Implementation of Inquiry-Based Learning (IBL) into Chemistry Teaching at Various Levels of Education

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A Habilitation Thesis

in form of a series of publications with a commentary,

elaborated at the Faculty of Chemistry,
Jagiellonian University in Kraków, Poland,

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I would like to express my deepest gratitude
to all who believed in me,
and never let me give up
in pursuing this goal.

Contents

Foreword

The presented study is constituted of a series of publications focused on implementation of the Inquiry-Based Learning (IBL) in teaching chemistry at various levels of education. The series consists of 12 publications written in years 2012-2021. All of them have been published in peer-reviewed international journals, 8 of them have Impact Factor, two are indexed in Web of Science, one is indexed in SCOPUS, and one [P5] is a newly established journal – *Chemistry Teacher International* (De Gruyter) – led by Committee on Chemistry Education of IUPAC (first issue in June 2019, not indexed yet). I am the corresponding author in 11 out of 12 presented papers and the first author in 9 of them. In each of them, I am the main interpreter of the experimental part.

Table 1. List of articles included in the study (*corresponding author)

Number	Publication	IF^{2020} (or index)
P1	**Paweł Bernard***, Iwona Maciejowska, Ewa Odrowąż, Karol Dudek, Rory Geoghegan (2012). Introduction of inquiry based science education into polish science curriculum – general findings of teachers' attitude. *Chemistry-Didactics-Ecology-Metrology*, *17*(1–2), 49–59. https://doi.org/10.2478/cdem-2013-0004	WoS
P2	**Paweł Bernard***, Iwona Maciejowska, Małgorzata Krzeczkowska, Ewa Odrowąż (2015). Influence of In-service Teacher Training on their Opinions about IBSE. *Procedia – Social and Behavioral Sciences, 177*, 88–99. https://doi.org/10.1016/j.sbspro.2015.02.343	WoS
P3	**Paweł Bernard***, Karol Dudek-Różycki (2020). The Impact of Professional Development in Inquiry-Based Methods on Science Teachers' Classroom Practice. *Journal of Baltic Science Education*, *19*(2), 201–219. https://doi.org/10.33225/jbse/20.19.201	1.182
P4	**Paweł Bernard***, Karol Dudek-Różycki, Kinga Orwat (2019). Integration of inquiry-based instruction with formative assessment: the case of experienced chemistry teachers. *Journal of Baltic Science Education, 18*(2), 184–196. https://doi.org/10.33225/JBSE/19.18.184	1.182

P5	**Paweł Bernard***, Karol Dudek-Różycki (2019). Influence of training in inquiry-based methods on in-service science teachers' reasoning skills. *Chemistry Teacher International*, *1*(2), 1–12. https://doi.org/10.1515/cti-2018-0023	-
P6	Mária Babinčáková, **Paweł Bernard*** (2020). Online Experimentation during COVID-19 Secondary School Closures: Teaching Methods and Student Perceptions. *Journal of Chemical Education, 97*(9), 3295–3300. https://doi.org/10.1021/acs.jchemed.0c00748	2.979
P7	Kinga Orwat, **Paweł Bernard***, Anna Migdał-Mikuli (2016). Obtaining and investigating amphoteric properties of aluminum oxide in a hands-on laboratory experiment for high school students. *Journal of Chemical Education, 93*(5), 906–909. https://doi.org/10.1021/acs.jchemed.5b00314	2.979
P8	Kinga Orwat, **Paweł Bernard***, Szymon Wróblewski, James D. Mendez (2018). Traditional vs. UV-cured coatings – an inquiry-based experiment for introducing green chemistry. *Macedonian Journal of Chemistry and Chemical Engineering*, *37*(2), 215–224. https://doi.org/10.20450/mjcce.2018.1512	0.689
P9	**Paweł Bernard***, Paweł Stelmachowski, Paweł Broś, Wacław Makowski, Andrzej Kotarba (2021). Demonstration of the Influence of Specific Surface Area on Reaction Rate in Heterogeneous Catalysis. *Journal of Chemical Education, 98*(3) 935–940. https://doi.org/10.1021/acs.jchemed.0c01101	2.979
P10	**Paweł Bernard***, Gabriela Grzybek, Paweł Stelmachowski (2014). Tuning the electronic properties of heterogeneous catalysts: an authentic research-based laboratory course. *Chemistry: Bulgarian Journal of Science Education, 23*(3), 392–408.	SCOPUS
P11	**Paweł Bernard***, James D. Mendez (2020). Low-Cost 3D-Printed Polarimeter *Journal of Chemical Education*, *97*(4), 1162–1166. https://doi.org/10.1021/acs.jchemed.9b01083	2.979
P12	**Paweł Bernard**, James D. Mendez* (2020). Drawing in 3D: Using 3D printer pens to draw chemical models. *Biochemistry and Molecular Biology Education, 48*(3), 253–258. https://doi.org/10.1002/bmb.21334	1.160

Studies described in the above-mentioned papers may be divided into two main strands:

I. Studies on selected aspects of the Inquiry-Based Learning (IBL) implementation process. In general, these studies concern pedagogical aspects and are based on the methodology of humanistic and social research in qualitative and quantitative terms. The research subjects in this area included teachers' beliefs and attitudes toward IBL [P1, P2], development and evaluation of teacher training programmes in IBL [P2, P3], the influence of designed and applied professional development programmes on teachers' classroom practice [P3, P4 & P5], and elements of inquiry-based instructions used by teachers while distance education forced by COVID-19 pandemic [P6].
II. Studies aimed for the development and evaluation of new didactic aids to be applied in inquiry-based learning at various educational levels. These works are based on chemical investigations and processes, the methodology used is based on both, the methodology of natural science/chemical research – development of new teaching aids, and humanistic/social studies – assessment of the didactic suitability of the developed solutions. Among the topics undertaken the following can be distinguished: inquiry-based experiments for school students (open and guided inquiry) [P7, P8], inquiry-based experiments for university students (demonstrations and hands-on experiments) publications [P9, P10], and 3D-printed didactic tools enhancing inquiry-based teaching and learning [P11 & P12].

Studies described in the first part of this work were related to the realisation of projects funded by the European Union Seventh Framework Programme (FP7 UE): ESTABLISH – linking inquiry with industry; SAILS – focusing on formative assessment in IBL, and IRRESISTIBLE – linking inquiry-based education with informal education and with the idea of responsible research and innovations (RRI). Therefore, the described research was carried out during the implementation of the IBL methods to the school practice of Polish teachers. An exception in this area is the publication [P6], created as a result of the crisis related to the outbreak of the COVID-19 pandemic and concerning the practice of teachers using IBL in online education in Slovakia. The second part of the research is more international and universal. Admittedly, all the developed teaching aids have been created in Poland and fit the Polish curriculum, but this does not limit their universal usefulness. Some of the solutions were developed and tested in cooperation with partners from Indiana University − Purdue University Columbus in the United States [P8, P11 & P12]. Moreover, the didactic materials and classes scenario presented in the publication [P8] were developed in cooperation with the industry – PPG Polifarb Cieszyn S.A. Furthermore, the system supporting modelling of chemical molecules based on the 3D printing technology, described in the publication [P12], is the subject of a patent application (Paweł Bernard, James D. Mendez 'A Modular Modelling Kit for Drawing Geometric Structures'. Appl. PCT/PL2018/050019, 11.05.2018), and the invention was awarded a bronze medal during the International Trade Fair of the Invention and Innovation INTARG2018. It should be added that the research presented in publications [P3, P4, P5, P7 & P8] was related to the preparation of two doctoral dissertations in which I was a co-promoter (dissertation co-supervisor): Karol Dudek (2016) '*Thermal studies of lithium batteries under high current flow and other experiments for teacher training in inquiry-based methodology and assessment*', and Kinga Orwat (2019) '*Research of polymorphism of hexadimethylsulphoxidemagnesium chlorate(VII) and other experiments developed for their use in teaching chemistry at various educational levels*'.

Part I – Research on various aspects of implementation of IBL into school practice

1. Introduction

Teaching methods based on students' independent inquiry of knowledge are based on the constructivist paradigm of education. Klus-Stańska (2018) divides it into constructivist-psychological (developmental) trend, the sources of which are the works of Piaget (1929), and the constructivist-social trend, derived from the works of Vygotsky (1997, first published in 1926). The first one emphasizes the role of independent, active acquiring knowledge by students, while the second emphasizes the role of cultural aspects, cooperation on the teacher-student-group line, thanks to which the construction of knowledge is not only the result of the student's own activity but of the social process (Bruner, 1960, 1962, 1966). Both versions of constructivism have a common element – the cognitive and active attitude of students who are architects of their knowledge (Sajdak, 2013). However, constructivism is a theory of learning and is not, in itself, an instruction for action (Klus-Stańska, 2009). The beginnings of its implementation in science education can be found in German literature from the 1960s (Schwab, 1958), but the widespread use of this trend in education, its coexistence with the behaviourist trend, and even displacement of the latter in schools began almost 20 years later. The beginnings of a change in this direction in the United States should be associated with “A Nation at Risk” report by Gardner et al. (1983) which called for changes to the educational system in the US and introduction of inquiry-based methods especially in science and mathematics education (Johnson, Kahle, & Fargo, 2007). Preparations for changes took more than 10 years and a new science curriculum, in which inquiry-based methods became an essential strategy in science education, was launched by the National Research Council (1996). The European Union waited another 10 years with a shift of science education toward inquiry-based methods. Similarly to the US, the driving force of change was constituted by a report, so-called Rocard’s report (Rocard, Csermely, Jorde, Walberg-Henriksson, & Hemmo, 2007), which not only recommended using inquiry-based methods in science education, but also suggested that the use of these methods can encourage students to study sciences, mathematics and technical subjects. That direction was in line with an earlier Recommendation of the European Parliament (2006) concerning the promotion and growth of a knowledge society based on scientific education. The introduction of Inquiry-Based Learning (IBL) in Europe was different than in the US. United States have a unified and centralized educational policy, while in the European Union, every country has its own policy and curricula. Moreover, every country has its own culture, traditions and history of education, therefore, inquiry played a different role in each one at the beginning of the reform (McLoughlin, Finlayson, van Kampen, & McCabe, 2013). In general, Western European countries, especially United Kingdom, had more experience in using inquiry-based methods, while Eastern and South European countries were still immersed in behaviourism inherited from socialism with the dominant and leading role of both the school as an institution, and the omniscient and lecturing teacher. Therefore, the European Parliament decided that the European Union’s Seventh Framework Programme (FP7) would include “Supporting and coordinating actions on innovation in the classroom: Dissemination and use of inquiry-based teaching methods on a large scale in Europe” as one of the key elements in the “Science in Society” area. Projects in this area were realized from 2008 to 2017 in two main phases:

I. Projects focused on the introduction of basics of inquiry-based methods (Inquiry-Based Science Education, IBSE), development of dedicated didactic materials, and teacher professional development programmes (*i.a.* Fibonacci, INQUIRE, Pathway, Primas, PROFILES, S-TEAM, SECURE).

