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Assessing competency development in transformative teaching – a real-world lab case study on sustainability self-experiments

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Abstract

Purpose – The "Framework of Key Competencies in Sustainability" (KCS framework) is a central concept in higher education for sustainable development (HESD) studies. It describes a set of competencies to contribute to sustainability transitions. Its applicability has, however, not sufficiently been tested in real-life settings or fully operationalised. In particular, this study aims to focus on the under-explored link between competency development and teaching practice in transformative settings such as real-world labs. It addresses this gap by capturing the learning impacts in the case of a transformative teaching format applying the KCS framework.

Design/methodology/approach – To foster sustainability competencies in students, HESD must move towards transformative, problem-based and experiential learning, for example, using real-world labs (RWLs) as transformative learning environments. This case study therefore uses the transformative teaching format "Sustainability Self-Experiment", developed in the RWL "District Future – Urban Lab" to test and refine the KCS-framework. Competency development was assessed using a qualitative content analysis of students' research journals ($n = 27$).

Findings – Competency development in transformative teaching can be assessed using the KCS framework. However, gaps were identified, indicating that "action competence" requires refinement. In addition, this paper proposes adding "reflection competence" to capture experiential and reflexive learning mechanisms and introduces a "Circular Competency Model for Transformative Teaching" that aligns with an experiential learning cycle.

Originality/value – This research addresses the need to test the KCS framework empirically, both to develop it further and to bridge the only loosely connected discourses on sustainability competencies and transformative learning and teaching. Sustainability self-experiments serve as an innovative case study with a high potential for transfer. The resulting circular competency model supports transformative

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teaching formats in HESD through operationalising their educational impacts, as well as enhancing the discourse on RWL impacts.

Keywords Higher education for sustainable development, Key competencies in sustainability, Transformative teaching, Learning impact assessment, Real-world labs, Sustainability self-experiment

Paper type Research paper

1. Introduction

Society has to deal with numerous crises, such as climate change (IPCC, 2022), biodiversity loss, increasing inequality (Chancel *et al.*, 2022) and social division. Therefore, universities are increasingly challenged to contribute to sustainable development, both through research in the relevant fields and by preparing students with the skills and competencies to engage in transformation processes (Redman and Wiek, 2021; Thomas, 2009). Preparing students to tackle "wicked" sustainability problems demands a fundamental shift towards a type of education, "where students are encouraged to be experimental, take risks and bring their own experiences and ideas into their education" (Barrineau *et al.*, 2021, p. 268). For this, university education needs to shift from teaching facts towards creating environments for problem- and project-based learning that create action-oriented knowledge (Brundiers and Wiek, 2013; Tejedor *et al.*, 2019). This is in line with transformative learning theory, which addresses learning as both an impact and a core mechanism of societal change (Mezirow, 2006). One strategy is to draw from transformative and transdisciplinary learning and research (Baumber, 2022; Bernert *et al.*, 2022), introducing new teaching and learning formats (Leal *et al.*, 2017). One innovative research setting that has a particularly high potential to support transformative learning is real-world lab (RWL) research. Located at the intersection of science and society, RWLs provide experience-based learning environments, incorporated in real-world contexts. They belong to a family of sustainability-oriented labs (McCrory *et al.*, 2020) and have enjoyed a rise in popularity, especially in Germany (Schneidewind, 2014; WBGU, 2016, 2011). RWLs offer scientific and societal actors the chance to experiment with sustainability changes in real-life contexts (Parodi *et al.*, 2023; Wanner *et al.*, 2018), by providing an environment for co-creative, participatory experimentation and learning (Schäpke *et al.*, 2024). The experimental and action-orientated approach makes RWLs particularly suited to transformative teaching formats (Beecroft, 2019).

With growing demand for action-based approaches in higher education for sustainable development (HESD) (Brundiers *et al.*, 2010; Thomas, 2009) questions regarding their actual impact are becoming critical. A common evaluation strategy is to assess outcomes, such as the development of students' sustainability-related competencies (Baartman *et al.*, 2007). The "Framework of key competencies in sustainability" (KCS) has become a reference point (Redman and Wiek, 2021; Wiek *et al.*, 2011), However, colleagues still call for empirical studies to validate it in practice (Redman and Wiek, 2021; Waltner *et al.*, 2019). This research gap leads to our research interest:

Q. How suitable is the KCS framework for depicting the learning impacts of transformative teaching on students?

Linking this competency framework to transformative teaching practices could provide new insights, including new transformative competency-oriented teaching formats (Lozano *et al.*, 2017; Wilhelm *et al.*, 2019). Didactic concepts like the learning cycle (Kolb, 2014, 1984), peer learning and research-based learning are integral to our case study, the course "Sustainability self-experiments" (SSEs). SSEs were developed and implemented in the RWL "District Future – Urban Lab" (Beecroft, 2023; Parodi *et al.*, 2016). In SSEs, participants

experiment with more sustainable lifestyle alternatives (Trenks *et al.*, 2026). Initial studies indicate that SSEs initiate transformative learning processes, demonstrating their potential as a transformative teaching format (Szaghun, 2024).

This leads to the two research questions of this study:

RQ1. Which "Key Competencies in Sustainability" are promoted through the SSEs?

