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A participatory action research project on implementing a laboratory course on flow chemistry in a master's program at university

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Abstract
Flow chemistry is a popular method in both chemical industry and research but theoretical and practical learning opportunities for future chemists at university are scarce. To address this gap, we designed and evaluated experiments for a laboratory course of a master's program integrating current research questions with elements of inquiry-based learning. The laboratory course was developed and investigated within a participatory action research (PAR) design. This paper presents the results of students' pre- and post-surveys on students' perceived learning opportunities, research skills, and learning objectives. The findings indicate positive changes in students' self-assessed research skills and the inquiry-based elements of the designed flow lab were perceived as conducive to learning. Students' self-assessment of learning objectives achieved also improved. Following the principles of PAR, two iterative cycles of an innovative laboratory course were implemented and evaluated. This study contributes to research on curriculum innovation in higher education by providing empirical insights into the design and development of research-based laboratory courses in flow chemistry.

Keywords: participatory action research, higher education, curricular innovation and development, flow chemistry, laboratory course

INTRODUCTION

The importance of flow chemistry has increased significantly, especially in the last few decades. In research and industry, it has garnered significant attention particularly in the synthesis of fine chemicals and active pharmaceutical ingredients (APIs) due to its advantages compared to batch processes and the possibility to make syntheses more sustainable (Blanco-Ania & Rutjes, 2017; Britton & Jamison, 2017; Cerra & Gioiello, 2021; Dallinger & Kappe, 2017; Gutmann et al., 2015). The fundamental principle involves the continuous mixing of liquid or gaseous reagents in a flow reactor system, enabling a simultaneous reaction as the reagents combine. The use of a continuous flow reactor ensures precise control over reaction conditions thereby often improving product purity and enhancing safety standards. This is important, especially when handling hazardous chemicals. Flow chemistry further offers advantages in terms of simpler scale-up strategies (Plutschack et al., 2017). Additionally, it has a reputation as a green and sustainable synthesis approach due to minimized chemical waste and in situ production of intermediates (Dallinger & Kappe, 2017). These attributes contribute to the widespread adoption of flow chemistry in both industrial applications and research endeavors. Despite its broad use and high popularity in organic synthesis, it is surprising that flow chemistry is rarely implemented in chemistry curricula at university level.

To achieve widespread implementation of flow chemistry, didactically proven learning and education materials are needed (Blanco-Ania & Rutjes, 2017) as well as research on curricular innovation to introduce current topics into education (Parchmann et al., 2017). This is essential to prepare the students for their future career and underlines the necessity to integrate flow chemistry into academic curricula (Blanco-Ania & Rutjes, 2017).

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Contribution to the literature

- The purpose of this study was to design a laboratory course on flow chemistry in higher education based on action research.
- In contrast to previous studies on flow chemistry in higher education, this study examined students' learning opportunities on flow chemistry and offers suggestions on how to teach the principles of flow chemistry derived from research about students' self-assessment on learning objectives and the cognitive load of the experiments conducted.
- This study contributes to the curricular innovation research in higher education and the implementation of a laboratory course on flow chemistry with an inquiry-based learning approach.

Although many authors describe the importance of implementing flow chemistry into higher education, (Blanco-Ania & Rutjes, 2017; Kairouz et al., 2021) there are only a few experiments published in the context of teaching (Bayana et al., 2021; Kairouz & Collins, 2018; Kairouz et al. 2021; Kuijpers et al., 2020; Penny et al. 2021; Sun et al. 2021; van Summeren et al. 2021), and even fewer articles that provide explicit instructions or practical implementation strategies for laboratory practice. One obstacle for conducting flow chemistry experiments with students is that special equipment is needed (Kairouz & Collins, 2018) and some experiments are limited (Bayana et al., 2021). Further, supervision of proper handling the flow equipment may be needed. To overcome this lack of educational proven material and to contribute to teaching flow chemistry in higher education, we designed and evaluated a laboratory course on flow chemistry based on the principles of action research.

Aims of the Study Project

The main objective of this study was to develop well-researched material and a laboratory design to teach the principles of flow chemistry within a one-day practical course, based on a participatory action research (PAR) approach.

This study pursued four interrelated objectives: to close the gap in the curriculum by developing evidence-based teaching materials for flow chemistry at the university level, to empirically investigate the learning opportunities available to students to date, to evaluate the experiments and laboratory design, and to foster the collaboration between chemists, teachers and chemical education researchers, bridging the gap between these two domains to illustrate the benefits of a PAR project.

The laboratory course was conducted with groups of four to six master's students from the "technical chemistry" program at the end of the first semester, knowing that the students had different bachelor's degrees and different levels of prior knowledge in flow chemistry due to the curricula. To tailor the course to the learners' prior experience, we aimed to find out what learning opportunities the students of the master "technical chemistry" had with regard to flow chemistry and related topics such as continuous processing, laboratory experience, green and sustainable chemistry and organic chemistry. Based on these findings, we developed a lab course around three experiments at increasing levels of difficulty: the determination of flow rates, the Villermaux-Dushman protocol for determining the mixing efficiency of mixer types and a synthesis and optimization reaction. These experiments were designed to be conducted in a commercially available, easy to use and portable flow reactor (Penny et al., 2021) to combine content learning with the promotion of inquiry-based skills.

We wanted to determine the extent to which the designed experiments were suitable for laboratory teaching under the given conditions and learning objectives, and whether the implemented elements of research-based learning influenced the students' self-assessment according to their learning progress and the achievement of learning objectives, including perceived cognitive load.

The following research questions (RQs) were derived from the objectives of the study.

RQ1. What learning opportunities relevant to the laboratory course on flow chemistry were offered to students of the master technical chemistry in the context of their previous science education?

RQ2. How do the students rate a one-day laboratory course on flow chemistry regarding structure of the lab day and the elements of guided inquiry learning?

RQ3. Are the experiments designed for the laboratory course on flow chemistry appropriate to achieve the learning objectives?

To address these RQs, we investigated the didactic concept of this laboratory course along with the experiments it entails and the corresponding evaluation data across two PAR cycles. This approach provided valuable insights into the development of a flow chemistry laboratory course and enabled us to disseminate new knowledge regarding the practical aspects of teaching flow chemistry in a university-level laboratory setting.

METHODOLOGICAL AND PEDAGOGICAL FRAMEWORK

The development and research of the laboratory course on flow chemistry were guided by two approaches: first, PAR provides the methodological framework of the collaborative design and the iterative refinement of the laboratory course as it is seen as an effective approach for developing enduring teaching concepts, particularly in higher education (Tolsdorf & Markic, 2018, 2019). Secondly, an inquiry-based learning approach informs the educational concept and learning activities within the course. Together, these frameworks support the development of curricula innovation by the implementation of current scientific topics and enabling collaboration between flow chemists and researchers in teaching chemistry in higher education.