II. Projects introducing inquiry-based methods combined with specific issues, *e.g.* the ESTABLISH project – industrial aspects of IBSE, SAILS and AssistMe projects – the assessment of students learning through inquiry, or the IRRESISTIBLE project – implementing principles of Responsible Research and Innovation to IBSE (Scientix, 2021).

Additionally, at the beginning of realisation of the FP7 projects, there were countries in which the IBL was used for many years, as well as countries in which those methods were not used at all. Therefore, at the beginning of the realisation of the aforementioned projects, educators had various experiences and understanding of inquiry-based teaching and learning, and its characteristic features. Probably the most frequently used definition of IBL became the one proposed by Linn, Davis, & Bell (2004), who stated that inquiry is the: *'…intentional process of diagnosing problems, critiquing experiments, and distinguishing alternatives, planning investigations, researching conjectures, searching for information, constructing models, debating with peers, and forming coherent arguments. (p. 4)'.* It can be treated as a generalization of students' activities while inquiry, defined by the US National Research Council (1996): *'When engaging in inquiry, students describe objects and events, ask questions, construct explanations, test those explanations against current scientific knowledge, and communicate their ideas to others. (p. 2)'.*

Therefore, inquiry in science education refers to students' investigations that mimic scientific research. Obviously, the research process cannot be strictly unified and operationalized; however, various models of inquiry-based investigations were developed over years (Atkin & Karplus, 1962; Martin, Sexton, & Gerlovich, 1999; McComas, 2014) with the most widespread cycle by the National Research Council (1996) presented in Fig. 1.

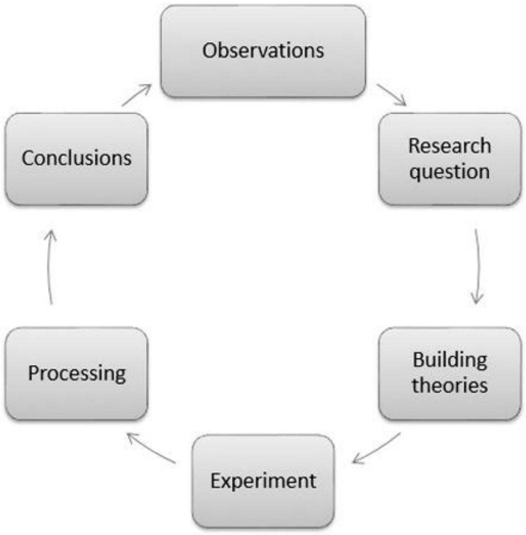

Fig. 1. A 6-stage cycle for inquiry investigations and modelling (Council, 1996), the figure originally published in [P2] (Bernard, Maciejowska, Krzeczkowska, & Odrowąż, 2015).

Alternatively, the process of inquiry can be divided into five phases: *Engage; Explore; Explain; Elaborate or Extend; Evaluate* (Bybee, 2000, 2002), a so-called 5E cycle, presented in Fig. 2. in adaptation used by the project ESTABLISH (2010). In this case, the model does not provide the sequence of specific actions, rather general phases of the lesson based on inquiry. In the first phase, interest and curiosity in the topic should be developed, then the students should be engaged in the inquiry. Next, the teacher facilitates discussion based on gathered data and evidence. After that, it's time for generalization and extension of the concepts to new situations. All earlier mentioned phases should be monitored and assessed by a teacher with a focus on formative feedback, and keeping the learners in a leading role throughout the process.

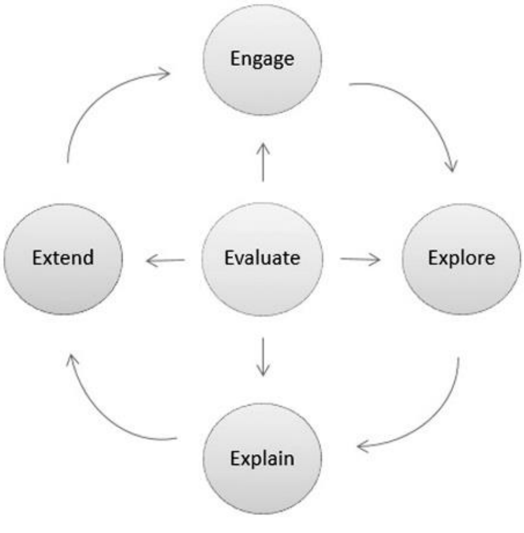

Fig. 2. The 5Es learning model used in ESTABLISH project, the figure originally published in [P2] (Bernard et al., 2015).

2. Implementation of IBL into chemistry curriculum in Poland

Publication of EU Parliament Recommendations involving advised application of inquiry-based methods in science education and support for FP7 projects promoting inquiry coincided in time with the publication of new Polish core curriculum for lower and upper secondary school (Polish Core Curriculum, 2008), which have been implemented since 2009 in lower secondary schools (K6-9) and from 2012 in upper secondary schools (K10-12). This act contained updated chemistry teaching content, new general objectives of education, and key competencies that should be mastered by students. In general objectives for chemistry, we can find:

- **at lower secondary school level** – in area III. Mastering practical activities – *The student safely uses simple laboratory equipment and basic chemicals; designs and carries out simple chemical experiments*.
- **at upper secondary school level (basic course)** – in area II. Reasoning and applying the acquired knowledge to problem solving – *The student acquires chemical knowledge by research – observes, checks, verifies, concludes and generalizes…*, and in area III. Mastering practical activities – *The student safely uses laboratory equipment and chemicals; designs and carries out chemical experiments.*
- **at upper secondary school level (extended course)** – in area II. Reasoning and applying the acquired knowledge to problem solving – *The student... formulates hypotheses to explain chemical problems and plans experiments to verify them; on this basis, they independently formulate and justify opinions and judgments.* And further, in area III. Mastering practical activities – *The student safely uses laboratory equipment and chemicals; designs and carries out chemical experiments.*

Moreover, in advised conditions and method of implementation, we can read:

> '*...teachers should set aside time for experimenting, activating methods and carrying out educational projects, as well as for didactic trips. During the classes, the student should have the opportunity to observe, research, investigate, discover laws and dependencies, achieve satisfaction and joy in acquiring knowledge on their own. ...*
>
> *The scope of the teaching content creates many opportunities to work using the educational project method (especially projects of a research nature), the chemical experiment method or other activating*

> *methods, which will allow students to obtain and process information in various ways and from various sources. The student's independent observation is the basis for experiencing, inferring, analyzing and generalizing phenomena, hence the very important role of the experiment in the implementation of the above content.*'
>
> (Polish Core Curriculum, 2008)

It is evident that inquiry-based methods were included in the reformed Polish chemistry curriculum in 2008. Similar recommendations can be found in descriptions for physics, biology and geography. Further reforms of Polish education, first changing the structure of educational system, introducing 8-years-long primary school (K1-8), and four-years-long secondary school (K9-12) (Polish Core Curriculum, 2012), and later curriculum updates to the new structure (Polish Core Curriculum, 2017, 2018) didn't bring significant changes to recommended teaching methods and conditions of curriculum realization.

Therefore, actions of the European Parliament and Polish educational reforms forced the introduction of inquiry-based methods to school practice. That created a huge gap between traditionally used school practices and new expectations. New professional development (PD) programmes for in-service and pre-service teachers had to be developed and applied; moreover, the process of implementation of the changes had to be monitored and analysed.

3. The wind of change – a study of Polish teachers' beliefs and attitudes toward IBL

Teachers beliefs concerning teaching and learning process have a tremendous effect on the way they are running classes (Brickhouse & Bodner, 1992; Nespor, 1987; Pajares, 1992). Teaching habits are shaped over years, first, based on own experiences from the learner position, and then from "the other side of the desk" (Brouwer & Korthagen, 2005; Zeichner & Tabachnick, 1981). Those very often result with their own "folk pedagogy" acquired through lifelong experiences (Arce, Bodner, & Hutchinson, 2014; Bruner, 1996; Windschitl, 2004). Moreover, there come "attitudes" that can positively or negatively affect the individual response to an external stimulus (Zimbardo & Gerrig, 1999). Therefore, the construction of a PD programme for teachers requires analysis of the existing situation and crafting content and method to it.

A study of Polish chemistry teachers' beliefs and attitudes toward IBL was carried out during the realization of the FP7 ESTABLISH project in years 2010-2014, described in the publication [P1] (Bernard, Maciejowska, Odrowąż, Dudek, & Geoghegan, 2012). The research was realized in 2011, and the research group covered 33 in-service lower and upper secondary school teachers participating in the project. The study was carried out before teacher training, however, for clearness of used terminology, participants were asked to familiarise themselves with provided basic definitions of IBL. The study was based on a questionnaire covering questions from 5 areas of IBL: ‘The nature of method’, ‘Teachers’, ‘Students’, ‘Curricula,’ and ‘Public’. The responders expressed their degree of acceptance of the presented statements using a five-point, bipolar Likert-type scale: strong disagreement, disagreement, not sure, agreement, strong agreement. Because of a limited number of responders, the analysis had a *quasi*-quantitative character, and was reduced to visual comparison of agreement and disagreement level with presented statements.

The obtained results revealed that Polish teachers have a positive attitude towards IBL. They also believe that using IBL may have a positive impact on teaching outcomes, is interesting and attractive for students, and has a high educational value. On the other hand, teachers were concerned by the students’ lack of skills for independent laboratory work, insufficient laboratory equipment to run IBL classes, not adequate curriculum, syllabuses and textbooks. Also, the problem seemed to consist in a lack of time for inquiry-based investigations during ordinary classes. The teachers’ answers suggested also that they lacked a deep understanding of IBL process, and they identified inquiry with other methods like learning by doing, ‘cookbook’ experiments or project method. Those results allowed to adapt the PD framework to Polish teachers’ needs.

The influence of participation in the PD programme on teachers beliefs and attitudes was described in [P2] (Bernard et al., 2012). The same group of teachers completed the same questionnaire once again after a one-week-long training. First of all, the results showed a better understanding of the aim and meaning of IBL by teachers. After the training, they were more convinced that it was possible to teach according to the existing curriculum using IBL methods, the time required for IBL might fit existing classes, and laboratory requirements were quite similar for inquiry investigations and ‘cookbook’ hands-on activities. Also, much fewer teachers considered IBL as favouring better students. More teachers were convinced that using IBL lead to better grades at final exams, but they noticed also that the assessment of students learning by IBL was far more complex and problematic. Furthermore, the training didn’t change the teachers’ opinion on existing textbooks, which they assessed as not adequate for IBL.