RQ2. How suitable is the KCS framework for operationalising competency development in this transformative teaching format and which adaptations are necessary?

Our research tests the KCS framework empirically, and links transformative teaching in HESD to transdisciplinary research processes.

This also contributes to the discourse on impacts of RWLs (Augenstein *et al.*, 2022; Kok *et al.*, 2023; Kampfmann *et al.*, 2022). As learning and competency development are considered key impact dimensions in a RWL (Schäpke *et al.*, 2018; Singer-Brodowski *et al.*, 2018), a model to depict and asses its impact can serve as a valuable tool in this field.

The paper is structured as follows: Section 2 elaborates on the KCS framework. Section 3 introduces RWLs as transformative settings, and Section 4 describes the SSE course, detailing its structure. Section 5 introduces the data set and the analytical approach. Section 6 presents the findings, including an adopted competency model. Sections 7 and 8 discuss the potential of the KCS framework.

2. Key competencies for enhancing sustainability transformations

"Sustainability education should prepare future change agents with the competencies necessary to contribute to transformation processes by enabling students to analyse and solve sustainability problems, to anticipate and prepare for future sustainability challenges, as well as to create and seize opportunities for sustainability" (Wiek *et al.*, 2011, p. 204). Higher education institutions can play a central role in this (Barrineau *et al.*, 2021), yet the quality of implementation of HESD is quite heterogeneous (O'Byrne *et al.*, 2015; Weiss and Barth, 2019), leading to discussion on how to describe, foster and assess sustainability-related competencies (Barth *et al.*, 2007; Brundiers *et al.*, 2021). In this discourse, terms such as competencies, skills, capacities, abilities and capabilities are often used inconsistently (Baartman *et al.*, 2007; Wiek *et al.*, 2011), creating a "sea of labels" (Sterling *et al.*, 2017, p. 153). In this paper, the term "competencies", is defined as "complexes of knowledge, skills, and attitudes that enable successful task performance and problem solving with respect to real-world sustainability problems, challenges, and opportunities" (Wiek *et al.*, 2011, p. 204).

The "Framework of Key Competencies in Sustainability" (KCS) features highly in the discussion on competencies for change agents (Grosseck *et al.*, 2019; Redman and Wiek, 2021). It synthesises the competency discussion how to "enable and empower students to become effective in positively contributing to sustainability problem-solving in their lives, professions and communities"(Brundiers *et al.*, 2010, p. 23) into a consistent framework. It describes a set of discipline-independent key competencies for engaging in sustainability problem-solving (Redman and Wiek, 2021). Since its first publication, the KCS framework has been discussed and further developed (Brundiers *et al.*, 2021; Evans, 2019; Giangrande *et al.*, 2019; e.g. Lozano *et al.*, 2017; Trencher *et al.*, 2018). Two publications summarise its current state comprehensively: Redman and Wiek, 2021 provides an overview of the framework's development and introduces recent additions, while Brundiers *et al.*, 2021 discusses this unified framework with experts.

The KCS framework is comprised of eight interconnected competencies (detailed description in Supplementary material 1): "systems-thinking, futures-thinking, values-thinking

and strategies-thinking enable crafting sustainability action plans that yield sustainability outcomes if successfully implemented (which requires implementation competence). Inter- and intra-personal competencies […] enable that planning and implementation are undertaken in collaborative and self-caring ways […] Finally, integration competence enables a coherent combination of collaborative and self-caring planning and implementation efforts." (Redman and Wiek, 2021, p. 5). The first four are also referred to as "planning competencies", while integration competence [also "integrated problem-solving competence"] is described as a "meta-competence" for integrating the key competencies (Brundiers *et al.*, 2021). All these competencies need to be integrated to advance sustainability transformations (ibid). They are underpinned by complementary (discipline-specific) competencies, which are not considered key competencies. The authors acknowledge that these competencies are abstract and need to be operationalised to the specific learning context (Brundiers *et al.*, 2021; Wiek *et al.*, 2016). The operationalisation process in this study is described in Supplementary material 1).

3. Real-world labs as transformative learning environments

Transformative learning theory was developed by Mezirow in the context of adult education (Mezirow, 1991; Mezirow and Marsick, 1978) and has since been refined and expanded (Kitchenham, 2008; Mezirow, 2006; Taylor, 2007). It is described as a process in which individuals critically examine their own assumptions and beliefs to "make them more inclusive, discriminating, open, reflective and emotionally able to change" (Mezirow, 2006, p. 92). It is systematised by a phase model that, when triggered by a disorientating dilemma, focuses on challenging and transforming personal meaning perspectives and, ideally, leading to thoughtful changes in action. Transformative learning has become a prominent framework within the transdisciplinary educational discourse (e.g. Sonetti and Vienni-Baptista, 2021) and RWL teaching practice (Beecroft, 2019; Wanner *et al.*, 2020).

RWLs are located at the interface of science and society and characterised by their transdisciplinary and action-oriented nature. They represent "places and incubators to develop and research sustainability solutions […] to experiment and examine desirable societal futures" (Parodi *et al.*, 2023, p. 287). RWLs provide a supportive environment for learning processes (Singer-Brodowski *et al.*, 2018) through hands on-experience, experimentation and reflection (Parodi *et al.*, 2017; Schäpke *et al.*, 2018). This often takes place in the form of real-world experiments (Groß *et al.*, 2015; Parodi *et al.*, 2017), creating a bridge between transformative research and transformative learning. By fostering collaborative and experimental processes within the protected niche of the RWL, they enable participants to explore how to initiate change in their own life worlds, lowering barriers to implementation and fostering an understanding of systemic processes.