Curricular Innovation in Higher Education

As a context for our study, curricular innovation in higher education builds on a broad body of knowledge regarding recent findings and innovative topics in science, technology, environment and life sciences. Relevant content is selected and adapted using appropriate educational methods for (higher) education and the design of approved teaching materials (Parchmann et al., 2017; Tausch, 2004).

In the context of flow chemistry, translating recent findings and ongoing research into educational settings is particularly important. The objective of the presented laboratory course was to develop and tailor experiments for application in higher education that elucidate the fundamental principles of flow chemistry and highlight its relevance for industrial and academic research. Close collaboration with experts in the field of flow chemistry ensures that current research content is combined with effective teaching methods in chemistry education.

Participatory Action Research as Methodological Framework

The integration of current scientific topics is considered a key criterion for good quality in higher education (Berendt, 2000). Accordingly, research experience plays an important role in connecting theory and practice, as research offers opportunities for both basic and applied learning (Bargel, 2012).

PAR is a collaborative and interactive research approach in which researchers and/or teachers and/or learners jointly contribute to the development and evaluation of educational concepts. The iterative nature of PAR is characterized by cyclical phases of planning, action, observation, and reflection, allowing for continuous improvement based on empirical evidence and collaborative insights (Eilks & Ralle, 2002). It is an effective approach for developing enduring teaching concepts, particularly in higher education (Tolsdorf & Markic, 2018, 2019).

In this study, the role of the chemical education researchers was to devise a didactic form of the laboratory course, to create digital supporting material as well as the design of the study around this laboratory course. This collaborative setting enables the implementation of research references in courses and the participation in research-related activities enables the implementation of research references in courses and the participation in research-related activites which students consider, which students consider to be important (Multrus, 2009). Explicitly, a laboratory course is designed to acquaint students with new research methodologies like those of APIs, in flow reactors. We applied a cyclical and iterative PAR process, adapted from Eilks' and Ralle's (2002) model, which is well researched in secondary school chemistry education and has been extended to university-level education by Tolsdorf and Markic (2018).

An Inquiry-Based Learning Approach

Through inquiry-based learning opportunities, students have the chance to get away from the usual recipe-experiment regulations. Instead, students have the opportunity to work together as a team to solve the problem and thus improve their teamwork and problem-solving skills (Huang, 2022). With the aim to implement elements of guided inquiry learning, the laboratory course includes experiments derived from an ongoing research project, which is to be optimized by the students to reach full conversion of the educts. The planning of experiments, the formulation of hypotheses, the discussion in groups and the consideration of further experiments can be seen as typical phases of inquiry-based learning (Pedaste et al., 2015). Following Huber (2004) and Griffiths (2004) the course can be classified as research-led type of inquiry learning as it builds on current research topics while gradually engaging students in research-related activities. This type applies to the experiment where students are asked to conduct a synthesis reaction and optimize it. Overall, the course aims to foster students' research competencies in line with established principles of inquiry-based learning, which is crucial in science education (Bruckermann & Schlüter, 2017). Hodson (2014) distinguishes between learning through inquiry methods and learning the inquiry methods themselves. Building on this distinction and the classification of inquiry levels proposed by Banchi and Bell (2008), our laboratory course can be categorized as guided inquiry (Hodson, 2014). Students are guided through an increasing number of experiments, ranging from handling the flow reactor and determining flow rates and mixing efficiencies, to independently optimizing a synthesis reaction. Moreover, students are required to apply previously acquired knowledge and to discuss and select synthesis

Table 1. Experiments and corresponding learning objectives labeled according to the categories of learning goals of Hodson (2014)

Experiment	Definition
Experiment 1. Determination of flow rates	Students determine different flow rates by changing the setting and equipment of the flow reactor. To avoid any hazards, the solvent of choice is water.
Learning objectives	This experiment is designed to teach students about the principles of flow chemistry, as the determination of flow rates is a basic operation for syntheses in flow (category 1). Students can learn how to use the flow reactor and its accessories (category 1) without using any hazardous materials
Experiment 2. Mixing efficiency	Using the Villermaux-Dushman protocol (Commenge & Falk, 2011) with inline UV-Vis detection, students can investigate up to three different mixer types for determining the mixing efficiency.
Learning objectives	The learning objective of this experiment is to gain knowledge of the principles of flow chemistry such as the effect of flow rates on mixing, mixer types of geometries and steady state conditions (category 1). Students are able to evaluate the effect of each mixer type on the mixing efficiency and further on a synthesis reaction in flow (category 2). Students will learn how to collect data (category 2) and should be able to use the collected data to answer research questions (category 3). The aim of this experiment is to find the most efficient type of mixer.
Experiment 3. Synthesis/optimization	The third experiment aims to combine the knowledge gained in the experiment 1 and experiment 2 to optimize a synthesis reaction. To achieve this, students carry out a synthesis with given starting conditions. Afterwards, they should choose parameters for the optimization by discussing in the group and finding arguments for the chosen parameters. Parameters could be (1) flow rate/reaction time), (2) type of mixer, and (3) temperature. The reaction and optimizations will be analyzed by HPLC to obtain results on conversion and yield.
Learning objectives	The knowledge and skills acquired previously is used in further experiments to choose parameters for the optimization reaction through discussion and argumentation, achieving/constituting a knowledge transfer (experiment 3). Students collect data on the conversion and yield of the reaction and the optimizations (experiment 2). The data collected will be used to answer research questions (experiment 3).

conditions in order to achieve the highest possible reaction conversions.

Through experimental work in the laboratory course, students were not only engaged in “doing science” but also in developing an understanding of research principles and underlying theoretical concepts (Bruckermann & Schlüter, 2017; Hodson 2014). The three experiments developed for this laboratory course are structured with an increasing level of difficulty and are aligned with the intended learning goals summarized in **Table 1**. In particular, the use of flow reactors requires students to acquire a foundational understanding of the key principles of flow chemistry while progressively applying this knowledge in experimental contexts. To systematically describe and analyze the intended learning goals of the laboratory course, we use the framework proposed by Hodson (2014), which defined four categories of learning objectives in science education:

1. **Category 1:** Learning science: acquiring theoretical and conceptual knowledge (e.g., understanding chemical principles and mastering calculations)
2. **Category 2:** Learning about science: developing knowledge about scientific research principles and the role of scientific knowledge in society and research community (e.g., understanding experimental design and recognizing the role of optimization in research)
3. **Category 3:** Doing science: engaging in authentic (scientific inquiry to solve a problem (e.g., conducting experiments, collecting and analyzing data, and making evidence-based decisions)
4. **Category 4:** Addressing socio-scientific issues: developing (critical thinking according to different aspects of socio-scientific issues like ethical issues (e.g., evaluating sustainability aspects)

The three experiments in our laboratory course address categories 1, 2, and 3 with varying emphasis (**Table 1**).

