksen, & MacKinnon (Eds.), *Exploring the landscape of scientific literacy* (pp. 11–217), Routledge.

Roberts, D. A. & Bybee, R. W. (2014). Scientific literacy, science literacy, and science education. In N. G. Lederman, & S. K. Abel (Eds.), *Handbook of research on science education* (pp. 545−558), Routledge.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher,15*(2), 4–14. https://doi.org/10.3102/0013189X015002004

Siarova, H., Sternadel, D., & Szőnyi, E. (2019). Research for CULT committee–Science and scientific literacy as an educational challenge. EPRS: European Parliamentary Research Service. Belgium. https://policycommons.net/artifacts/1335164/research-for-cult-committee/1941452/

Simms, L., Asselin, M., & Falkenberg, T. (2020). Environmental and sustainability education pedagogical approaches in pre service teacher education. *Canadian Journal of Environmental Education*, *2*, 14–32.

Sipos, Y., Battisti, B., & Grimm, K. (2008). Achieving transformative sustainability learning: Engaging head, hands and heart. *International Journal of Sustainability in Higher Education*, 9, 68–86.

Sjöström, J., & Eilks, I. (2018). Reconsidering different visions of scientific literacy and science education based on the concept of *Bildung*. In Y. J. Dori, Z. R. Mevarech, & D. R. Baker (Eds.), *Cognition, metacognition, and culture in STEM Education. Innovations in Science Education and Technology*, *24*, 65−88, Springer. https://doi.org/10.1007/978-3-319-66659-4_4

Sjöström, J., Eilks, I., & Talanquer, V. (2020). Didactic models in chemistry education. *Journal of Chemical Education, 97*(4), 910–915. https://doi.org/10.1021/acs.jchemed.9b01034

Stapp, W. B. (1969). The concept of environmental education. *Environmental Education, 1*(1), 30–31. doi:10.1080/00139254.1969.10801479

Stengers, I. (2010). Including nonhumans in political theory: Opening Pandora's box? In B. Braun & S. J. Whatmore (Eds.), *Political matter: Technoscience, democracy, and public life* (pp. 3–34), University of Minnesota Press. http://www.jstor.org/stable/10.5749/j.ctttv6sg.5

Sterling, S. (2001). *Sustainable education – Re-visioning learning and change, Schumacher Briefing Nr. 6*, Schumacher Society/Green Books.

Sterling, S. (2003). *Whole systems thinking as a basis for paradigm change in education: explorations in the context of sustainability*. [Doctoral dissertation, Centre for Research in Education and the Environment], University of Bath.

Sterling, S. (2004). An analysis of the development of sustainability education internationally. Evolution, interpretation and transformative potential. In C. Cullingford & J. Blewitt (Eds.), *The sustainability curriculum. The challenge for higher education* (pp. 43–62), Routledge.

Sterling, S. (2008). Sustainable education – Towards a deep learning response to unsustainability. *Policy & Practice, A Development Education Review, 6*, 63–68.

Sterling, S. (2010-11). Transformative learning and sustainability: sketching the conceptual ground. *Learning and Teaching in Higher Education, 5,* 17–33.

Sterling, S. (2010). Learning for resilience, or the resilient learner? Towards a necessary reconciliation in a paradigm of sustainable education. *Environmental Education Research, 16*, 511–528. https://doi.org/10.1080/13504622.2010.505427

Sterling, S., Blake, J., & Goodson, I. (2013). Transformative learning for a sustainable future: An exploration of pedagogies for change at an alternative college. *Sustainability*, *5*(12), 5347–5372. https://doi.org/10.3390/su5125347

Sterling S., Dawson, J., & Warwick, P. (2018). Transforming sustainability education at the creative edge of the mainstream: A case study of Schumacher College. *Journal of Transformative Education, 16*(4), 323–343. https://doi.org/10.1177/1541344618784375

Taylor, N., Quinn, F., Jenkins, K., Miller-Brown, H., Rizk, N., Prodromou, D., Serow, P., & Taylor, S. (2019). Education for sustainability in the secondary sector - A review. *Journal* of *Education for Sustainable Development*, *13*(1), 102–122. https://doi.org/10.1177/0973408219846675

Tilbury, D. (1995/2006). Environmental education for sustainability: defining the new focus of environmental education in the 1990s. *Environmental Education Research, 1*(2), 195–212. doi: 10.1080/1350462950010206

Torres-Coronas, T., Vidal-Blasco, M.., & Simón-Olmos, M. J. (2014). Aligning educational outcomes to boost employment and workforce employability. In V. Wang (Ed.), *Handbook of research on education and technology in a changing society* (pp. 407–417), 10.4018/978-1-4666-6046-5.ch031.