Previous studies emphasised individual competency development in transdisciplinary settings (Barth *et al.*, 2023), highlighting RWLs as supportive learning infrastructure to promote personal competency development (Singer-Brodowski *et al.*, 2018). While first connections between RWL research and the KCS have been drawn (ibid), their applicability in RWLs has not been empirically investigated. Hilser (2016) analysed how transdisciplinary learning supports five of the sustainability competencies, but without a connection to RWLs, while Szaguhn (2025) analyses SSEs with entrepreneurs using the updated KCS, but outside the RWL context.

To address this gap, this study tests the KCS framework "in real-world problem-solving settings" (Redman and Wiek, 2021, p. 8) to assess its practicability for transformative teaching formats in a RWL.

4. Case study – sustainability self-experiments

SSEs were developed in the context of the RWL "District Future – Urban Lab" in Karlsruhe, Germany. The aim of the RWL is to support a sustainable city transformation in dialogue-based processes with citizens to establish a "culture of sustainability" (Parodi *et al.*, 2016). The SSEs were developed for a sustainability science festival. Its aim was to let students experiment with their everyday actions and test more sustainable lifestyle alternatives for a limited timespan in a self-experiment setting (Trenks *et al.*, 2026). SSE is defined as "a method of transformative education that provides an entry point into processes of change and design in the context of sustainable development" (ibid). SSEs share similarities with HomeLab Experiments (Davies and Doyle, 2016) focusing on household consumption, Climate Governance Experiments (Turnheim *et al.*, 2018) designed to support governance innovations and the Challenge Lab-Course (Larsson and Holmberg, 2018) to enhance engagement between academia and private or public stakeholders.

In contrast to these approaches, SSEs emphasise the systematic documentation and reflection of impacts by the students. Furthermore, students develop their own research design based on their personal scope for action and deepen their understanding of the challenges and constraints through a combination of direct experience, systematic documentation and peer learning (Trenks *et al.*, 2026). The aim is to build participants' capacity to shape transformation processes through a research-based, experiential learning strategy for transformative learning. The SSE is structured in three phases (planning – implementing – reflecting), following a learning cycle (Kolb, 2014, 1984). For a brief description of the three phases see Table 1 in Supplementary material 2, for a comprehensive explanation see Trenks *et al.*, 2026. The SSE consisted of two block courses, framing an interval of five to six weeks for the independent self-experimentation phase. Figure 1 shows the elements of the course.

Using a pre-structured journal (student research diary, see Beecroft *et al.*, 2025) as a tool for systematic documentation is one of three didactical features characteristic of the SSE; the second is the collaboration of students in pairs ("tandems") undertaking comparable self-experiments. The third feature is theoretical and methodological input on sustainability experimentation based on RWL research.

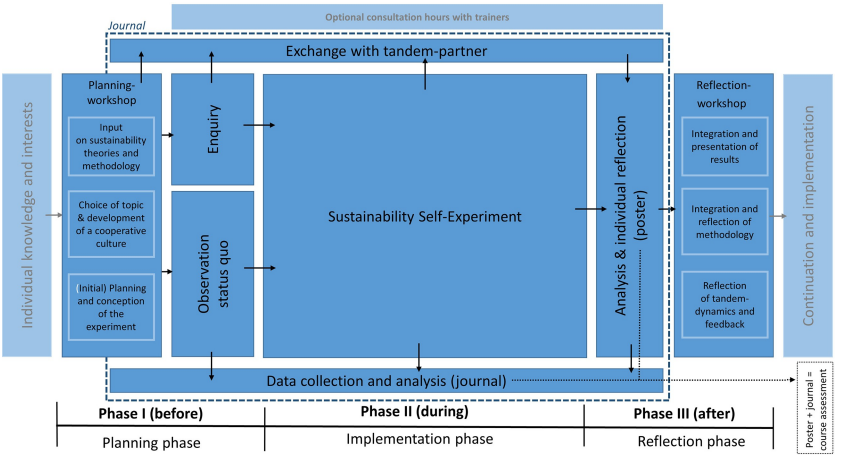


Figure 1. The elements of the SSE in chronological order across its three phases

Source: Authors' own work, adopted and extended from Trenks *et al.* (2026)

5. Material and methods

5.1 Data collection

The SSE was developed in an iterative process to refine its design. Courses were held between 2018 and 2022 (with one break in 2020 due to COVID-19). The first two years served as a prototyping, to develop the didactics and analytical strategy for the format.

The final version of the student journal was applied in 2021 and 2022 forming the empirical sample of this study ($n = 27$, the sampling is explained in Supplementary material 2). This approach aligns with recommendations on competency assessment (Redman *et al.*, 2021).