Experiment 1 focuses on category 1 (theoretical knowledge of flow rates and residence times). Experiment 2 integrates categories 1, 2, and 3, while experiment 3 most comprehensively addresses category 3.

METHODS

The laboratory course was implemented and investigated across two consecutive PAR cycles, conducted once per year at the end of the winter

Table 2. Overview of methods and research interests for each cycle

Cycle	Instrument	Timing	Content/purpose	RQ	Source/adaptation
1	Curricula analysis	Pre-course	Analysis of ECTS distribution for laboratory courses, organic chemistry, chemical engineering, and green chemistry in admitted Bachelor programs	**RQ1**	Document analysis of curriculum materials
1	Post-survey	After lab	Lab day structure, inquiry-based learning elements, general feedback	**RQ2**	Self-developed; adapted from Gillies (2020), PRIMAS Project (2013)
2	Pre-survey	Before lab	Prior learning opportunities in flow chemistry, continuous processing, laboratory practice	**RQ1**	Self-developed based on curricula analysis
2	Pre-survey	Before lab	Research skills (reflective, subject-specific knowledge, communication, methodological)	**RQ2**	Adapted from Böttcher-Oschmann & Thiel (2016)
2	Pre-survey	Before lab	Self-assessment of learning objectives	**RQ3**	Self-developed based on course learning objectives (**Table 1**)
2	Post-survey	After lab	Research skills (reflective, subject-specific knowledge, communication, methodological)	**RQ2**	Adapted from Böttcher-Oschmann & Thiel (2016)
2	Post-survey	After lab	Self-assessment of learning objectives	**RQ3**	Self-developed based on course learning objectives (**Table 1**)
2	Post-survey	After lab	Cognitive load (concentration, mental effort, perceived difficulty per experiment)	**RQ3**	Adapted from Leppink et al. (2013); 11-point scales reduced to 5-point
2	Post-survey	After lab	Lab day structure, general feedback	**RQ2**	Self-developed

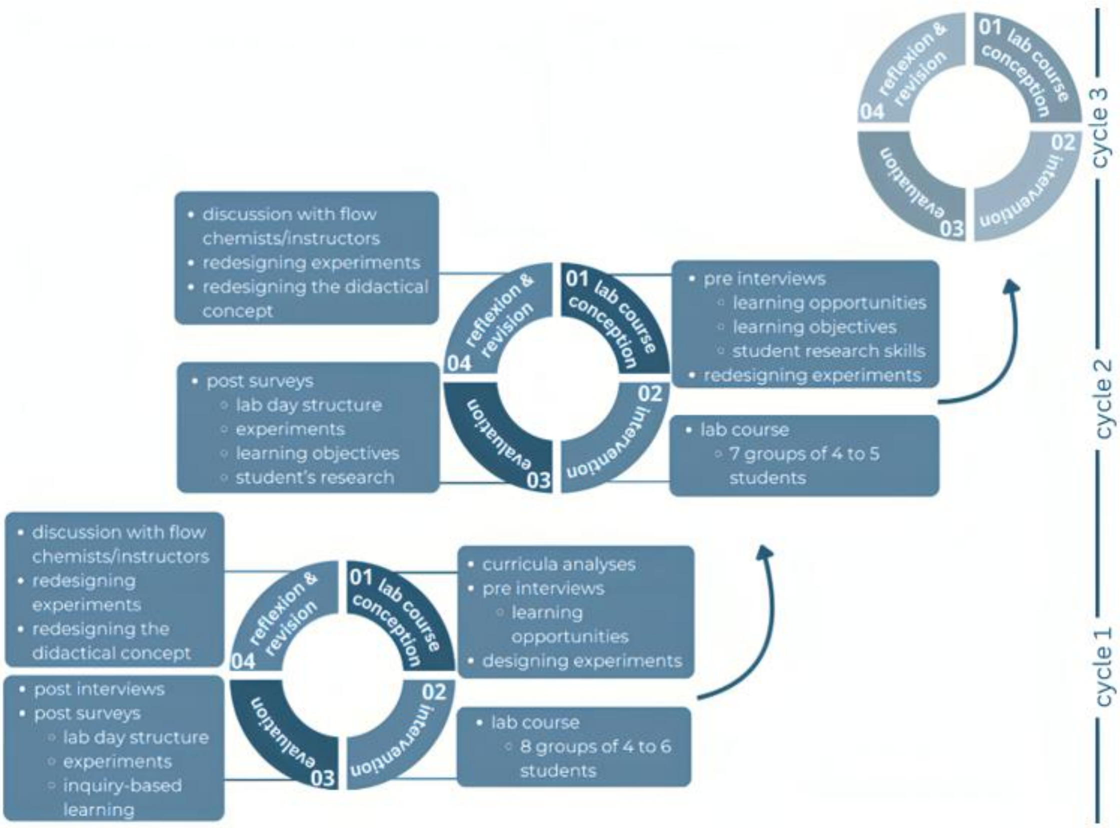

Figure 1. Iterative participatory action research design (Source: Authors' own elaboration)

semester. The overall project includes both quantitative surveys and qualitative interviews. However, the present manuscript focuses exclusively on quantitative data collected in cycle 1 and cycle 2.

Table 2 provides a structured overview of the study design, the data collection instruments used, and the specific RQs addressed in each cycle.

Qualitative interview data and a third planned cycle are part of the broader project but are not reported here to maintain a clear quantitative focus.

Regarding the PAR design, **Figure 1** illustrates the two PAR cycles implemented and one cycle planned in this study. Each cycle consisted of four phases:

(1) lab course conception,

(2) implementation,

(3) evaluation, and

(4) reflection and revision.

Cycle 1 started with the analyses of the curricula of the bachelor's degree programs admitted to the master's degree program in technical chemistry. In the first cycle, we did guideline-based pre- and post-interviews (Kruse 2015) with student groups of the bachelor program chemistry, sustainable development with the focus on natural sciences and technology (USW/NAWI-Tech) and comparable bachelor programs finished at other universities. Based on the findings, we designed three experiments and the didactic concept for the laboratory course. 40 students attended the laboratory course in cycle 1 (BSc chemistry: 37 students, sustainable development with the focus on natural sciences and technology [USW/NAWI-Tech]: two students, comparable bachelor's degree: one student).