4. Development of the teacher education programme

Development of a teacher education programme (TEP) is a challenging, complex and time-consuming process. Even subtle aspects can influence its progress, results and finally impact on classroom practice (Taitelbaum, Mamlok-Naaman, Carmeli, & Hofstein, 2008). Moreover, teachers need to experience every new pedagogy approach and learning method as learners (Harrison, Howard, & Matthews, 2016; Loucks-Horsley, Hewson, Love, & Stiles, 1998). Many studies suggest that teachers learn in a very similar way to students (Liberman & Miller, 1992): they learn by doing and reflecting, by collaborating with peers, by analysing their work, and by exchanging insights and conclusions (Darling-Hammond & McLaughlin, 1995). Therefore, there is no doubt that teachers trained in using IBL must be treated as learners, be engaged actively in the process, and experience successful learner-centred teaching. Previous research has shown that such an active approach to teachers’ PD programmes is effective and changes their knowledge and practice (Brooks & Brooks, 1993; Bybee, 1993; Layman, Ochoa, & Heikkinen, 1996; Sparks & Hirsh, 1997).

Another crucial element of a TEP is the opportunity for participants to discuss the changes that have been or can be put into practice (Cordingley, Bell, Thomason & Firth, 2003; Griffin, 1983; Harrison, Hofstein, Eylon & Simon, 2008; Mule, 2006). This element leads to a better understanding of the new method, brings new ideas and encourages to try them. Therefore, a TEP should create space for effective communication between participants, not only in time of the core training, but lasting much longer while follow-up experiences, initiate and create multiple opportunities for interaction (Luft, 2001). In fact, the character of the long-term training with sustained support is mentioned as one of the most important elements of an effective PD programme for teachers (Garet, Porter, Desimone, Birman & Yoon, 2001; Loucks-Horsley et al., 1998; Posnanski, 2002). Such support and communication can be ensured by Learning or Practice Communities, established and developed within the TEP (Garet et al., 2001; Maciejowska, Čtrnáctová, & Bernard, 2015; Vescio, Ross, & Adams, 2008). Another crucial element of successful training in IBL is understanding the nature of inquiry. According to Anderson (2002) there are three aspects of inquiry that should be considered: (1) scientific inquiry – referring to the process of scientific research, (2) inquiry teaching – focusing on the organization of the process of inquiry-based teaching, and (3) inquiry learning – analysing the process of knowledge assimilation while inquiry-based investigations. Therefore, the teachers should know how scientific research are run and be able to model these processes with their students. For this purpose, there were attempts to engage trained teachers in authentic research (Abd-El-Khalick et al., 2004; Lustick, 2009). Unfortunately, such an approach occurred to be ineffective. Teachers were engaged in ongoing research without the possibility to investigate their own research questions, nor independently carry out experiments (Capps, Crawford, & Constas, 2012). Therefore, a model-based inquiry experience seems to be the best alternative. In this approach, the investigation is prepared and moderated by trainers/educators, and teachers participate in the inquiry process from the perspective of students. They experience the entire inquiry process, starting with the formulation of the research question and hypotheses, through planning and carrying out the investigation, and finish with conclusions and process evaluation. (Chin & Osborne, 2008; Council, 1996; Gyllenpalm, Wickman, & Holmgren, 2010; Jeanpierre, Oberhauser, & Freeman, 2005; Taitelbaum et al., 2008). They have also a chance to experience various forms of inquiry (Blanchard, Southerland, & Granger, 2009; Wenning, 2005). Of course, in this approach, a major challenge for educators is to find adequate, interesting and challenging tasks, and design the investigation process so that the TEP participants could get engaged in the process, experience as many approaches as possible, and gain confidence in a high value of the learned method. Moreover, it is preferable that the inquiry activities used during the training could be easily adapted to the school conditions and used by the teachers in the classroom. Many results suggest that this approach not only shapes teachers' abilities to use inquiry-based methods in practice, but also has a positive impact on their content, and pedagogical-content knowledge (Bazler, 1991; Caton, Brewer, & Brown, 2000; Loucks-Horsley et al., 1998; Luft, 2001; Westerlund, García, Koke, Taylor, & Mason, 2002).

One of the first teacher education programmes for chemistry teachers in Poland focusing on IBL was the one developed within the FP7 ESTABLISH project. Content of the TEP was based on the framework proposed in the project and adjusted by each of the partner countries according to local needs and preferences. In the Polish case, adaptation was based *i.e.* on results of the study on teachers beliefs and attitudes described above. The content of this TEP was published in [P2] (Bernard et al., 2015, Appendix A-C, pp. 96-98). The presented TEP underwent further development within FP7 ESTABLISH project and, in the next years, within FP7 SAILS project, where was enriched with components for biology and physics teachers, and covered only on IBL but also assessment of students who learn by inquiry. The TEP on IBL with embedded assessment was established in 2014 and used in the following years. The training included two stages: I – core training and II – extended support. The core training involved 5 intense days of workshops, laboratories and seminars, in total 33 hours of classes. The extended support was based on a Community of Practice (CoP) in which teachers participated at least for one year (Coakley, 2013). The community was gathered around a dedicated social media platform. Tutors initiated and moderated discussions, delivered new didactic materials, motivated and assisted teachers. After a year, the teachers were invited to participate in a national conference and present their experiences and developed didactic materials. The most active participants could participate in an international conference gathering teachers from all partner countries (Melia, McLaughlin, McCabe, & Finlayson, 2015). Details of the Polish version of the TEP used within SAILS project were presented in the article [P3] (Bernard & Dudek-Różycki, 2020).

5. The impact of professional development in inquiry-based methods on teachers' classroom practice

In the years 2007-2015, there were many EU 7th Framework Programme projects realized that focused on IBL implementation and teacher training. Even though, there has been limited information on how effective those trainings were, and how teachers brought theory into practice. In Poland, groups of in-service science teachers who participated in the TEP on IBL in years 2014 and 2015 organized within the FP7 SAILS project undergo the study on influence of the training on their classroom practice. One hundred six teachers in two groups: 2014 (N = 60) and 2015 (N = 46) participated in this study. The groups consisted of 93 women and 13 men, teachers of chemistry (33), biology (39), and physics (34). Participation in the study was voluntary and anonymous, run according to the Jagiellonian University ethical standards. The participants could withdraw from the study at any stage, or simply not fill out the delivered questionaries. Finally, data for the analysis covered 92 persons, 57 in 2014 and 35 in 2015; with subgroups of the subject taught: biology – 31 teachers; chemistry – 35; and physics – 26. Results of the study were discussed in the article [P3] (Bernard & Dudek-Różycki, 2020).

The research was based on the Self-reflection Tool for Teachers developed within the FP7 Fibonacci project (Harlen & Borda Carulla, 2012). It covered 38 questions in 3 sections: A) The teacher's role – 10 questions, B) Students' activities – 21 questions, C) Student's records – 7 questions.

The questionnaire contained questions which teachers could ask themselves analysing learning sequences that they used while the introduction of IBL in their classes. The questions were accompanied by examples of good practices, facilitating a proper understanding of the question. The scale contained YES, NO, NA (not adequate) answers. Positive answers confirmed that the responder uses the mentioned element of IBL in their classroom practice.

The same questionnaire was fulfilled three times at successive stages of the research: Ist – pre-test stage, directly before the training; IInd – post-test stage, 3-4 weeks after core training, and IIIrd – distance post-test stage, about one year after the core training (after extensive support phase). The research had a quantitative character involving comparative analyses of variances (ANOVA) (Howell, 2002), and a nonparametric counterpart (the *U* test) when necessary (King, Rosopa, & Minium, 2011; Levene, 1960; Mann & Whitney, 1947; Mauchly, 1940). *Post hoc* analysis used the HSD Tukey's tests. The significance level was defined as $\alpha = .05$ for the entire study. The analysis run in StatSoft 'Statistica', v.13.

The results of the study let to identify the elements of IBL which teachers claimed to use before training. The teachers said they practised the following IBL elements with students: making predictions, making notes, drawing conclusions, asking questions, and carrying out organized work in groups.

The results showed that the training was effective. There is an increase in the number of positive answers visible (see Fig. 3), and statistical analysis confirmed the observed increase was significant ($\alpha < .05$). However, the *post hoc* test results confirmed only statistical significance of increase between Ist and IInd stages.

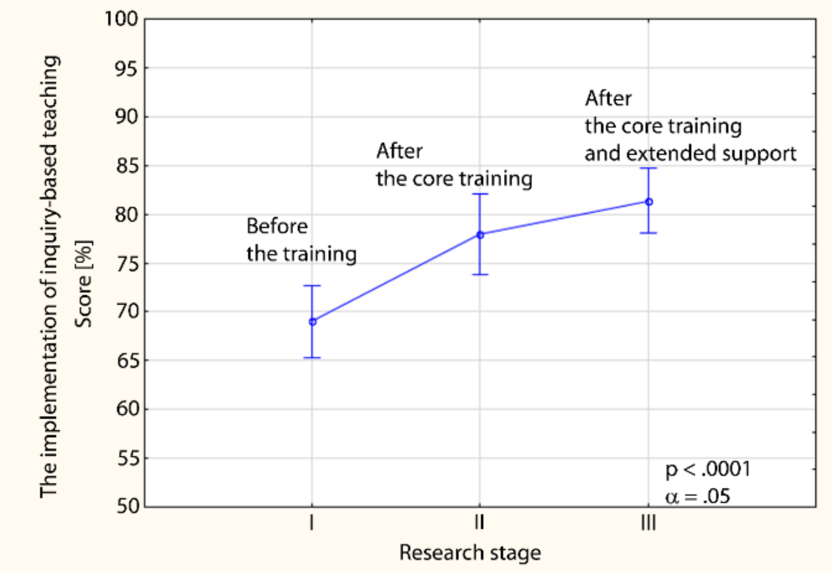

Fig. 3. The average result for the whole questionnaire at subsequent survey stages, with the 95% confidence interval marked, the figure originally published in [P4] (Bernard & Dudek-Różycki, 2020).

The obtained results allowed us to confirm the efficiency of the training, and identify the inquiry's features that were adopted by the teachers. Moreover, the subsequent analysis allowed us to conclude about the dynamics of adaptation of different IBL features, so it was possible to identify those inquiry elements that were adopted immediately after core training, those that were introduced during the extended support phase, and those that were not implemented at all. The first group – features adopted immediately after the training – includes formulating research questions, predictions and reflections, and evaluation of investigations. The second group – features adopted after a longer period (one year) – includes experiment planning by students, investigations based on students' ideas, independent making notes and data collection, as well as presenting results. The third group – features that were not adopted at all – includes using fair testing, formulation of further research questions (closing inquiry cycle), independent carrying out investigations by students, and some aspects of group work (discussions of the results with peers and various elements of written records).