The data were collected in journals throughout the SSE, which were structured to guide the experiments through a set of questions. Participants planned their SSE according to a self-defined sustainability goal, carried it out, documented it along self-defined research criteria and analysed the results in the light of the initial goal to create a full learning cycle (Kolb, 1984; Lewis and Williams, 1994). For the planning phase this includes questions about the experimental design, motivation and a data collection plan, as well as the documentation of the status-quo for reference. During the implementation phase, it helps document effects and experiences along self-developed observation categories. The final part (reflection phase) supports data analysis and reflection of experiences and methodology, also including Illustrations, photos, diagrams, and tables.

5.2 Data analysis

Qualitative content analysis was applied to the journals, based on Kuckartz and Rädiker (2022), starting with an deductive coding strategy. Building on the latest definitions of the KCS (Brundiers *et al.*, 2021; Redman and Wiek, 2021) the competencies were contextualised to make them operational to the SSE (Wiek *et al.*, 2016; Wilhelm *et al.*, 2019). A "complementary professional and disciplinary competence" was added to the coding system, to depict further supportive competencies (Redman and Wiek, 2021, p. 1). The definitions can be found in Supplementary material 1.

A two-phase qualitative content analysis was applied using MAXQDA software (Verbi, 2022). Initially, the approach involved coding text passages that indicate the application of the respective competencies (Kuckartz and Rädiker, 2022). Multiple codes were possible. The temporal structure was coded according to the three phases of the experiment. The deductive coding system was tested on more than 20% of the data by two team members of the research team and discussed in a "collegial validation process" (Kuckartz and Rädiker, 2022, p. 136). Besides minor clarifications in the code book, this led to the inductive addition of a reflection competency (see also Section 6) and to the selection of an evaluative content analysis strategy for the integrated problem-solving competence. As this meta-competence aims to describe the integration of key competencies for solving sustainability problems, it became visible only in an overall view of each journal. Building on the prior analysis, this made it possible to assess "the level of the case as a whole" (Kuckartz and Rädiker, 2022, p. 174). A four-part scale (3 – strong degree, 2 – medium degree, 1 – low degree, 0 – no degree of integrated problem-solving competency) was used to reflect competency integration across the journal. This final coding system was applied to the whole data set by one researcher.

6. Results

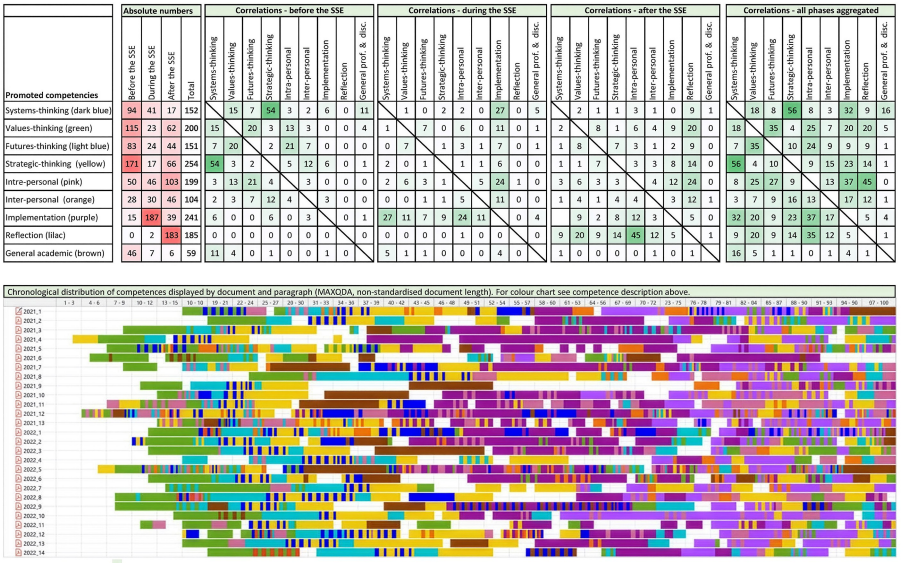
Findings are organised following the research questions. Firstly, the competencies emerging during each phase of the SSE are identifies, shedding light on the processes facilitating their development. Secondly, an evaluation is provided of the SSE as a whole. Based on these findings, the KCS framework was revisited. To enhance the applicability of the KCS for

transformative teaching and support its further development, an adapted competency model is provided based on this analysis.

6.1 Key competencies in sustainability promoted through the SSEs

To answer *RQ1*, the competencies identified in the students' journals were analysed across the SSE's three phases as well as a whole. Figure 2 provides an overview of the identified competencies and their interrelations. Detailed material and examples can be found in Supplementary material 2.

6.1.1 Competencies in the planning phase. In this phase, the planning competencies *(strategic-, systems-, values- and futures-thinking)* were observed most frequently. Students devised their documentation strategies and methods independently *(strategic-/systems-thinking).* Defining observation parameters and data collection methods challenged them to combine quantitative and qualitative approaches. A reflection strategy was developed with their tandem partner, whose support was highly valued and expected to be crucial for the reflection process *(interpersonal competence).* Participants contributed their specialised knowledge, expanding it through topic-specific research *(complementary academic competence).* Sustainability, particularly the importance of preserving nature and personal sustainability, frequently motivated the SSE. Students explored various sustainability strategies, linking their experiments with frameworks like the SDGs or the Brundtland Report, as well as aspects of personal sustainability *(values-thinking, intrapersonal competence).* To deepen understanding of their sustainability issue, students analysed current trends for comparison with their baseline data to create comparative references *(systems-thinking)*, often accompanied using discipline-