After the lab course, we conducted pre- and post-surveys to gain a more comprehensive insight into learning opportunities and further for evaluating the lab day structure, experiments, learning objectives, and inquiry-based learning elements. The evaluation revealed areas for improvement, which were discussed collaboratively among flow chemists and chemical education researchers. Cycle 2 incorporated the insights from cycle 1. We redesigned the experiments and the didactic concept and refined the survey instruments. The revised course was implemented with seven groups of 4 to 5 students and completed by 34 students. 24 students took part in the complete study and the pre-post surveys (BSc chemistry: 21 students, sustainable development with the focus on natural sciences and technology [USW/NAWI-Tech]: two students, comparable bachelor's degree: one student). Post-surveys again were used to evaluate the lab day structure, experiments, learning objectives, and students' research skills. This study reports on the findings from these two completed cycles. As shown in **Figure 1**, the iterative PAR process continues, with a third cycle planned for future implementation.

Instruments Used to Address RQ1-3

The pre- and post-surveys consisted of a combination of adapted items from validated instruments and self-developed items aligned with the learning objectives of the laboratory course. Items on research skills were adapted from Böttcher-Oschmann and Thiel (2016), while selected items on cognitive load were adapted from Leppink et al. (2013). Items assessing learning objectives were developed based on the course design and Hodson's framework (2014).

Reliability analyses were not conducted for all scales, as the instruments consisted of selected and adapted items rather than complete validated scales. The items were therefore analyzed descriptively and inferentially at the item level. No claims are made regarding latent constructs such as cognitive load as a unified construct.

RQ1 was addressed through a curriculum analysis of relevant bachelor's programs prior to course design and a pre-survey in cycle 2 capturing students' self-reported prior learning opportunities.

RQ2 was investigated by the students in both cycles by completing a pre- and post-survey on the lab day. The post survey of the first cycle included feedback questions to the lab day in general and items on inquiry-based learning (Gillies 2020; The PRIMAS Project, 2013). In the second cycle, instead of the questions on inquiry-based learning, the questionnaire from Böttcher-Oschmann and Thiel (2016) on student research skills was used (pre and post) in the categories relevant to the laboratory course to find out in which areas of research skills students perceive changes. This change was made to improve the alignment between the instrument and the inquiry-based elements of the laboratory course and to gain more specific insights into perceived changes in research competencies.

To answer **RQ3,** the authors examined through the pre- and post-surveys of the second cycle included questions on the learning objectives and items addressing the cognitive load (Leppink et al., 2013). In the instrument presented by Leppink et al. (2013), a Likert scale from 1 to 9 and 0 to 10 is used in the original instrument. The original 11- and 9-point scale was reduced to a 5-point scale (**Table 3**) for reasons of simplicity and with a view to embedding it in the overall questionnaire. In our view, a 10-point scale was not necessary for the purpose of the items. Furthermore, 5-point scales are considered typical (Döring et al., 2016) and contribute to a greater test economy. A small number of levels were excluded due to the associated lower reliability (Boateng et al., 2018). Given that students completed the survey immediately after an intensive laboratory day, minimizing response burden was a priority to ensure data quality. We acknowledge that this adaptation means our items are not directly comparable to the original Leppink et al. (2013) instrument, and we do not claim to measure cognitive load as a validated construct. Instead, the adapted items were used pragmatically to capture experiment-specific perceived cognitive demands at the item level. Also, reliability analyses were not conducted because the instrument was not designed to measure unified latent constructs. Instead, items were purposefully selected from a validated source (Leppink et al., 2013) based on their specific relevance to the learning objectives of this laboratory course.

Table 3 summarizes the original items by Leppink et al. (2013) and their adapted versions used in this study, which were included in the post-survey of cycle 2.

Table 3. Original and adapted items on aspects of cognitive load

Original items presented in Leppink et al. (2013)	Adapted items
11 point Likert scale	5-point Likert scale
The topic/topics covered in the activity was/were simple.	This experiment was simple.
The activity covered concepts and definitions that I perceived as very complex. The instructions and/or explanations during the activity were very unclear. The instructions and/or explanations were full of unclear language.	I could easily follow the experimental on this experiment.
9-point Likert scale	5-point Likert scale
To learn from the lecture was (*very, very easy* to *very, very difficult*).	I was able to learn something from this experiment.
How much did you concentrate during the lecture? (*very, very little* to *very, very much*)	I was able to concentrate well on this experiment.
In the lecture that just finished I invested (*very, very low mental effort* to *very, very high mental effort).*	The mental effort in this laboratory course was high.

Note. The last item was not used for each experiment but for the complete laboratory course

Table 4. ECTS distribution in the respective curriculum

	BSc chemistry	USW NAWI-Tech
Laboratory courses	41	14
Organic chemistry (excl. labs)	22	3
Technological chemistry	12	4

Note. In the curriculum of USW NAWI-Tech additional lectures and/or a laboratory course on chemical technology (8 ECTS) are included as compulsory subject in an elective module; therefore, students can choose not to attend a laboratory course in this module

All instruments used in cycle 2 consisted of adapted or self-developed items and were analyzed at the item level. Descriptive statistics (medians and frequencies) were calculated. Normality was assessed using Shapiro-Wilk and Kolmogorov-Smirnov tests. For non-normally distributed data, Wilcoxon signed-rank tests and effect sizes (r) were computed.

RESULTS

RQ1. Which Learning Opportunities Were Offered to Students of the Master Technical Chemistry in the Context of Their Previous Education on Continuous Flow Chemistry?

Cycle 1

In our curricula analyses of the bachelor's degree programs, descriptive comparisons of curriculum structures were conducted, revealing that the distribution of European credit transfer and accumulation system (ECTS) of relevant content varies in these two bachelor programs. This analysis was conducted based on curriculum documents and course materials. These curriculum-based findings were later contextualized through students' self-reported experiences in the pre-survey of cycle 1 and cycle 2. **Table 4** compares the amount of ECTS on learning opportunities in practical skills according to the curricula. **Table 4** shows that the number of laboratory courses in the BSc sustainable development with the focus on natural sciences and technology (USW/NAWI-Tech) is much lower than in the BSc chemistry program, although both studies are admitted to the master program technical chemistry. Further, content-related prior knowledge of organic chemistry is necessary, as organic syntheses are conducted in the flow laboratory course. For the basic understanding of continuous flow processes, learning opportunities on chemical engineering are required. Flow chemistry is often described as green and sustainable, therefore, the course also provides learning opportunities on green and sustainable synthesis, as the third experiment can be ascribed to this research topic.