Those results are very useful for educators constructing and running the TEPs in IBL. First of all, the training consisting of two phases – core training and extended support – is essential. Thanks to the obtained results, constituent elements of the core training and the extended support can be prepared, and the tutors can adapt didactic materials to stimulate teachers' adequate actions at selected phases of the training. It was suggested to reserve more time of the core training for a discussion of those elements of IBL that were not adopted at all in the research group. These aspects should be extensively discussed and trained to ensure understanding of their meaning within the inquiry process. At the beginning of the extended support later phase, emphasis should be put at first on these aspects of inquiry which were used by teachers earlier, and those that can be easily implemented. The educators can design a self-assessment checklist which can be a guide and motivation for teachers. Subsequently, more challenging elements of the inquiry can be introduced, so materials stimulating the introduction of those aspects of IBL whose implementation require more time, and finally, those that were not implemented at all in the discussed study.

6. Integration of inquiry-based learning with formative assessment

Development of IBL and its introduction into school practice required a revision of existing assessment strategies. In many countries, at the lower secondary (K6-9) and upper secondary (K10-12) school levels, the educational process is focused on the preparation of students for external exams, and achievement of the best possible grades which can ensure qualification for the next educational level, to a school or university with the highest standard. Such an approach is based on summative assessment (SA) and its role is to sum up the evidence, thus, it is usually used at the end of a particular part of the educational process (Harlen, 2000; 2005; Taras, 2010; Trotter, 2006). Meanwhile, the educational process based on a cognitive approach requires broader assistance and immediate personalized assessment which guides students during the inquiry process. Historically, this approach has been called assessment for learning, and nowadays the term in use is formative assessment (FA) (Black & Wiliam, 2007). FA is based on the feedback that should be provided to the student when they still has the opportunity to use it and improve its learning (Black & Wiliam, 1998; Sadler, 1989). Black & Wiliam (2009) stated that formative assessment can be conceptualised of five key strategies:

1. *clarifying and sharing learning intentions and criteria for success;*
2. *engineering effective classroom discussions and other learning tasks that elicit evidence of student understanding;*
3. *providing feedback that moves learners forward;*
4. *activating students as instructional resources for one another;*
5. *activating students as the owners of their own learning. (p. 4).*

Recently, educational policy in many countries has been changed and includes a formative assessment in secondary school and higher education curricula (Murphy, Holme, Zenisky, Caruthers, & Knaus, 2012; Wei & Ou, 2018; Yan & Cheng, 2015; Yorke, 2003; Yüksel & Gündüz, 2017). Moreover, combined and balanced summative and formative assessment has been advised by many researchers (Barnett, 2007; Sambell, McDowell, & Montgomery, 2012; Taras, 2005).

The inquiry cycle presented in Fig. 1 describes successive steps of the inquiry process but without competencies and skills developed through the inquiry. Those can be divided into 4 groups as presented in Fig. 4.

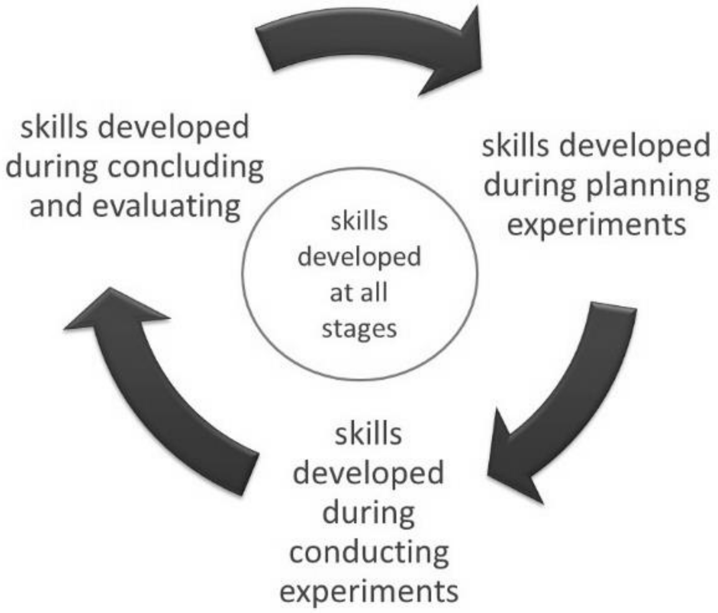

Fig. 4. A simplified version of the experimental cycle based on the groups of skills being developed via IBL, originally published in [P4] (Bernard, Dudek-Różycki, & Orwat, 2019).

Dividing further presented groups into particular skills can involve various taxonomies, including those probably the most popular: by Fradd, Lee, Sutman & Saxton (2015), and by Wenning (2007). Author's own classification based on a combination of the two mentioned above was developed over years and presented successively in articles (Orwat, Bernard, & Dudek, 2016, 2014), with the most complete and recent version published in [P4] (Bernard et al., 2019) and presented here in table 2.

Table 2. List of skills that can be developed *via* IBL and undergo assessment, originally published in [P4] (Bernard et al., 2019)

Stage of the inquiry	**Developed skills**
Planning	Formulation of a research question Formulation of a research hypothesis (with justification) Defining variables Development of a method to control variables (mathematical relations) Development of a method to collect raw data (experimental procedure)
Conducting an experiment	Collection of raw data Processing data and determination of measurement error Calculation/estimation of experimental errors Presentation of results
Conclusions and evaluation	Drawing conclusions Evaluation of the plan and application of the experiment Proposals of modifications, and improvement of the experiment
Skills developed at all stages	Searching for information, critical analysis of information Teamwork Working safely at the laboratory Using Information and Communication Technologies

The character of the assessment and skills chosen for the assessment do not determine the tools that should or can be used in particular cases. Llewellyn (2007) suggests using, *i.a.* multiple-choice questions, laboratory reports, concept maps, monitoring charts, oral presentations and rubrics. In fact, the rubrics (analytical and holistic ones) are considered by many educators as the most effective tool (Barron & Darling-Hammond, 2008). Moreover, since IBL enables also the development of higher-order reasoning skills, more complex tools like Lawson's tests (Lawson, 1978) or constructive response questions (Llewellyn, 2007) might be very useful. Finally, many studies underline the importance of self-assessment and peer-assessment in the FA process (Bedford & Legg, 2007; Sung, Chang, Chang, & Yu, 2010).

Combining all aspects of the assessment mentioned above with a newly trained method (IBL) can be very challenging. Therefore, this process was studied and the results were described in [P4] (Bernard et al., 2019). Two experienced chemistry teachers from groups trained within PF7 SAILS project in years 2014 and 2015 were chosen for the research. Both had a broad pedagogical-content and content knowledge (Ph.D. in chemistry), experience in pre-service and in-service teachers' tutoring, and a positive attitude toward IBL. They teach at different educational levels, one at the lower, and the other at the upper secondary school level. The teachers were asked to prepare and run classes based on the inquiry and assess chosen inquiry skills during the process. They could use materials delivered within the framework of the project – the final version of materials by Finlayson et al., (2015a, 2015b) – covering a theoretical background of the chosen activity, an advised strategy of educational approach, suggested skills for evaluation, and exemplary assessment strategy, but without exact assessment tools and evaluation criteria. The study had a qualitative character and was realised just after a core part of TEP. Therefore, it was carried out while teachers' first try to use inquiry investigation supported by formative assessment in the classroom. The study was based on teachers' reports describing the used strategy and assessment tools, educators notes from observation of classes, and a semi-structured interview run after classes.

The results showed how complex and difficult is the introduction of IBL together with integrated assessment for freshly trained teachers. Even experienced teachers with broad content knowledge and practise in conducting research had major difficulties with this task. The main problem was the implementation of the formative assessment, which was surely caused by the long-standing total domination of SA in the Polish educational system. Both teachers had troubles reconciling the leading role of the students and the application of FA during inquiry process. Moreover, both teachers decided to use analytic rubrics for the assessment, but they had problems with estimating the level of their students' skills and formulation of adequate criteria. The rubrics contained disproportionate criteria, where the highest skill level reflected the proficiency, not reachable for their students. Other noticed problems included the timing of the feedback, the tendency to assess all students at the same time, and the lack of meaningful feedback leading to the lock of the inquiry process.

The obtained results allowed us for a better understanding of the dilemmas of teachers starting to implement IBL with integrated formative assessment, helped to adapt and expand the core teacher training with adequate exercises, and guide teachers during the extended support phase more intentionally.

7. How does training in IBL influence teachers' reasoning skills?

Reasoning skills (RS) can be defined as abilities to use knowledge to recognize and solve problems, reflect, and conclude basing on empirical observations. There are three groups of RS specified, according to their complexity (Csapó et al., 2012; Johnson-Laird, 2006):

- **Basic reasoning skills** – called Piagetian reasoning (Caroll, 1993) or operational reasoning (Csapó, 1992) due to their clear operational structure.
- **Higher-order thinking skills** – involving complex thinking processes and combinations of several basic skills (Williams, 1999).
- **Scientific reasoning** – concerning using symbols to represent phenomena via variables and dimensions, often considered the most advanced form of human thinking (Lawson, 2005, 2010).

Teaching based on inquiry-based methods can stimulate the development of reasoning skills (Csapó, 1997; Csapó et al., 2012). There is no doubt that teachers should have highly developed reasoning skills, to have confidence in designing and solving tasks engaging higher-order thinking processes (Utomo, Narulita, & Shimizu, 2018). Unfortunately, the teachers currently working in Eastern European schools (*e.g.* in Poland) have had no opportunity to experience inquiry-based learning or practice solving tests focused on reasoning (Dudek, Bernard, & Odrowąż, 2015). Therefore, a question arises if participation in a TEP focused on IBL can fill the gap in learning through inquiry, unlock teachers potential and lead to a gain in teachers' scores in tests focused on reasoning.

There are several programs for assessment of students' scientific reasoning competencies, *i.a.* the Programme for International Student Assessment (PISA) (OECD, 2013), Evidence-Based Reasoning Assessment System (EBRAS) (Brown, Nagashima, Fu, Timms, & Wilson, 2010), Trends in International Mathematics and Science Study (TIMSS) etc. Moreover, there are several dedicated frameworks and instruments for the assessment of reasoning skills (Amsel et al., 2008; Drummond & Fischhoff, 2017; Gormally, Brickman, & Lutz, 2012; Lovelace & Brickman, 2013). Probably the best-known tool for RS measuring are Lawson's Classroom Tests of Scientific Reasoning (Lawson, 1978). These tests are intended for secondary school and college-age students and they consist of multiple-choice questions. There are separate biology, chemistry, and physics tests, but the first 6 questions focus on the general science and are the same for all subjects.

In Poland, in years 2014 and 2015, within the FP7 SAILS project, a study on the level of chemistry, biology and physics teachers' reasoning skills, and the influence of training in IBL on the level of those skills was realised [P5] (Bernard & Dudek-Różycki, 2019). One hundred six teachers participated in the training, however, participation in the study was voluntary, and incomplete questionnaires were excluded from the analysis. Therefore, the research group consisted of 71 teachers in two groups: 2014 (n = 32) and 2015 (n = 39), the research group covered teachers of the following subjects: in 2014 – chemistry: 10, biology: 12, physics: 10; and in 2015 – chemistry: 16, biology: 11, physics: 12. Most of the participants graduated from uniform master's degree studies or a combination of BA/BSc and supplementary MA/MSc studies in a taught area of science.