Promoted competencies	Absolute numbers: Before the SSE	During the SSE	After the SSE	Total
Systems-thinking (dark blue)	94	41	17	152
Values-thinking (green)	115	23	62	200
Futures-thinking (light blue)	83	24	44	151
Strategic-thinking (yellow)	171	17	66	254
Intra-personal (pink)	50	46	103	199
Inter-personal (orange)	28	30	46	104
Implementation (purple)	15	187	39	241
Reflection (lilac)	0	2	183	185
General academic (brown)	46	7	6	59

Correlations - before the SSE	Systems-thinking	Values-thinking	Futures-thinking	Strategic-thinking	Intra-personal	Inter-personal	Implementation	Reflection	General prof. & disc.
Systems-thinking (dark blue)		15	7	54	3	2	6	0	11
Values-thinking (green)	15		20	3	13	3	0	0	4
Futures-thinking (light blue)	7	20		2	21	7	0	0	0
Strategic-thinking (yellow)	54	3	2		5	12	6	0	1
Intra-personal (pink)	3	13	21	4		3	0	0	0
Inter-personal (orange)	2	3	7	12	4		3	0	0
Implementation (purple)	6	0	0	6	0	3		0	1
Reflection (lilac)	0	0	0	0	0	0	0		0
General academic (brown)	11	4	0	1	0	0	1	0	

Correlations - during the SSE	Systems-thinking	Values-thinking	Futures-thinking	Strategic-thinking	Intra-personal	Inter-personal	Implementation	Reflection	General prof. & disc.
Systems-thinking (dark blue)		1	0	2	2	0	27	0	5
Values-thinking (green)	1		7	0	6	0	11	0	1
Futures-thinking (light blue)	0	7		1	3	1	7	0	1
Strategic-thinking (yellow)	2	0	1		1	1	6	0	0
Intra-personal (pink)	2	6	3	1		5	24	1	0
Inter-personal (orange)	0	0	1	1	5		11	0	0
Implementation (purple)	27	11	7	9	24	11		0	4
Reflection (lilac)	0	0	0	0	1	0	0		0
General academic (brown)	5	1	1	0	0	0	4	0	

Correlations - after the SSE	Systems-thinking	Values-thinking	Futures-thinking	Strategic-thinking	Intra-personal	Inter-personal	Implementation	Reflection	General prof. & disc.
Systems-thinking (dark blue)		2	1	1	3	1	0	9	1
Values-thinking (green)	2		8	1	6	4	9	20	0
Futures-thinking (light blue)	1	8		7	3	1	2	9	0
Strategic-thinking (yellow)	1	1	7		3	3	8	14	0
Intra-personal (pink)	3	6	3	3		4	12	24	0
Inter-personal (orange)	1	4	1	4	4		3	12	1
Implementation (purple)		9	2	8	12	3		5	0
Reflection (lilac)	9	20	9	14	45	12	5		1
General academic (brown)	1	0	0	0	0	1	0	1	

Correlations - all phases aggregated	Systems-thinking	Values-thinking	Futures-thinking	Strategic-thinking	Intra-personal	Inter-personal	Implementation	Reflection	General prof. & disc.
Systems-thinking (dark blue)		18	8	56	8	3	32	9	16
Values-thinking (green)	18		35	4	25	7	20	20	5
Futures-thinking (light blue)	7	35		10	24	9	9	9	1
Strategic-thinking (yellow)	56	4	10		9	15	23	14	1
Intra-personal (pink)	8	25	27	9		13	37	45	0
Inter-personal (orange)	3	7	9	16	13		17	12	1
Implementation (purple)	32	20	9	23	37	17		5	4
Reflection (lilac)	9	20	9	14	35	12	5		1
General academic (brown)	16	5	1	1	0	1	4	1	

Figure 2. Top: absolute numbers (red) and correlations between the competencies in the phases of the SSE (three in the middle) and for the entire SSE; bottom: distribution of competences across the journals

Source: Authors' own work, MAXQDA

specific scientific methods *(complementary academic competencies)*. The vision of a more sustainable future was frequently mentioned as motivation. Students expressed the desire to experience "what they can achieve", gain new skills and discover personal insights. Many aimed at adopting more sustainable behaviour and expected personal and social impacts from their self-experiments. Some saw themselves as examples of change, *(futures-/values-thinking)*, as well as the development of a change-agent mindset *(intrapersonal competence)*. Mindfulness, examining personal needs, as well as (physical and mental) health also influenced their choice of experiment *(intrapersonal competence)*. Managing negative emotions at the beginning of the experiments was part of this. *Interpersonal competence* was shown by effort to include their social environment in the SSE design.