A more detailed analysis of the curricula and course materials of relevant courses corroborated the hypothesis that students in the bachelor's degree program sustainable development with the focus on natural sciences and technology (USW/NAWI-Tech) had fewer learning opportunities in practical laboratory areas.

Cycle 2

Our pre-surveys administered in the second laboratory course cycle of this research project give a more detailed view on the students' self-reported prior learning opportunities related to flow chemistry (**Table 5**). As the pre-survey consisted of adapted and self-developed items rather than validated scales, no reliability analyses were conducted, and no latent constructs were assumed. According to a Shapiro-Wilk test and a Kolmogorov-Smirnov test the data are not normally distributed ($p < .001$), therefore the medians are reported.

Students of all surveyed bachelor programs stated to have had learning opportunities in general lab practice frequently (Mdn = 4), but the learning opportunities in theory and lab practice in continuous flow chemistry and continuous flow processes in general are little (Mdn = 2, Mdn = 1).

Table 5. Frequencies of learning opportunities in previous studies relevant to the flow laboratory course, reported with the median answer (cycle 2)

Learning opportunities	Frequencies of learning opportunities			
Range from 1 (never) to 4 (frequently)	n	Median	Minimum	Maximum
General lab practice	24	4.0	3	4
Theory of green and sustainable chemistry	24	2.0	1	4
Lab practice in green and sustainable chemistry	24	1.0	1	3
Theory of process engineering	24	3.0	1	4
Lab practice in process engineering	24	1.0	1	4
Theory of organic chemistry	24	4.0	2	4
Lab practice in organic chemistry	24	4.0	1	4
Theory of continuous flow/continuous processing	24	2.0	1	4
Lab practice in continuous flow/continuous processing	24	1.0	1	3

RQ2. How Do Students Evaluate a One-Day Laboratory Course on Flow Chemistry With Regard to the Structure of the Lab Day and the Elements of Guided Inquiry Learning?

Cycle 1. Structure of the lab day

In cycle 1, students' perceptions of the laboratory course structure and inquiry-based learning were collected via a post-survey including 5-point Likert-scale items and open-ended questions. The results show that 86 % of the students on the first cycle (n = 35) found the laboratory course to be well structured. It has to be noted that post interviews with students of this cycle revealed problems with the third experiment due to the lack of time and also technical problems with the flow reactor (Ringdorfer et al., 2024).

Cycle 2. Structure of the lab day

Based on insights from cycle 1, the laboratory course was revised, and students' perceptions were again collected in a post-survey. Due to these results of cycle 1, key findings include the redesign of the optimization experiment and additional flow reactor due to little workload for the whole students' group. Positively, time issues were not mentioned as difficulties in the second cycle of the laboratory course. Other difficulties mentioned were problems with the stoichiometric calculations for preparing the stock solutions for the experiments. What can be clearly seen by examining the post surveys of cycle 2 is that students wish for more lab days on flow chemistry and that the laboratory course would address the usage of flow chemistry in the industry.

Cycle 1. Inquiry-based learning approach

In relation to the elements of research-based learning and the aim to encourage students' inquiry skills, we revealed that there has been an increase in students' self-assessment to the elements of inquiry-based learning: almost all respondents (81%) totally agreed or agreed that this lab day gave them the opportunity to try out their own ideas, that group discussions are supportive when carrying out experiment 3 and that they found independent work is beneficial to learning (blinded, 2024). Of the 38 students of cycle 1 who completed the post survey, 76% totally agreed or agreed that they used positive statements to encourage their group members by working in groups. Surprisingly, only 60% indicated to have helped others in their group to learn.

Cycle 2. Students' research skills

In cycle 2, research skills were assessed using an adapted survey of Böttcher-Oschmann and Thiel (2016), covering: reflective skills, subject-specific knowledge, communication skills and methodological skills. We observed a significant change in the students' self-assessment in one item of reflective skills ($r = 0.46$, $p = .03$). An increase was also observed for two items in the area of subject-specific knowledge ($r = 0.48$, $p = .035$; $r = 0.52$, $p = .018$). In the category of communication skills, only one item achieved a significant increase ($r = 0.47$, $p = .028$). According to the results, methodological competence appeared to have been influenced most positively. Here, we found an increase in self-assessment in the subcategory "selection and application of methods" (see **Table 6**).

Three of the four items in the subcategory "selection and application of methods" as part of methodological skills showed significant values with high ($r > .50$) and medium effect sizes ($r > .30$) (Cohen, 1988). For the other categories of student research competencies, significant differences were only found for one or two items.

RQ3. Are the Designed Experiments Appropriate for the Laboratory Course on Flow Chemistry According to the Learning Objectives?

Cycle 2

In the second laboratory course cycle, the post surveys showed that there was a significant change in the students' self-assessment regarding the learning objectives after the laboratory course. **Table 7** shows the change in students' self-assessment with regard to the learning objectives formulated for this laboratory course. It reveals that there has been an increase in students' self-assessment in the learning objectives.

Table 6. Students' self-assessment on research skills (Wilcoxon rank sum test)

		n	Z	Median	Significance†	r
Pre	I can confidentially apply more complex procedures for	24	-2.693	3.0	.008	0.56
Post	the analysis of data/sources/materials.	23		4.0		
Pre	I can apply different research methods according to my	24	-2.519	3.0	.010	0.53
Post	research question.	23		4.0		
Pre	It is easy for me to decide which methods are best for	24	-2.122	3.0	.034	0.44
Post	investigating a particular research topic.	23		3.0		
Pre	I can assess well which methods are not suitable or	24	-1.904	3.0	.074	0.40
Post	inappropriate for dealing with a special research question.	23		4.0		

Note. According to Shapiro-Wilk test and Kolmogorov-Smirnov test the data are not normally distributed ($p < .001$), from 1 (does not apply at all) to 5 (definitely applies) & †Exact significance (two-sided)