Turner, J. C., & Fulmer, S. M. (2013). Observing interpersonal regulation of engagement during instruction in middle school classrooms. In S. Volet, & M.Vauras (Eds.), *Interpersonal regulation of learning and motivation: Methodological advances* (pp. 147–169), Routledge.

UNECE (United Nations Economic Commission for Europe). (2012). *Learning for Future. In Competences in Education for Sustainable Development. Strategy for Education for Sustainable Development,* The Netherlands. https://www.unece.org/fileadmin/DAM/env/esd/ESD_Publications/Competences_Publication.pdf

UNESCO (United Nations Educational, Scientific and Cultural Organization). (2014). Global citizenship education: Preparing learners for the challenges of the 21st century. Paris, France. https://unesdoc.unesco.org/ark:/48223/pf0000227729

UNESCO (United Nations Educational, Scientific and Cultural Organization). (2016). Unpacking Sustainable Development Goal 4: Education 2030.https://unesdoc.unesco.org/ark:/48223/pf0000246300.

UNESCO (United Nations Educational, Scientific and Cultural Organization). (2019). SDG 4 - Education 2030: Part II, Education for Sustainable Development beyond 2019. https://unesdoc.unesco.org/ark:/48223/pf0000366797

UNESCO (United Nations Educational, Scientific and Cultural Organization). (2020). Education for sustainable development: A roadmap Paris, France. https://unesdoc.unesco.org/ark:/48223/pf0000374802

Valladares, L. (2021). Scientific literacy and social transformation. *Science & Education*, *30*(3), 557–587. https://link.springer.com/article/10.1007/s11191-021-00205-2

Varis, K., Jäppinen, I., Kärkkäinen, S., Keinonen, T., & Väyrynen., E. (2018). Promoting participation in society through science education. *Sustainability*, *10*(10), 3412. https://doi.org/10.3390/su10103412

Vesterinen, V.M., Tolppanen, S., & Aksela, M. (2016) Toward citizenship science education: what students do to make the world a better place? *International Journal of Science Education, 38*(1), 30-50, doi: 10.1080/09500693.2015.1125035

Vieira, R. M., & Tenreiro-Vieira, C. (2016). Fostering scientific literacy and critical thinking in elementary science education. *International Journal of Science and Mathematics Education, 14,* 659–680. doi:10.1007/s10763-014-9605-2

Wei, B., & Lin, J. (2022). Manifestation of three visions of scientific literacy in a senior high school chemistry curriculum: A content analysis study. *Journal of Chemical Education*, *99*(5), 1906–1912. https://doi.org/10.1021/acs.jchemed.2c00013

Wickman, P. O., Liberg, C., & Östman, L. (2012). Transcending science: Scientific literacy and Bildung for the 21st century. In D. Jorde, & J. Dillon (Eds.), *Science education research and practice in Europe. Cultural Perspectives in Science Education*, 5 (pp. 39-61). Rotterdam. https://doi.org/10.1007/978-94-6091-900-8_3

Wiek, A., Withycombe, L., & Redman, C. L., (2011a). Key competencies in sustainability – A reference framework for academic program development. *Sustainability Science*, *6*(2), 203-218. doi: 10.1007/s11625-011-0132-6

Wiek, A., Withycombe, L., Redman, C.L., & Banas Mills, S. (2011b). Moving forward on competence in sustainability research and problem solving. *Environment: Science and Policy for Sustainable Development*, *53*(2), 3-12.

Wiek, A., Bernstein, M. J., Foley, R. W., Cohen, M., Forrest, N., Kuzdas, C., Kay, B., & Withycombe Keeler, L. (2016). Operationalising competencies in higher education for sustainable development. In M. Barth, G. Michelsen, M. Rieckmann, & I. Thomas, (Eds.), *Handbook of Higher Education for Sustainable Development* (pp. 241-260). Routledge.

Yli-Panula, E., Jeronen, E., Koskinen, S., & Vesterkvist, S. (2020). Biologian ja maantieteen opetuksessa käytettävät ilmastonmuutoksen opetusmenetelmät [Climate change teaching methods used in biology and geography education] *Ainedidaktiikka,* [Subject didactics] *4*(3), 102–124. *https://doi.org/10.23988/ad.98284* http://journal.fi/ainedidaktiikka

Zeidler, D. L., Applebaum, S. M., & Sadler, T. D. (2011). Enacting a socioscientific issues classroom: Transformative transformations. In T. Sadler (Ed.), *Socio-scientific issues in the classroom: Teaching, learning and research* (pp. 277–305). Dordrecht: Springer Netherlands. https://link.springer.com/chapter/10.1007/978-94-007-1159-4_16

Zohar, A. (2023). Scaling-up higher order thinking, demonstrating a paradigm for deep educational change. Springer. https://doi.org/10.1007/978-3-031-15967-1

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