6.1.2 Competencies promoted in the implementation phase. In the implementation phase, a wide range of experiences was reported by the participants (strong *implementation competence)*. They applied experimental and documentation strategies *(strategic thinking)* using both qualitative methods (e.g. diary entries, mood logs, mind maps) and quantitative approaches (e.g. observations, measurements or comparisons; *systems-thinking competence*, see Supplementary material 2). This engagement led to insights about their "sustainability problem", behaviours, needs and unconscious assumptions *(intrapersonal competence)*. Participants reported acquiring new skills and knowledge about their behaviour patterns through the self-experiment, documenting both positive and negative experiences. Positive feedback and collaboration were particularly beneficial for maintaining motivation, while challenges in some cases also acted as catalysts for change. Students highlighted learning from failures and developing adjustment strategies, *(strategic-thinking, implementation competence)*. In some cases, the self-experiment sparked awareness of other sustainability issues, indicating a spill-over effect. Many experiments already incorporated elements of personal sustainability; however, it became visible that the SSE overall enhanced participants' awareness of their needs *(intrapersonal competence)*.

Most participants planned to integrate new behaviours into their routines *(values-thinking, future-thinking)*. Some indicated plans to refine their self-experiment further. Many highlighted the importance of the exchange with their tandem partner. Many also involved their social environment, motivated others to participate or acted as mediator to overcome obstacles (confirming *interpersonal competence* indicated in the planning phase).

6.1.3 Competencies promoted in the reflection phase. After the experiment, students were asked to reflect on their experiences, learning and personal development. This involved relating their experiences and results to their goals. While the reflection process touches upon the established competencies, the ability to deeply and consciously engage with one's experiences and to contextualise this for personal learning, is a distinct skill essential for addressing sustainability challenges. Thus, *reflection competence* was inductively added to the framework. It refers to participants' ability to critically reflect on their plans, experiences and results, gaining insights about themselves (including assumptions, stereotypes, values, inner motivators and inhibitions) and the context of the sustainability issue. The reflection process is retrospective, personal and oriented towards deep understanding (see Supplementary material 1).

Reflection competence was most evident in this phase, closely linked to other competencies. Participants reflected on their learning experiences and obstacles, retrospectively analysing their approaches and identifying areas for improvement. Many reported some anticipated effects but also acknowledged challenges and the need for adjustments (*implementation competence)*. Some students observed a familiarisation effect or a routinisation of their activities. They also noted indirect effects like engaging in conversations, and increased awareness of their consumer behaviour, but also more stress at the beginning of the experiment.

Some students expressed pride in their achievements and gaining new knowledge. They assessed the effectiveness of their measurement and observation methods *(strategic-thinking)*. Partner exchanges were again highlighted as beneficial *(interpersonal competence)*. Reflecting on their experiences, participants frequently described personal development, particularly insights into emotions and needs (*intrapersonal competence*). While questioning their motives was partly perceived uncomfortable, it was viewed as constructive for personal development. Participants emphasised the importance of learning from mistakes, although opinions varied on the generalisability from viewing findings as purely individual to seeing good comparability with other areas of life (*reflexive competence)*. Most agreed they now better understand their potential for action and have a heightened awareness of environmental issues. Many emphasised a societal imperative, underscoring the collective need for action (*values-/futures-thinking)*.

6.1.4 Assessing the whole process through integrated problem-solving competence. This meta-competence describes the ability to integrate various key competencies, enabling a comprehensive approach to address a sustainability challenge (Redman and Wiek, 2021; Brundiers *et al.*, 2021). As the students tackled a sustainability problem and found new, sustainable approaches through self-experimentation, such integration can be seen as a learning goal of the SSE. To assess the degree of *integrated problem-solving competence*, each journal was evaluated as a whole (see Section 5.2). The analysis shows connections between and combinations of key competencies across all phases in most cases (see Figure 2). Integration often varied throughout the self-experiment but was usually highest in the planning and reflection phases. The evaluative analysis revealed that most journals showed a medium integrated problem-solving competence, while high and low integrated problem-solving competence were lower with approximately 15% (high) and 30% (low). Only one journal did not show sufficient connections. Journals with a high number of codes (high/medium problem-solving competence) also showed frequent interconnections and a strong combination of competencies, as well as a positive development of the self-experiment.

6.2 Suitability of KCS for depicting transformative teaching formats

The KCS framework sheds light on transformative learning. However, it became clear that three adaptations of the framework are required:

(1) Transformative learning requires reflexive competency:

A gap identified in the empirical analysis is the weak representation of reflection in the KCS framework. It depicts a linear process to address sustainability problems, focusing strongly on planning competencies. This overlooks the importance of experiential learning during and after the implementation phase. An important step in transformative learning, in line with Kolb's experiential learning cycle (Kolb, 2014, 1984), is reflecting on experiences and personal development. To adapt the KCS framework for transformative teaching, it should cover iterative processes, including reflection, to describe how learners integrate experiences.

(2) Appropriate representation of implementation competence:

SSEs emphasise the experiences gained through implementation as a key element of transformative learning. Previous representations (Redman and Wiek, 2021; Brundiers *et al.* (2021) overrepresented the planning competencies compared to implementation competencies. For transformative teaching formats, planning, implementation and reflection competencies need to represent equal importance.

(3) Addressing integrated problem-solving competence as a learning goal:

With the KCS framework, the relation of the integrated problem-solving competence to the other competencies has become somewhat unclear. Although it is described as a "meta-competence" for integrating the key competencies, its function remains underspecified. Understanding integration as an effective combination of competencies to solve a sustainability problem, integration as meta-competence has to be an overarching goal within the competency framework. For transformative teaching formats, integration competence should be treated as a central learning goal. From an analytical perspective, this also requires an empirical approach that evaluates the entire learning process.