Table 7. Students' self-assessment on the learning objectives (Wilcoxon rank sum test)

		n	Z	Median	Significance †	r
Pre	I can explain how to use flow chemistry.	24	-3.217	3.0	< .001	0.66
Post		24		4.0		
Pre	I can name parameters that influence synthesis in the flow	24	-4.017	3.0	< .001	0.82
Post	system.	24		4.0		
Pre	I can document obtained measured data.	24	-3.444	3.0	< .001	0.70
Post		24		4.0		
Pre	I can determine the flow rate in a flow system with simple	24	-3.976	3.0	< .001	0.81
Post	tools.	24		4.0		
Pre	I can use knowledge already gained to answer research	24	-3.3	3.5	= .001	0.67
Post	questions.	24		4.0		
Pre	I can determine the mixing efficiency of mixing types.	24	-4.137	3.0	< .001	0.64
Post		24		4.0		
Pre	I can assess the influence of mixing types on synthesis	24	-4.09	2.0	< .001	0.83
Post	reactions in flow reactors.	24		3.0		
Pre	I can optimize a synthesis in a flow reactor by changing	24	-3.602	2.0	< .001	0.74
Post	specific parameters.	24		4.0		
Pre	I can describe the basic principles of flow chemistry.	24	-1.761	2.0	> .05	0.36
Post		24		4.0		
Pre	I can explain the differences between syntheses in flow	24	-2.496	2.0	= .020	0.51
Post	and in "batch" processes.	24		4.0		
Pre	I can explain what is meant by flow chemistry.	24	-3.153	2.0	= .002	0.64
Post		24		3.0		
Pre	I can argue what advantages flow chemistry brings with	24	-2.504	3.0	= .014	0.51
Post	it.	24		4.0		

Note: According to a Shapiro-Wilk test and a Kolmogorov-Smirnov test the data are not normally distributed ($p < .001$), range from 1 (no sufficient skill after the laboratory course) to 4 (sufficient skill after the laboratory course) & †Exact significance (two-sided)

The results show a significant increase in the students' self-assessment regarding the learning objectives in all areas after the laboratory course compared to before except for the learning objective "I can describe the basic principles of flow chemistry" ($p = .05$). The effect size of all set learning objectives is higher than 0.5 and corresponds to a strong effect according to Cohen (1988).

Further, the analyses of the post survey of cycle 2 showed that the first experiment on determining the flow rates is perceived as simple by 75 % of the students. The experiment to determine the mixing efficiency is perceived as a little bit more demanding, as 83 % of the students stated that the experiment was rather simple. In contrast, synthesis/optimization was perceived as the most difficult experiment (**Table 8**). This underlines the intended differences in difficulties of the experiments.

According to the students' assessment, concentration was good in all experiments, but a slight decrease was observed in the self-assessment. 21 % of the students rated their mental effort on the lab day high, 46 % stated that this was not or absolutely not the case.

DISCUSSION

RQ1 (Learning Opportunities)

The curricula analyses showed little learning opportunities in flow chemistry and continuous processing in the bachelor programs chemistry and sustainable development with the focus on natural

Table 8. Reported students' self-assessment on four items on each experiment

		n	Median	Minimum	Maximum
Experiment 1	The experiment was simple.	24	5	3	5
	I was able to learn something from this experiment.	24	5	3	5
	I could easily follow the experimental	24	5	3	5
	I was able to concentrate well on this experiment.	24	5	3	5
Experiment 2	The experiment was simple.	24	4	2	5
	I was able to learn something from this experiment.	24	5	3	5
	I could easily follow the experimental	24	5	3	5
	I was able to concentrate well on this experiment.	24	5	3	5
Experiment 3	The experiment was simple.	24	4	1	5
	I was able to learn something from this experiment.	24	5	3	5
	I could easily follow the experimental	24	4	2	5
	I was able to concentrate well on this experiment.	24	4.5	1	5

sciences and technology (USW/NAWI-Tech). Our findings on the learning opportunities are somewhat surprising since the students of all bachelor programs reported that they had learning opportunities in general lab practice frequently or often, although the curricula analyses showed differences in the ECTS-amount of laboratory courses. In contrast, the frequencies of learning opportunities in the field of continuous flow/continuous processing are little, only a few students reported to have experience in flow chemistry. Also, the frequencies of learning opportunities in students' previous education at the university in the areas of lab practice in green and sustainable chemistry and process engineering are low. This supports the hypothesis that students need special support in handling the equipment and that the laboratory design should be structured accordingly. These findings reinforce the general point that flow chemistry is hardly taught at universities. To summarize, not all branches of bachelor programs have the same amount (ECTS) of laboratory practice in the curriculum, students still feel that they have frequent opportunities to learn about general laboratory practice during their studies.

RQ2 (Evaluation of the Lab Day Structure, Inquiry-Based Learning)

In cycle 1, students stated that the lab day was well structured, but they also mentioned time problems when conducting the last experiment. Further, the group size seemed to be too large for the workload they had to cope with and students suggested an additional flow reactor for parallel work. Also, the results underline the methodological intention to implement elements of inquiry-based learning as they were perceived as positive and conducive to learning. The most obvious finding to emerge from the analysis is that the methodological intention to have an experiment carried out as an independent optimization could match the aim to acquire inquiry-based, more specific inquiry-led, learning.

In the second cycle, students' research skills were investigated with a pre- and post-survey. The results of this study show significant increases in some of the students' research skills, especially in the category of methodological skills. This observation may support the hypothesis that the laboratory course with inquiry-led elements supported the students' self-assessment on their research skills. However, these results need to be interpreted with caution because of the small sample size. The students' prior learning opportunities and skills can vary in a high range, so these findings cannot be extrapolated to all students. This goes hand in hand with the validity of the students' research skills. It cannot be ruled out that other lectures and other laboratory courses are responsible for positive changes in methodological skills in the period between the pre- and post-survey. In this context it is also questionable whether it is even possible to observe a meaningful change in the students' research skills given the small sample. In general, our study was able to show that the structural design and structure of this laboratory course was suitable for the students. It is important to note that the time frame of the laboratory course is limited to one day, therefore, it would be useful to offer a multi-day laboratory course on flow chemistry, especially in order to train new skills and abilities.

RQ3 (Experiments and Learning Objectives)

On the question of the suitability of the designed experiments, the data on the modified items on the cognitive load of the experiments prove that the goal of selecting experiments with increasing levels of difficulty was achieved. In the second cycle, the optimization experiment had to be re-designed with the aim of developing an experiment, which can be optimized in shorter time.