The research was based on the latest available version of Lawson's tests (Lawson, 2000). Test no. 1 was completed before the training, and test no. 2 just after the training, according to a subject taught. The research was anonymous but participants were asked to sign pre and post-test with the same nickname to enable comparative analysis before and after the training (Dudek, Bernard, & Migdał-Mikuli, 2014). The research had a quantitative character and covered a comparison of results for the entire test, results for common questions for all subjects (Q 1-6), and subject-specific questions separately.

The analysis of variance (ANOVA) (Howell, 2002) was the major method, and nonparametric counterpart – *H* test (Kruskal & Wallis, 1952) when necessary (King et al., 2011; Levene, 1960; Shapiro & Wilk, 1965). For *post hoc* analysis HSD Tukey's tests were applied. The significance level was defined as $\alpha = .05$.

The average result of the test before the training for all the respondents has been equal to 73%, which may seem satisfactory, but considering the fact that it has been achieved by teachers with a master's degree, it is not very good. Scores at this level are achievable for university and even upper secondary school students (Coletta & Phillips, 2005; Maloney, 1981). Further analysis revealed that the scores for physics teachers were significantly higher than in the case of other subjects' teachers, and this difference was caused not by scores in common questions (Q 1-6), but subject-specific ones.

The influence of the training on the total score of the group was not significantly different. However, an analysis of the subject-specific subgroups, as well as common and subject-specific parts of the tests showed various changes (see Fig.5 a-c), with a statistically significant increase in scores for a group of biology teachers in the area of subject-specific questions.

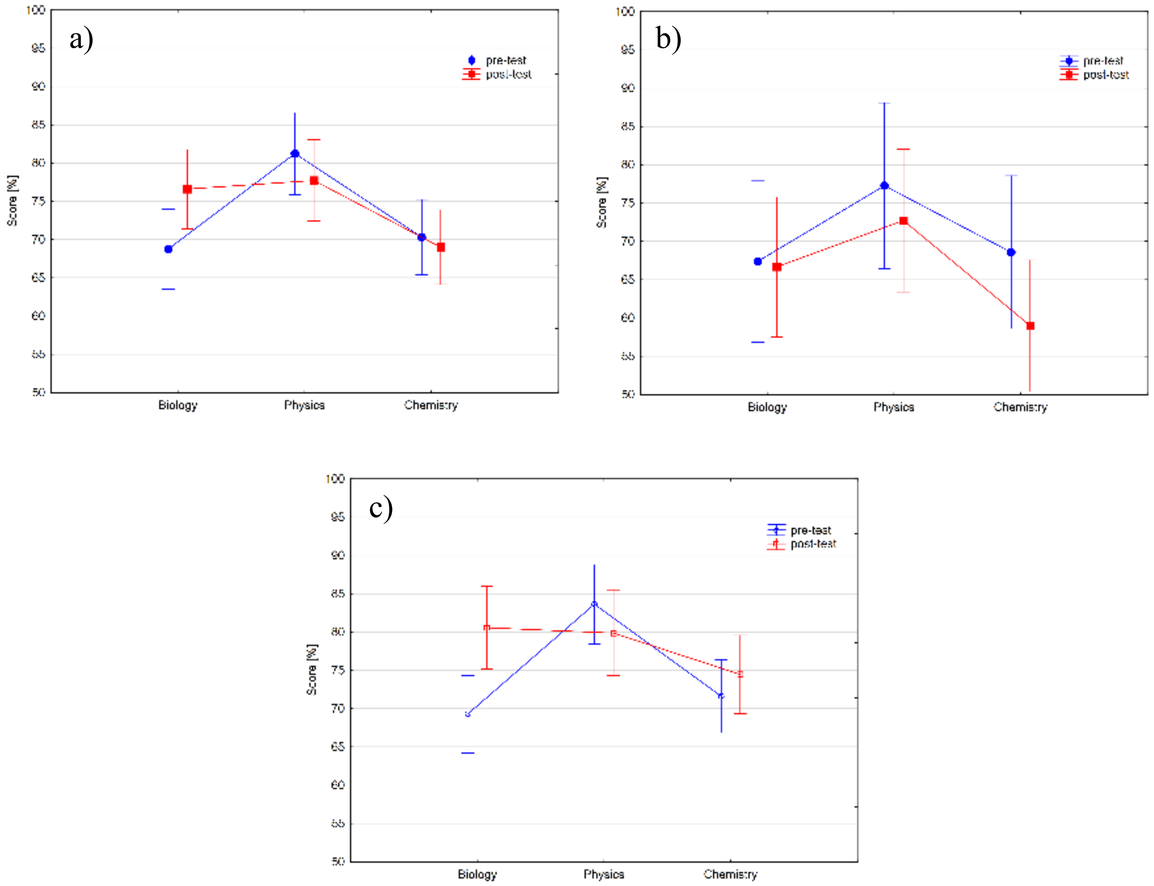

Fig. 5. Average scores of pre- and post-tests in RS for various subject teachers, with 95% confidence intervals; a) for the entire test; b) for common questions (Q 1-6); c) for subject-specific questions. Figures originally published in [P5] (Bernard & Dudek-Różycki, 2019).

The most important observation may be the fact that after the training, subject group scores are not statistically different anymore: neither for the entire test, nor for common questions, nor for the subject-specific area. Therefore, it can be concluded that the core training in the IBL doesn't solve the problem of general low scores of teachers in RS tests, but it can influence positively the subgroups with the lowest scores and fill the gap in scores between teachers of various subjects.

8. Usage of IBL by chemistry teachers during emergency online teaching caused by COVID-19 pandemic outbreak

The COVID-19 pandemic outbreak challenged all levels of education. Classical, face-to-face teaching had to be replaced with online classes within a few days. In general, universities and higher education institutions were better prepared for this situation. They had the required infrastructure and experience in using at least some elements of e-learning and blended learning. Unfortunately, remote education at primary and secondary school level never was considered a valuable alternative before, therefore, schools had no adequate software, hardware, and staff trained for such a situation. Teachers tried to run online classes based on freeware software, but many of them struggled with technical and methodological issues. Another side of the problem was the students' perspective, dealing with lack of hardware, lack of a fast internet connection or a decent place to learn in their houses. Moreover, distance teaching of obligatory subjects at the school level was barely studied before, so students' concerns and expectations remained unknown.

Comparing various subjects teaching practices, one may conclude that chemistry/science schoolteachers faced an especially great challenge. They had to figure out how to present not only the theoretical knowledge but also the experimental aspects of the subject. It is well-known that not only presentation of scientific knowledge is important in chemical education, but also students' anxiety, curiosity, emotional satisfaction, interactions between instructor and students, and between peers (Hensen & Barbera, 2019). Therefore, teachers who wanted to base online lessons on solving problems, observations, evidence, experiments, inquiry investigations were in an especially difficult situation. Many of them lacked IT knowledge, software and hardware to put their ideas into practice.

There were also exceptions from the general situation described above. Teachers participating in the IT Academy project run in Slovakia (CVTISR, 2018) were trained in applying modern didactic methods and Information and Communication Technologies (ICT) to enhance school education (Adamko et al., 2018; Antoni et al., 2018; Derjaninova et al., 2017; Jurkova et al., 2019; Kires et al., 2019). In the chemical education domain, the training was focused on IBL enhanced by data logging devices (Babinčáková, 2020; Babinčáková, Ganajová, & Sotáková, 2020) and formative assessment (Babinčáková, Ganajová, Sotáková, & Bernard, 2020). Schools participating in the project were equipped with sufficient software and hardware, and teachers learned how to use those in summer

2019. Therefore, these teachers were in a privileged position when the public lockout was announced, they had access to a wide range of ICT tools, and fresh knowledge and skills to use them. Moreover, their training was in the extended support phase, so thanks to the project, just after the lockout announcement, trainings in using video conference software like Google classroom, Zoom, Teams were organized. Project tutors provided also further assistance whenever it was necessary. Monitoring of the project in May 2020, after 12 weeks of the lockout, created the possibility to check how chemistry teachers who have freshly gained ICT skills and equipment incorporate experiments in online lessons, and what are students' perceptions of their efforts [P6] (Babinčáková & Bernard, 2020).

The study was based on two short questionnaires, the first was intended for the teachers, and the second – for their students. Analysis of the gathered data showed that teachers and students were facing many serious general problems, and their struggles were quite universal. Therefore, those results can be interesting and useful for all science educators who assist and train teachers during the pandemic. Moreover, tips and tricks advised to the teachers participating in the project can be useful for other chemistry/science teachers. Questionaries were sent to 20 chemistry teachers participating in the project, teaching grades 7 to 12. They were asked to fulfil the form and spread a student version of the questionnaire among their classes. The research group included 17 teachers who filled out the questionnaire, and their students (n = 78). Students' answers were anonymous, however, one of the questions included the teacher's name, so student answers could be related to techniques used by the teacher. The study was run remotely.

Results provided information on teachers' practices and their approaches to the presentation of chemical experiments during remote chemistry teaching. In the research group, all teachers used experiments during online classes, but they were doing it in various ways. Approaches used and their combinations are presented in Table 3 and Fig. 6.

Table 3. Teachers' experimental approaches used during remote education, originally published in [P6] (Babinčáková & Bernard, 2020)

Letter	Experimental Method	Number of teachers (N = 17)
A	Showed pictures with captions	10
B	Showed videos	11
C	Demonstrated live during online class	10
D	Students conducted experiments at home	11

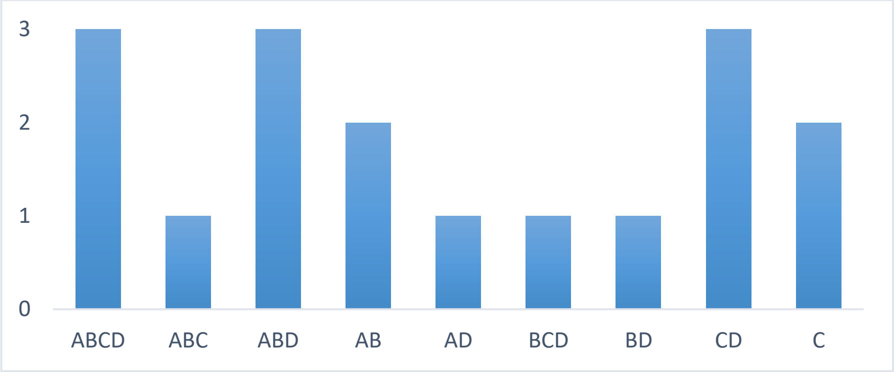

Fig. 6. Distribution of the sets of teachers' experimental approaches used during remote education (A, B, C and D as defined in Table 3), originally published in [P6] (Babinčáková & Bernard, 2020).