6.2.1 A circular competency model for transformative teaching. Based on the analysis and identified adjustments, a CC-Model was developed, shown in Figure 3.

The CC-Model follows a learning cycle and demonstrates how key competencies support addressing sustainability problems in an iterative process. The inner cycle is structured around three competencies, corresponding to the phases of planning, implementing and reflecting (planning competencies are consolidated in one "slice"). Our analysis confirmed that each phase is predominantly characterised by one of these competencies, although they are interlinked. For instance, planning competencies build the foundation for implementation competence. As experiences are reflected upon, new insights emerge, further refining the planning competencies. These connections and iterations are depicted by the learning cycle at the centre.

This representation displays the competencies for planning, implementation and reflection as equally important, adjusting their size and placement within the model accordingly. Reflection becomes particularly relevant during iterative cycles, to integrate experiences, impacts and new competencies. The intra- and interpersonal competencies frame the process of addressing sustainability problems, fostering a collaborative and healthy transformation process and thus surrounding the "inner" competencies. The

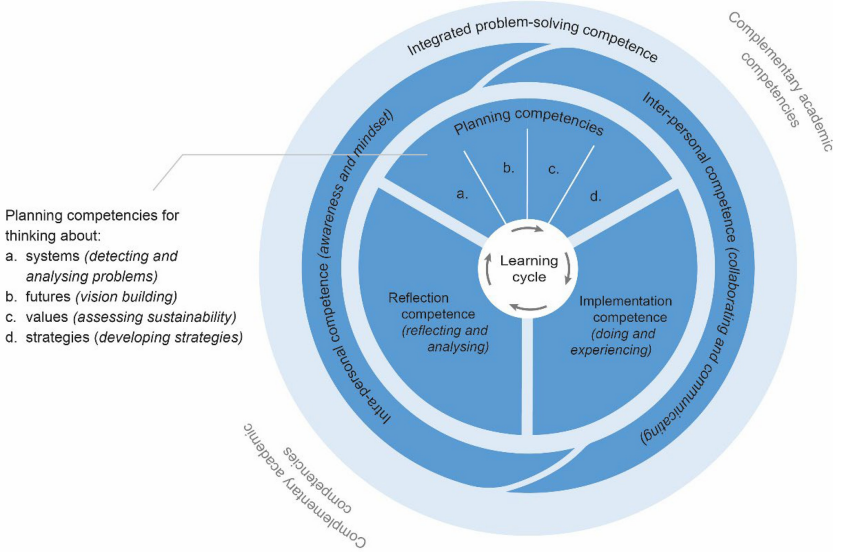


Figure 3. Circular Competency Model for transformative teaching formats
Source: Authors' own work

integrative problem-solving competence is depicted as a meta-competence, integrating the key competencies into one framework.

7. Discussion

This study investigated how the KCS framework can be applied to capture the impact of transformative learning and teaching formats, analysing SSE as a case study. The three goals were to test the applicability of the KCS-framework based on empirical evidence, to establish a stronger link between the KCS-framework and transformative teaching practice, and to contribute to a better understanding of the learning impacts of RWLs.

7.1 Applicability of the KCS framework for assessing transformative teaching

The transformative learning format SSE supported students effectively in developing and applying key competencies to carry out their self-experiments. Rather than merely using these competencies as a "'checklist" to measure the impact of the SSE, the KCS framework was applied to understand the learning processes and elucidate the mechanisms which shaped students' competency development.

Throughout the SSE, all key competencies were observed, often occurring in combination *(RQ1: Which "key competencies in sustainability" are promoted during the SSE?)*. This interplay of competencies presents both a challenge and an advantage in the qualitative analysis; while it complicates the coding, it also highlights the students' capacity for integration and holistic thinking. Such integration of key competencies is considered crucial for implementing sustainability transformations (Redman and Wiek, 2021; Wiek *et al.*, 2011). It became evident that different competencies were dominant at various phases of the SSE. During the planning phase, the four planning competencies were particularly pronounced, while implementation competence was most prominent during the implementation phase of the experiment. This highlights the "action-orientation" of SSE (Trenks *et al.*, 2026). In the final phase, reflective processes were pivotal, requiring a representation in the framework. Intra- and interpersonal competencies were present in all three phases, with intrapersonal competence pointing towards the emergence of a change-agent mindset among many students during the experiment.

Regarding the *competency framework's suitability for mapping competency development in transformative teaching and need for adaptations (RQ2)*, this analysis identified a gap, as reflection and implementation skills are only weakly covered in the KCS framework. The implementation- and action-oriented approach of the SSE emphasises a different focus to the current framework, which leans heavily on planning. While the 2021 version does integrate an implementation competence, implementation remains underrepresented. Given that transformative learning aims at changing not only individual perspectives but individual actions (Mezirow, 2006), the implementation competency is central to transformative teaching formats. In line with Mogensen and Schnack (2010), this paper argues for a more action-driven focus of teaching and learning for sustainability (ibid). The findings emphasise the importance of real-life experience for acquiring sustainability competencies. This aligns with studies that highlight the significant value of real-world problem settings and active student involvement in supporting competency development (Hilser, 2016; Wanner *et al.*, 2020). To make the KCS-framework applicable for transformative teaching, the implementation competence needs more emphasis.