These results provide initial evidence that the experiments were a learning success. The first part of the questionnaire revealed that, according to the students' assessment, the achievement of the learning objectives set for this laboratory practical course with regard to their previous experience and learning opportunities increased after completing the laboratory practical course. The effect sizes are particularly high for those learning objectives that relate to the second experiment and the third experiment, where mixing, flow rates and residence time are important parameters. With respect to **RQ1**, a possible explanation for this might be the little learning opportunities in the field of flow chemistry and continuous processing itself. Students have the feeling that they know more about these learning objectives after the laboratory course than before, however, it is also possible that these results are biased due to the self-reported nature of assessment. Nevertheless, it must be said that these findings may support the belief that independent work, as required in the optimization experiment, has a positive effect on learning. The results on the items of cognitive load also show that the experiments are designed with increasing levels of difficulty. However, several limitations must be acknowledged. First, our assessment of learning outcomes relied entirely on students' self-reported measures rather than objective assessments of knowledge or skill acquisition. While self-assessments provide valuable insights into students' perceived learning and confidence, they are subject to bias and may not accurately reflect actual learning gains. Students may overestimate or underestimate their competence, and increased confidence does not necessarily equate to increased competence. Second, the small sample size (N = 24 in cycle 2) limits the generalizability of the findings.

CONCLUSION AND OUTLOOK

Within a PAR framework, we successfully designed, implemented, and iteratively refined a one-day laboratory course on flow chemistry for master's students in technical chemistry. The findings indicate that the developed laboratory course represents a feasible and research-informed approach to introducing flow chemistry in higher education. Across both cycles, the results highlight heterogeneous prior knowledge among students and confirm the relevance of providing structured learning opportunities in flow chemistry within the master's curriculum.

The iterative PAR process enabled systematic refinements of the experiments, the didactic concept, and the evaluation instruments. While the quantitative data suggest positive developments in students' self-assessed learning outcomes and research skills, the reliance on self-report measures constitutes a central limitation of this study. Furthermore, the relatively small sample size and the context-specific implementation limit the generalizability of the findings. Future research should therefore extend the evaluation beyond self-assessment data by incorporating performance-based measures of learning outcomes and observational data on inquiry processes. The planned third PAR cycle should serve to further refine both the instructional design and the evaluation strategy. In addition to introducing a second flow reactor system to broaden students' technical exposure, structural adjustments to group organization should be implemented to optimize workload distribution and learning efficiency. Beyond the local context, future studies could investigate the transferability of the developed laboratory concept to other institutional settings and explore its integration into longer-term curricular structures. In this way, the project may contribute to the sustainable implementation of flow chemistry as a regular component of higher chemistry education.

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REFERENCES

Banchi H., & Bell, R. (2008). The many levels of inquiry. *Science and Children, 46*(2), 26-29.

Bargel, T. (2012). Bedeutung von Praxisbezügen im Studium. In W. Schubarth, K. Speck, A. Seidel, C. Gottmann, C. Kamm & M. Krohn (Hrsg.), *Studium nach Bologna: Praxisbezüge stärken?! Praktika als Brücke zwischen Hochschule und Arbeitsmarkt* (pp. 37-46). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-531-19122-5_3

Bayana, M., Blacker, A. J., Clayton, A. D., Jolley, K. E., Labes, R., Taylor, C. J., & Reynolds, W. (2021). A practical experiment to teach students continuous flow and physico-chemical methods: Acetylation of ethylene diamine in liquid bi-phase. *Journal of Flow Chemistry, 11*(1), 31-36. https://doi.org/10.1007/s41981-020-00114-5

Berendt, B. (2000). Was ist gute Hochschullehre [What constitutes good university teaching]? In A. Helmke, W. Hornstein, & E. Terhart (Eds.), *Qualität und Qualitätssicherung im Bildungsbereich; Schule, Sozialpädagogik, Hochschule, Zeitschrift für Pädagogik, Beiheft* (pp. 247-260). Beltz. https://doi.org/10.25656/01:8495

Blanco-Ania, D., & Rutjes, F. P. J. T. (2017). Continuous-flow chemistry in chemical education. *Journal of Flow Chemistry*, *7*(3), 157-158. https://doi.org/10.1556/1846.2017.00023

Boateng, G. O., Neilands, T. B., Frongillo, E. A., Melgar-Quiñonez, H. R., & Young S. L. (2018). Best practices for developing and validating scales for health, social, and behavioral research: A primer. *Frontiers in Public Health, 6*. https://doi.org/10.3389/fpubh.2018.00149

Böttcher-Oschmann, F., & Thiel, F. (2016). Der Fragebogen Zur Erfassung Studentischer Forschungskompetenzen-Ein Instrument auf der Grundlage des RMRK-W-Modells zur Evaluation von Formaten forschungsorientierter Lehre [The questionnaire for assessing student research competencies–An instrument based on the RMRK-W model for evaluating research-oriented teaching formats]. In B. Berendt (Eds.), *Neues Handbuch Hochschullehre* (pp. 57-74). DUZ Verlags-und Medienhaus.

Britton, J., & Jamison, T. (2017). The assembly and use of continuous flow systems for chemical synthesis. *Nature Protocols, 12*, 2423-2446. https://doi.org/10.1038/nprot.2017.102

Bruckermann, T., & Schlüter, K. (2017). *Forschendes Lernen im Experimentalpraktikum Biologie: Eine praktische Anleitung für die Lehramtsausbildung* [Inquiry-based learning in the experimental biology course: A practical guide for teacher training]. Springer. https://doi.org/10.1007/978-3-662-53308-6

Cerra, B., & Gioiello, A. (2021). Future medicinal chemists experience flow chemistry: Optimization by experimental design of the limiting synthetic step to the antifungal drug econazole nitrate. *Journal of Flow Chemistry, 11*(1), 67-73. https://doi.org/10.1007/s41981-020-00136-z

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Erlbaum.

Commenge, J.-M., & Falk, L. (2011). Villermaux-dushman protocol for experimental characterization of micromixers. *Chemical Engineering and Processing: Process Intensification, 50*(10), 979-990. https://doi.org/10.1016/j.cep.2011.06.006

Dallinger, D., & Kappe, C. O. (2017). Why flow means green – Evaluating the merits of continuous processing in the context of sustainability. *Current Opinion in Green and Sustainable Chemistry*, *7*, 6-12. https://doi.org/10.1016/j.cogsc.2017.06.003

Döring, N., Bortz, J., & Pöschl, S. (2016). *Forschungsmethoden und Evaluation in den Sozial-und Humanwissenschaften* [Research methods and evaluation in the social sciences and humanities]. Springer. https://doi.org/10.1007/978-3-642-41089-5

Eilks, I., & Ralle, B. (2002). Partizipative Fachdidaktische Aktionsforschung. Ein Modell für eine begründete und praxisnahe curriculare Entwicklungsforschung in der Chemiedidaktik [Participatory subject-specific action research: A model for well-founded and practice-oriented curricular development research in chemistry education]. *CHEMKON, 9*(1), 13-18. https://doi.org/10.1002/1521-3730(200201)9:1<13:AID-CKON13>3.0.CO;2-5