It was noticed that the teachers were using 2 or 3 preferred approaches, but they carried out the experiments using one, the most appropriate in their opinion way for a particular experiment. Confronting this approach with students' answers, it could be advised to use multiple approaches to each experiment. Students look forward to chemical experiments and they like to see them done live, but many of them complained about slow internet connection and the necessity to use small-screen devices (mobile phones) during classes, therefore, they have troubles receiving high-quality videos during video meetings. Teachers should consider providing these students written descriptions with pictures, and recordings of the presented experiments. The students could watch those videos later when the Internet is not that overloaded, and use another (large-screen) device when available.

Another noticed major problem was the dynamics of the classes. Many teachers pointed out as a positive fact that during online lessons they can do many parts quicker – run measurements, show videos recorded earlier, and then focus on the interpretation of gathered data and conclusions. Unfortunately, more than one-third of the students complained that the classes were run too quickly; they had problems with understanding the material, there was no time for discussions, asking questions, and taking notes. In general, many students claimed their teachers "explain problems better" in the classroom. Therefore, the teachers should take an effort to mimic classical classes online. For example, they can make hand-written notes on the screen using a touchscreen or touchpad and virtual blackboard. Moreover, these notes combined with used presentations can be shared after classes, to help students having troubles taking their own notes during the lesson.

Despite its interventional character, the study delivered information that can be useful for educators running TEPs in IBL. It has become clear that training in inquiry-based methods enhanced with modern ICT cannot be limited to the use of data-logging devices. Methodology of e-learning and blended learning had been developed for more than 30 years, and its fundaments and actual technical solutions should be known and used not only at higher education level, but also by school teachers, not only for the case of another emergency online teaching, but also for more effective everyday blending virtual and face-to-face environments.

Part II – New didactic tools supporting the implementation of IBL while chemistry classes at various levels of education

9. Investigation of amphoteric properties of aluminium oxide

Analysis of teachers' beliefs and attitudes in Poland showed that the teachers see possibilities to apply IBL to existing curricula; however, they expect syllabuses, books and activities to be adapted to the method (Bernard, Maciejowska, Krzeczkowska, & Odrowąż, 2015; Bernard et al., 2012). Therefore, there is a need for the development of new materials enhancing IBL, and a revision of existing ones to fit the inquiry-based process. The urgent issues include the acidic properties of substances. These properties are discussed at all levels of chemical education, starting from simple inorganic acids and bases, through hydrolysis effects, to complex interpretations of acidity of large organic molecules and the surface of solids. Especially hydrolysis occurred to be a problematic issue for Polish secondary school students (Orwat, Bernard, & Migdał-Mikuli, 2017). Therefore, a cycle of articles on this process was published for Polish chemistry teachers (Bernard, Orwat, & Dudek, 2014; Orwat & Bernard, 2015). Another problematic issue for teachers was a demonstration of the amphoteric properties of aluminium oxide. Aluminium oxide and hydroxide are introduced in Polish syllabuses as the first substances with amphoteric properties. Demonstration of this phenomenon is not problematic for hydroxide, but more difficult for oxide. The problem is caused by polymorphism of alumina, which forms phases: γ, δ, κ, ρ, η, θ, χ, α, with the highest stability commercially accessible phase α, and only γ-Al_2O_3 with amphoteric properties (R. B. King, 1994; Macêdo, Bertran, & Osawa, 2007). Therefore, a simple method of obtaining γ-Al_2O_3 and procedures for investigating its acidic properties were developed and described in the article [P7] (Orwat, Bernard, & Migdał-Mikuli, 2016). The proposed investigation scenario involves three methods of calcination of aluminium hydroxide: 1) at low temperature (250°C) always leading to the amphoteric product, 2) using a Bunsen burner (450-700°C) leading to products with various properties depending on the duration and temperature of calcination, and 3) in a microwave always leading to the non-amphoteric product. The microwave technique uses carbon as susceptor of a microwave radiation that allows reaching a temperature of 1283°C in a crucible in approximately one minute (Mingos & Baghurst, 1991). It requires a dedicated vessel called AST (from German Die Aktivkohle-Suszeptor-Tiegel) that can be made of a clay flowerpot strengthened with refractory mortar (Lühken & Bader, 2001). The AST vessel has a recess in which a crucible with the sample is placed, and the space between the vessel and crucible is filled with granular carbon, as shown in Fig. 7. Microwave technique may be used also for phase transition of products obtained by techniques 1 and 2, and leads to the non-amphoteric product.

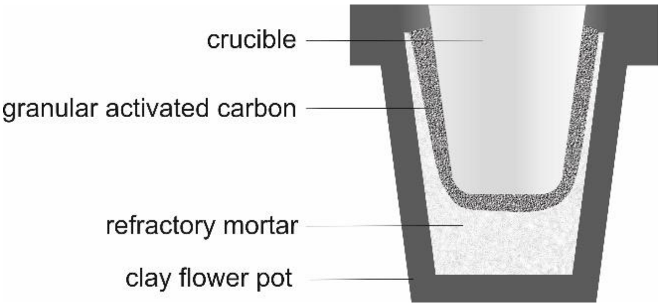

Fig. 7. The AST element construction (cross section) for microwave calcination technique, originally published in [P7] (Orwat, Bernard, & Migdał-Mikuli, 2016).

Investigation of acidic properties of alumina can be incorporated into a larger scenario concerning the properties of third-period oxides, as it was done while piloting implementation of the developed activity. The results showed that the developed scenario can be easily completed by secondary school students, the investigation is interesting for participants, and, what is the most important, it leads to an increase in students outcomes in both domains, knowledge and laboratory/inquiry skills.

10. Introduction of green chemistry principles based on investigation of traditional and UV-cured lacquers properties

Global warming and fast climate changes in recent years require immediate actions, not only in the industry, but also in education, to teach the young generation about rules and the importance of sustainability. Green chemistry plays an important role in sustainable development (Anastas & Warner, 1998; Matlack, 2001). In 1990, The Pollution Prevention Act (1990) contributed to creation of 12 Principles of Green Chemistry (Anastas & Warner, 1998). The idea of green chemistry and its principles promote sustainable methods of synthesis and usage of inert, environmentally friendly substances (Sharma, Gulati, & Mehta, 2012). Unfortunately, it is not easy to find examples of "green" industrial processes that fit the school curriculum and are known by students from their everyday life. (Kitchens et al., 2006). One of the possible topics is the technological processes of lacquer manufacturing and application. Recently, conventional solvent-based (SB) lacquers are being replaced by radiation curable (UV – ultraviolet or EB – electron beam) coatings (Bonifant, 1994). Those technological processes can be adapted to school laboratory conditions and connected with the existing curriculum. Such a scenario of hands-on activity based on investigation of classical and UV-cured lacquer properties for lower and upper secondary school students was developed and described in [P8] (Orwat, Bernard, Wróblewski, & Mendez, 2018).

Classical lacquers contain two main parts: a volatile solvent and a dissolved non-volatile coating (Holton, 1928). The volatile part – VOCs (Volatile Organic Compounds) – constitutes up to 800 g in 1 kg of applied product. These solvents are released to the atmosphere while drying. The most common coating ingredient in this technology is nitrocellulose, which is highly flammable and explosive. The drying process was schematically presented in Fig. 8.

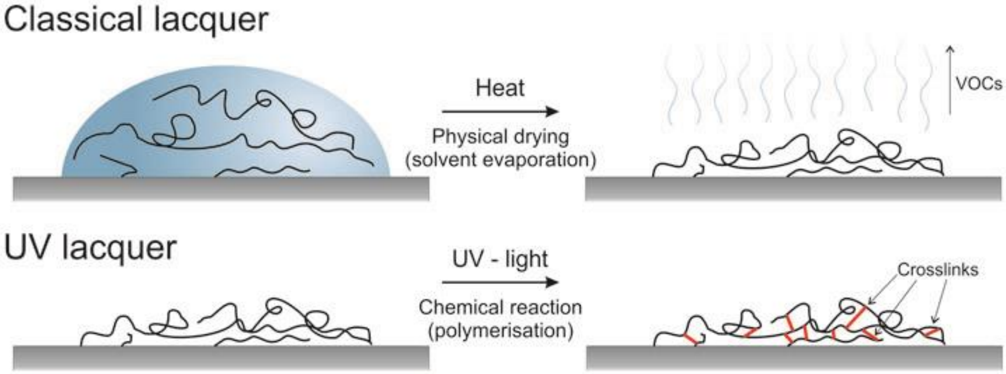

Fig. 8. Comparison of UV-cured and classical lacquer curing processes, originally published in [P8] (Orwat et al., 2018).

UV-lacquers involve a radical polymerization for the conversion of a liquid into a solid, initiated by UV radiation (Bogoeva-Gaceva & Buzarovska, 2013; Davidson, 1999; Xiao & Hao, 2010). The basic UV-cured coatings are mixtures of three types of ingredients: oligomers (prepolymers), monomers (a reactive diluent) and a photoinitiator (PI). Oligomers contain several functional groups taking part in a polymerization process, they have relatively high-molecular-weight and high viscosity, for that reason reactive diluents are added to the mixture. These are usually mono/multifunctional acrylate esters, they decrease the viscosity of the mixture and help control the reactivity of the formulation. The photoinitiator absorbs light and generates radicals. As a UV-light source, Light Emitting Diodes (LED) are used due to their flexibility, low energy consumption, and low working temperature (Davidson, 1999).

The scenario consists of empirically developed preparation procedures of classical and UV-cured lacquers. The proposed classical formula is based on toluene and cellulose nitrate flakes or table tennis balls. The developed UV-cured lacquer recipe consists of urethane acrylates (Laromer 9033) as a prepolymer, trimethylolpropane triacrylate (Laromer TMPTA) as a reactive diluent, and a mix of 1-hydroxycyclohexyl phenyl ketone and benzophenone in 50:50 mass ratio (Irgacure 500) as a photoinitiator. The recipes are simple enough to be realized in a school laboratory and ensure good repeatability of the obtained products. The first phase of the activity – synthesis of lacquers – is described in detail, so the students can simply follow the instruction. This phase is not focused on inquiry but creates a good opportunity to introduce green chemistry ideas and principles. However, it can be easily modified and expanded with an investigation of the impact of selected components on the lacquers' properties, like viscosity, reactivity, flexibility, hardness, or gloss. Methods for these modifications are described in the article. The second phase of the exercise involves investigations of obtained lacquers' properties, centred around the general question: "Which lacquer is better?" The investigations require the application of lacquers on various surfaces, and testing the lacquers' and coatings' properties: density, mass loss, process completion, hardness, adhesion, flexibility. Therefore, the exercise can be run instantly by a whole class of students divided into groups, and each group can work on their own research question independently, using selected surfaces and investigating selected properties. This approach generates a large amount of data that can be analysed and discussed by the students later. Finally, the students can try to answer the general question, justify their answers, and explain which lacquer is "green".