Another essential aspect in an iterative transformative learning process is the ability to critically reflect on ones' assumptions and experiences (Mezirow, 2006). This forms the basis for personal development and future actions. A holistic competency framework also needs to cover these aspects of processual and iterative learning. This means realigning the

competency framework to iterative processes both in transformative learning (Kolb, 2014, 1984) and transformation processes. Finally, the integrated problem-solving competence has to be understood as a core learning goal, emphasising the ability to combine competencies in the problem-solving process (Redman and Wiek, 2021), highlighting its role as an integrative meta-competence (Brundiers *et al.*, 2021).

Based on these findings, the KCS framework was revised, reshaping its linear structure into a cyclical one where planning, implementation and reflection competencies are equally relevant. These changes were integrated into the proposed CC-Model.

7.2 Possible fields of application

The CC-Model can be used in different ways. Firstly, it serves as a guideline for designing transformative learning courses that focus on experiential, action-oriented learning, while also incorporating other learning mechanisms such as instruction, peer learning and reflective practices. These elements can be linked to promote competencies within a coherent learning process. Aligning the competency model to learning phases is practically advantageous as it mirrors learning processes in project-based and transformative learning formats, enabling a better fit between theory and practice in HESD.

Secondly, the CC-Model can be used to reflect and evaluate the learning impacts of transformative teaching in terms of competency development. For RWL research, the adapted framework can serve as a tool for planning, monitoring and evaluating real-world experiments. As such experimental approaches evolve temporally (Parodi *et al.*, 2024), different competencies are core in different stages. This progress can now be described and analysed using the CC-Model.

Furthermore, informal learning processes play an integral role in transformative research (Singer-Brodowski, 2023). For RWLs and other transformative settings, the CC-model helps to conceptualise formal and informal learning as intertwined processes. On the way to a consistent RWL methodology, this adapted model could serve as a core element to link experimental practices, their learning mechanisms and the competencies developed within them.

7.3 Limitations and further research

Capturing transformative processes in a short period of five to six weeks is challenging. A focus on competency assessment provides a way to capture transformative impacts. To draw conclusions about long-term effects, studies with follow-up participant interviews would be necessary. First follow-up interviews have been carried out independently in a master thesis (Allmann, 2020). This avenue should be pursued further, reflecting on and discussing the results of the competency assessment with the students in hindsight. In the student journals, confirmation bias is to be expected. While this data potentially draws an over-positive picture of each SSE, the underlying mechanisms of which competencies are relevant in which phase should not be strongly affected by this bias. No pre-post comparison is possible here, as the competencies of the students were not examined at the beginning of the SSE.

Although small-scale experiments are valuable starting points for facilitating learning in transition processes (van den Bosch and Rotmans, 2008), this analysis is based on a small sample ($n = 27$). Testing the CC-Model with larger samples in different learning settings would improve the validity of the results.

This study focusses on the individual level. Other sustainability-related experimental approaches call for a stronger link to governance and stakeholders (Larsson and Holmberg, 2018; Turnheim *et al.*, 2018). Future research could benefit from seeking to understand the impact of competency development in other types of transformative experiments.

Regarding the KCS framework, a further differentiation of the implementation competence is necessary. This empirical analysis could examine "learning from failure", competencies for impact monitoring or the integration of newly acquired skills. In addition, the new reflection competence needs theoretical foundation and further testing.

8. Conclusion

This research addressed several gaps: firstly, the KCS framework was tested empirically in real-world settings (Redman and Wiek, 2021; Wiek *et al.*, 2011), showing both how to operationalise it and where adaptations are needed. Secondly, a conceptual link was established between the competency discourse and transformative learning and teaching, to help its planning and evaluation. Thirdly, competency development was introduced into the discussion about the impact of RWL experiments (Schäpke *et al.*, 2024). To maximise the practicability of these contributions, the "Circular Competency Model for transformative teaching" was introduced, which aligns real-world experimentation with an experiential learning cycle and the respective competencies. The insights gained can be used to improve transformative teaching in HESD, and to monitor learning processes as a core impact dimension of RWL research.

Ethics statement

According to the KIT Guidelines for Ethical Principles no ethics committee review was required; confirmation by the KIT Ethics Committee is provided. A KIT data protection impact assessment indicated no increased risk. Data collection was recorded in the electronic processing directory of the KIT (ID 521). Journals were pseudonymised, after two years anonymised and scanned for not touching third party rights.

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Authors contribution

Both authors contributed to the prototyping and realisation of the SEE and the data collection. The conceptualisation of the paper and the data analysis was performed by Helena Trenks. The conceptual work on the competency model was caried out jointly. Helena Trenks carried out the literature screening and drafted the manuscript, both authors contributed to the revisions and the final version.

Informed consent

The participants of the seminar "Sustainability in a self-experiment" have given their written consent that the data collected in the experiment can be used for scientific purposes through the authors.

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Supplementary material

The supplementary material for this article can be found online (Sup. 1: doi: https://doi.org/10.35097/f2up411j63dtby2d; Sup. 2: doi: https://doi.org/10.35097/wvcw3r1nnk80nnzu).

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