Gillies, R. M. (2020). *Inquiry-Based Science Education*. CRC Press. https://doi.org/10.1201/9780429299179

Griffiths, R. (2004). Knowledge production and the research-teaching nexus: the case of the built environment disciplines. *Studies in Higher Education*, *29*(6), 709-726. https://doi.org/10.1080/0307507042000287212

Gutmann, B., Cantillo, D. & Kappe, C. O. (2015). Continuous-flow technology - A tool for the safe manufacturing of active pharmaceutical ingredients. *Angewandte Chemie (International ed. in English)*, *54*(23), 6688-6728. https://doi.org/10.1002/anie.201409318

Hodson, D. (2014). Learning science, learning about science, doing science: Different goals demand different learning methods. *International Journal of Science Education, 36*(15), 2534-2553. https://doi.org/10.1080/09500693.2014.899722

Huang, Y. (2022). Effectiveness of inquiry-based science laboratories for improving teamwork and problem-solving skills and attitudes. *Journal of Research in Science Teaching*, *59*(3), 329-357. https://doi.org/10.1002/tea.21729

Huber, L. (2004). Forschendes Lernen. 10 Thesen zum Verhältnis von Forschung und Lehre aus der Perspektive des Studiums [Inquiry-based learning. 10 theses on the relationship between research and teaching from the perspective of university studies.]. *Die Hochschule : Journal für Wissenschaft und Bildung*, *13*(2). https://pub.uni-bielefeld.de/record/2905236

Kairouz, V., & Collins, S. K. (2018). Continuous flow science in an undergraduate teaching laboratory: Bleach-mediated oxidation in a biphasic system. *Journal of Chemical Education, 95*(6), 1069-1072. https://doi.org/10.1021/acs.jchemed.7b00412

Kairouz, V., Charette, A. B., & Collins, S. K. (2021). Implementing flow chemistry in education: The NSERC CREATE program in continuous flow science. *Journal of Flow Chemistry, 11*(1), 13-17. https://doi.org/10.1007/s41981-020-00129-y

Kruse, J. (2015). *Qualitative Interviewforschung: Ein integrativer Ansatz* [Qualitative interview research: An integrative approach]. Beltz Juventa.

Kuijpers, K. P. L., Weggemans, W. M. A., Verwijlen, C. J. A., & Noël, T. (2020). Flow chemistry experiments in the undergraduate teaching laboratory: synthesis of diazo dyes and disulfides. *Journal of Flow Chemistry, 11*, 7-12. https://doi.org/10.1007/s41981-020-00118-1

Leppink, J., Paas, F., v. d. Vleuten, C. P. M., v. Gog, T., & v. Merriënboer, J. J. G. (2013). Development of an instrument for measuring different types of cognitive load. *Behavior Research Methods, 45*(4), 1058-1072. https://doi.org/10.3758/s13428-013-0334-1

Multrus, F. (2009). *Forschungs-und Praxisbezug im Studium: Erfassung und Befunde des Studierendensurveys und des Studienqualitätsmonitors. Hefte zur Bildungs-und Hochschulforschung* [Research and practical relevance in higher education: Data collection and findings from the student survey and the study quality monitor. Publications on educational and higher education research]. Konstanz.

Parchmann, I., Schwarzer, S., Wilke, T., Tausch, M., & Waitz, T. (2017). Von Innovationen Der Chemie Zu Innovativen Lernanlässen Für Den Chemieunterricht Und Darüber Hinaus [From innovations in chemistry to innovative learning opportunities for chemistry lessons and beyond]. *CHEMKON, 24*(4), 161-164. https://doi.org/10.1002/ckon.201790001

Pedaste, M., Mäeots, M., Siiman, L. A., d. Jong, T., v. Riesen, S. A. N., Kamp, E. T., Manoli, C. C., Zacharia, Z. C., & 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

Penny, M. R., Tsui, N., & Hilton, S. T. (2021). Extending practical flow chemistry into the undergraduate curriculum via the use of a portable low-cost 3D printed continuous flow system. *Journal of Flow Chemistry, 11*(1), 19-29. https://doi.org/10.1007/s41981-020-00122-5

Plutschack, M. B., Pieber, B., Gilmore, K., & Seeberger, P. H. (2017). The Hitchhiker's guide to flow chemistry. *Chemical Reviews, 117*(18), 11796-11893. https://doi.org/10.1021/acs.chemrev.7b00183

Ringdorfer, R., Dallinger, D., Kappe, C. O. & Spitzer, P. (2024). Realisierung eines Flow Chemistry Praktikums mit Masterstudierenden [Implementation of a flow chemistry internship with master's students]. In H. van Vorst (Hrsg.), *Frühe naturwissenschaftliche Bildung. Gesellschaft für Didaktik der Chemie und Physik. Jahrestagung in Hamburg 2023* (pp. 422-425). Universität Duisburg-Essen. https://doi.org/10.25656/01:30626

Sun, M., Liang, C., Shen, X., Li, J., Cheng, R., & Ye, J. (2021). Continuous flow science in an undergraduate teaching laboratory: Synthesis of ethylene glycol diacetate using heterogeneous catalysts in continuous flow. *Journal of Chemical Education, 98*(2), 572-576. https://doi.org/10.1021/acs.jchemed.0c01226

Tausch, M. W. (2004). Curriculare innovation. *Praxis der Naturwissenschaften - Chemie in der Schule, 53*(18-21).

The PRIMAS Project. (2013). Promoting inquiry-based learning (IBL) in mathematics and science education across Europe: IBL implementation survey report. *PRIMAS*. https://primas-project.eu/wp-content/uploads/sites/323/2017/11/PRIMAS_D-9.3_IBL-Implementation-survey-report.pdf

Tolsdorf, Y., & Markic, S. (2018). Participatory action research in university chemistry teacher training. *Center for Educational Policy Studies Journal, 8*(4), 89-108. https://doi.org/10.26529/cepsj.269

Tolsdorf, Y., & Markic, S. (2019). Entwicklung eines Seminarkonzepts zu Lesestrategien entwickelt nach dem adaptierten Modell der Partizipativen Aktionsforschung [Development of a seminar concept on reading strategies developed according to the adapted model of participatory action research]. *CHEMKON, 26*(3), 108-113. https://doi.org/10.1002/ckon.201800017

van Summeren, L. T. C. G., Gerretzen, J., Rutjes, F. P. J. T., & Bloemberg, T. G. (2021). Optimization of continuous-flow diphenyldiazomethane synthesis: An integrated undergraduate chemistry experiment. *Journal of Flow Chemistry, 11*(1), 59-66. https://doi.org/10.1007/s41981-020-00107-4