The exercise underwent piloting implementation with 6 groups of Polish secondary schools students (K9 and K11, n = 72), and a group of US university Introductory Chemistry students (n = 20). All students prepared fully functional lacquers. They tested various painting techniques on chosen surfaces and investigated several properties of the coatings. In general, application of the same thickness of a classical lacquer and UV-one leads to completely different results. The classical lacquer decreases its volume while drying, therefore creates a thin film that is quite elastic and adheres well, but the coatings are barely noticeable and don't protect the surface properly. The UV lacquer layer keeps its mass while curing, but high thickness has a negative influence on coating elasticity and hardness, see Fig. 9. Therefore, groups using different painting techniques, and controlling thicknesses of lacquer layers (advised range 30 to 100 μm), obtain various results. This fact poses a great opportunity for a discussion on the green aspects of these techniques.

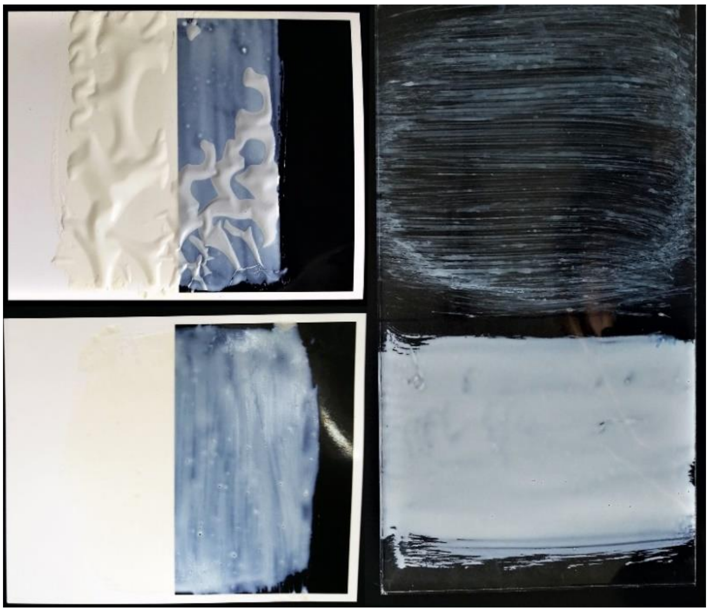

Fig. 9. Results of painting of selected surfaces: on the left – Leneta charts painted with the white UV-cured lacquer, top – paintbrush painting, bottom – Wire-Coater 32 μm; on the right – glass surface painted with the traditional lacquer (top) and the UV-cured lacquer (bottom) both applied with a Wire-Coater 32 μm, the figure originally published in [P8] (Orwat et al., 2018).

The results of tests carried out before and after the activity indicate that thanks to the exercise, the students improved their knowledge of lacquers and their properties. Initially, the students have had troubles describing the drying processes and had many misconceptions concerning traditional and UV-cured lacquers, *i.e.* they believed that the UV-cured lacquers are harmful to the environment, unsuitable to be applied with a paintbrush, cannot be applied in multiple layers, and are flammable. After the activity, most of the students were able to describe those lacquers correctly. Moreover, thanks to their own synthesis of lacquers, they knew that the process is similar and uncomplicated in both cases. Furthermore, the results concerning green chemistry issues indicated a 17% increase in the number of correct answers, and analysis showed that it was a statistically significant difference.

11. Demonstration of basic principles of heterogeneous catalysis

Heterogeneous catalysis plays an important role in the food production (fertilizers), in various industrial processes including fabrication of fuels, polymers, and chemicals (Oyama & Somorjai, 1988; White & Campbell, 1980), and environmental protection via reduction of air pollution, *e.g.* in NO_x removal from exhaust gases, catalytic soot oxidation, N_2O decomposition (Cusumano, 1995; Jakubek, Kaspera, Legutko, Stelmachowski, & Kotarba, 2015; Oyama & Somorjai, 1988; Rothenberg, 2008; Stelmachowski, Ciura, & Grzybek, 2016; White & Campbell, 1980). Basics of catalysis are discussed at the secondary school level, but details of heterogeneous catalysis are introduced at the university level as a part of general chemistry courses, and in further detail to students majoring in chemical engineering, inorganic chemistry or catalysis.

An idea of active site and catalyst specific surface area are key parameters, crucial for understanding the catalytic activity of solids and mechanisms of catalytic reactions. There are several well-known experiments that can be performed live in a lecture hall to illustrate heterogeneous catalysis phenomena. Unfortunately non of them is suitable for quantitative analysis and presentation of the impact of active sites' number (specific surface area) on the catalytic reaction rate. Thus, such a simple demonstration was designed and described in [P9] (Bernard, Stelmachowski, Broś, Makowski, & Kotarba, 2021). The demonstration was based on a reaction of hydrogen peroxide decomposition catalysed by the cobalt spinel (Co_3O_4). Cobalt spinel samples obtained by calcination of cobalt carbonate at various temperatures (range of 300÷600°C) are characterized by various values of specific surface area (15÷50 m^2/g), which decreases in higher temperatures due to recrystallization and sintering. The hydrogen peroxide decomposition is a perfect model reaction using a common and inexpensive substrate, a simple reaction setup, and results with harmless gaseous products. The procedure was based on observation of the volume of evolved foam like in the well-known demonstration called elephant's toothpaste (Carter, 1986; Conklin & Kessinger, 1996; Eldridge, 2015; Hernando et al., 2017; Ragsdale, Vanderhooft, & Zipp, 1998; Sattsangi, 2011; Trujillo, Senkbeil, & Krause, 2005), but catalysed by a solid which is insoluble in water, what reminds another popular experiment called "Genie in the Bottle" or "Aladdin's Lamp"(Alyea, 1969; Dolhun, 2014; Pratt, Curtright, Hill, & Clarke, 1988). The scheme of the procedure is presented in Fig. 10.

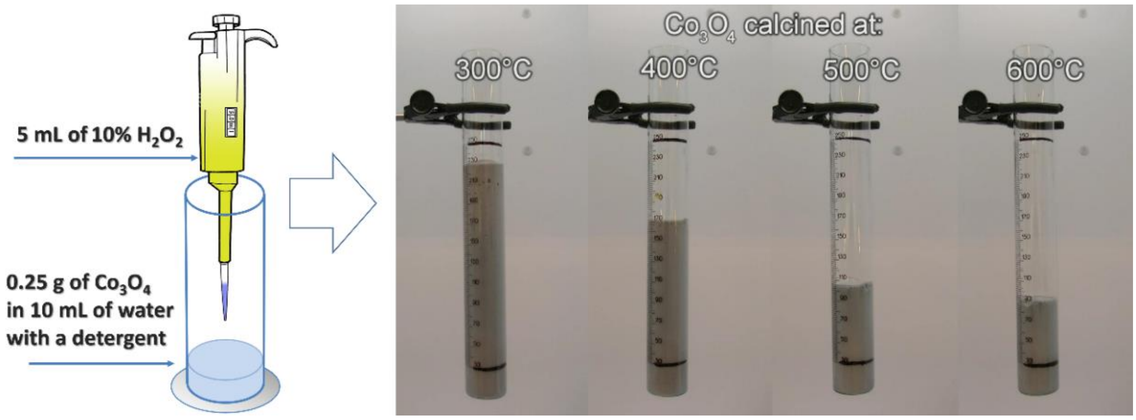

Fig. 10. Scheme of the experiment and a screenshot from a demonstration video after 20 seconds of reaction, originally published in [P9] (Bernard et al., 2021).

The differences in reaction rates are visible with a naked eye, but a simple video-tracking analysis of a video showing the experiment provides numerical data – the volume of gas evolved *vs.* time, as presented in Fig. 11a. The hydrogen peroxide decomposition reaction, shown by equation 1, undergoes according to the first-order kinetics. Therefore, a simple analysis of the obtained data allows for calculation of the reaction rate constants per unit mass of the catalyst, presented in Fig. 11b as orange bars. These values follow the specific surface area value changes, and show a clear dependence of reactivity on the number of the exposed active sites. Blue bars in Fig. 11b represent normalized (divided by specific surface area values) reaction rate constants and show that the specific activity of catalyst obtained in various temperatures is similar.

$$2H_2O_2 \rightarrow 2H_2O + O_2 \quad (1)$$

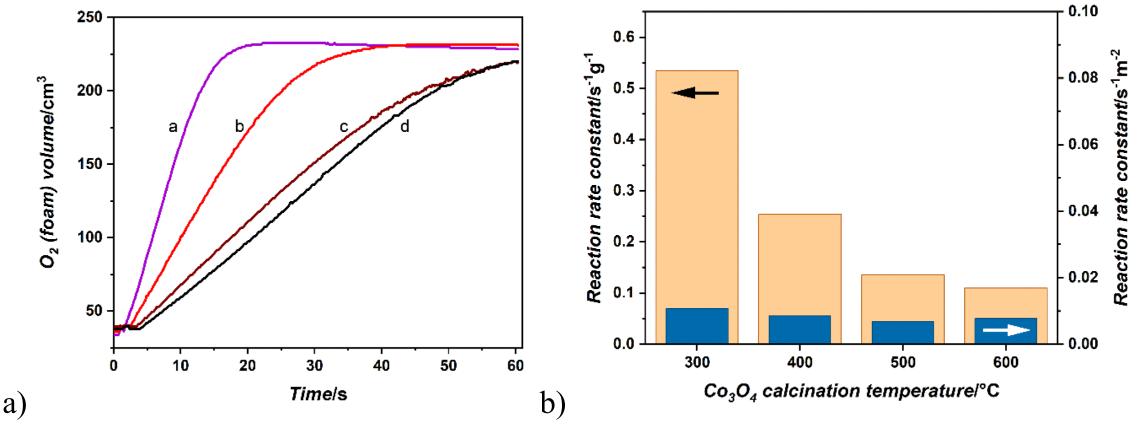

Fig.11. a) Video-based analysis of changes in O_2 (foam) volume evolved during H_2O_2 decomposition over time, demonstration using 0.25 g of spinel catalysts calcined at 300, 400, 500, and 600°C (lines a, b, c and d respectively).
b) Reaction rate constants determined per unit mass (orange) and unit surface area (blue), figures originally published in [P9] (Bernard et al., 2021).

The described experiment was designed to be suitable for live demonstration in a lecturing hall. Analysis of the relation between the reaction rate and the specific surface area can be limited to visual assessment, but also a simple kinetic analysis can be performed, and numerical values of the rate constants can be compared. Such analysis can be performed during the interactive lecture or independently by students after classes in form of guided inquiry. The presented experiment can be also adapted to laboratory activity, where the students can perform analysis of the volume of gas evolved and captured in the foam, or alternatively the reaction can be carried out in a closed vessel with a pressure sensor, similarly to the experiment described by Babinčáková (2020).

12. Authentic research-based laboratory course concerning modifications of the electronic properties of heterogeneous catalysts

The surface properties of material play a key role in heterogeneous catalysis. Nowadays, we are able not only to determine what are these properties but also modify them to optimize the catalytic activity of the material. Among the important parameters which can be modified are the electronic properties of surfaces. These properties can be quantified by the work function, which can be defined as the minimum energy required for moving an electron from the Fermi level of a solid into vacuum. The electronic properties of the surface can be modified by the deposition of alkali metal promoters (AMs), and the promotional effect of alkali metals is mainly related to their low ionization potentials which allow for a charge transfer to the catalyst surface, inducing an electric field gradient at the surface generated by the resulting dipole moment (Kotarba et al., 2004; Somorjai & Li, 2010), see Fig. 12.

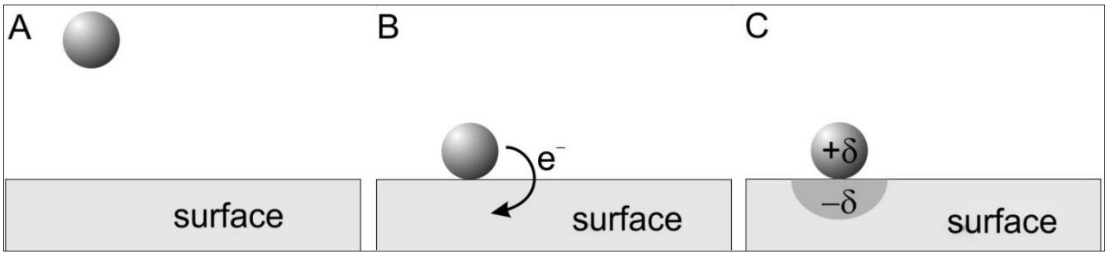

Fig. 12. Schematic illustration of localized surface dipole formation due to adsorption of alkali metal atom on metallic surface. A) AM and surface separated; B) Electron density transfer from AM to the surface; C) Formation of a localized surface dipole, originally published in [P10] (Bernard, Grzybek, & Stelmachowski, 2014).

This phenomenon can be investigated by students by measuring the reactivity of cobalt spinel (Co_3O_4) tuned by controlled doping with potassium carbonate [P10] (Bernard et al., 2014). The reaction suitable for catalytic tests is the decomposition of nitrous oxide into elements (Piskorz, Zasada, Stelmachowski, Kotarba, & Sojka, 2008; Stelmachowski, Maniak, Kotarba, & Sojka, 2009). This reaction is of tremendous environmental importance since N_2O is being considered the third most important greenhouse gas and destroyer of the ozone layer. The mechanism of N_2O decomposition over oxides containing transition metal ions can proceed via electron transfer route, which can be described in three steps: dissociation of the N_2O molecule (equation 2), diffusion of surface oxygen intermediates, and their recombination with the subsequent desorption of molecular oxygen (equation 3).

$$N_2O + e^- \rightarrow O^- + N_2{}^{\uparrow} \qquad (2)$$

$$O^- + O^- \rightarrow 2e^- + O_2{}^{\uparrow} \qquad (3)$$

Initiation of the reaction occurs at active sites – redox centres with electron transfer from the catalyst to the anti-bonding orbital of the N_2O molecule, which leads to the cleavage of the NN–O bond and release of the nitrogen molecule. Next, the surface oxygen intermediates undergo diffusion and recombination followed by desorption of molecular oxygen (Pietrzyk, Zasada, Piskorz, Kotarba, & Sojka, 2007; Piskorz et al., 2008). Each step involves the transfer of electrons from and towards the surface, therefore, it can be considered a redox process and depends strongly on the electronic properties of the catalyst surface (Stelmachowski et al., 2009).

The activity scenario consists of 3 phases: 1st – preparation of catalysts (plain and K-dopped Co_3O_4), time: 4 hours, 2nd – work function measurements, 6 hours, 3rd – activity tests, 10 hours (2 hours/sample), 20 hours in total. The variant of the experiment described herein shows the relation between the number of nominal potassium atoms per surface area unit of Co_3O_4 spinel and its catalytic activity, see Fig. 13. The experiment can be easily modified and the influence of other parameters on catalytic activity can be investigated, *e.g.* type of alkali metal, type of spinel, type of doping agent (electropositive *vs.* electronegative). Many of those relations were not studied and described in the literature, therefore, this activity can be considered as authentic research-based students' investigation or in other words, an open-ended inquiry.

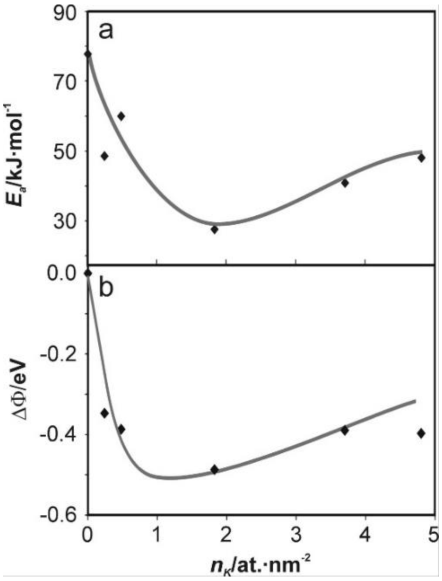

Fig. 13. Dependence of a) activation energy (E_a) of N_2O decomposition and b) work function changes of the catalyst on potassium loading, originally published in [P10] (Bernard et al., 2014).

Piloting implementation of the scenario was run with students of the 3rd year of chemistry studies specializing in inorganic and structural chemistry. The experiment was introduced as part of the Open Laboratory classes, the course that was meant to prepare students for independent bachelor research.

An evaluation was based the pluses-minuses-interesting (PMI) thinking tool (de Bono & British Broadcasting Corporation, 1985), and on a short survey concerning difficulty and students' engagement during the experiment. The survey was followed by a short interview during which students answered two questions: 'What have you learned during the experiment?', 'Do you think knowledge and skills you gathered during the experiment were useful?'. The experiment was piloted by 3 groups with 4 students in each. The evaluation survey and the interview were completed by 9 participants. The evaluation was conducted 6-12 months after completion of the course.

The answers in PMI tool showed that students were satisfied with the possibility of making a research-based investigation with high autonomy, and work in catalysis on a topic related to environmental protection. The main problem was working in groups. They considered groups of 4 people too large, but each of them tried to participate in all measurements personally what was often hard to achieve. Moreover, none of the groups chose a leader, and they tried to make decisions collectively, which lead to conflicts. The experimental part of the investigation was pointed as the easiest one, but demanding the most work. Planning of the research was moderately difficult but the least fatiguing.

Writing the laboratory report was considered most difficult, and requiring only a little less work than the experimental part. Students were convinced that they gained many laboratory skills during the experiment, useful for their bachelor research.

13. Enhancement of chemical education with 3D printing – construction and usage of low-cost 3D-printed polarimeter

Measurements are an inseparable part of inquiry-based learning. Therefore, there are many data-logging systems on the market, which enable carrying out quite advanced measurements and are suitable for use at lower and upper secondary school levels. Dedicated sensors include various electrodes, gas probes, spectrometers, mini gas chromatographs, automatic titrators, polarimeters, etc. Unfortunately, such equipment is quite expensive, and many schools cannot afford to buy even one complete set of sensors, not to mention establishing separate measuring sites for each student. Luckily there is a cheap alternative. Decreasing prices and the wide accessibility of 3D printers encouraged science educators to create 'do-it-yourself' (DIY) measuring devices for educational purposes. There are many designs on the marked shared under the Creative Commons license that are free and ready to use. For chemistry teachers, designs of colourimeter, fluorimeter, UV-Vis spectrophotometer, and various reactors may be especially useful (Grasse, Torcasio, & Smith, 2016; Porter, Chapman, & Alaniz, 2017; Porter, Washer, Hakim, & Dallinger, 2016; Stefanov, Lebrun, Mattsson, Granqvist, & Österlund, 2015; Tabassum et al., 2018). All these can be printed and built with a tiny effort and at a small fraction of the price of commercial solutions. However, there was no 3D-printable polarimeter design on the market, until the publication [P11] (Bernard & Mendez, 2020b).

There are avaliable several designs of inexpensive DIY polarimeters (Breton, 2015; Garvin, 1960; Lisboa, Sotomayor, & Ribeiro, 2010; Nechamkin, 1954; Shaw, 1955; Stary & Woldow, 2001; Vennos, 1969), including those based on a shoebox (Mehta & Greenbowe, 2011) or PVC pipes (Breton, 2015), but the application of 3D printing technology allowed for the construction of a device which is durable, precise and easy to assemble. A simple polarimeter requires a sample chamber, source of monochromatic light, and two polarization filters, one before and one behind the sample (Kapauan, 1973), where the second filter is rotatable (see Figure 14). A measurement yields the angle of rotation of polarized light after passing through a sample of an optically active substance/solution (Eichlin, 1927; Evans & Tietze, 1964; Kiplinger, 1930; Knauer, 1989; Mickey, 1980).

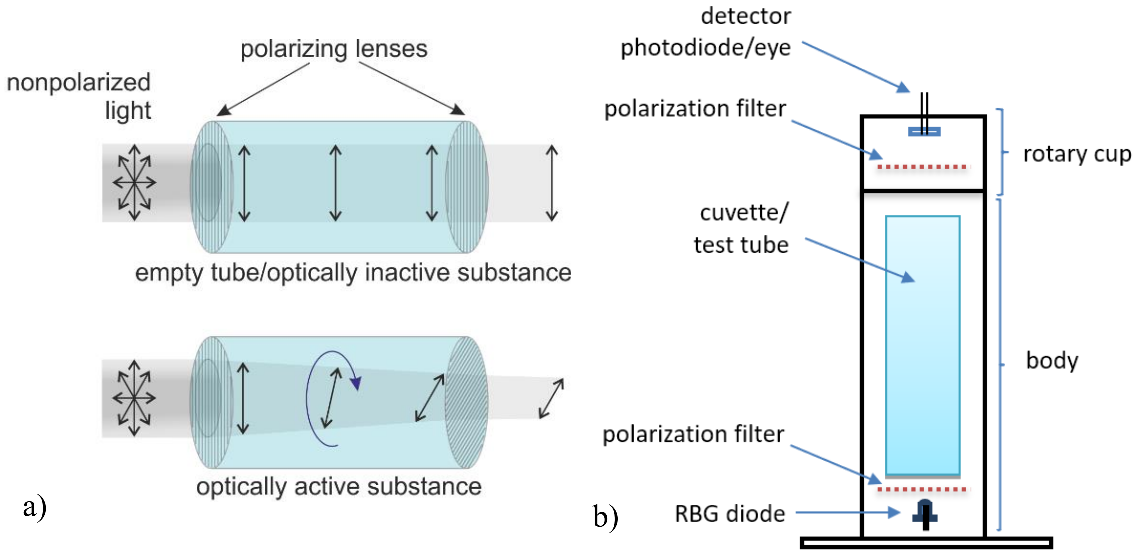

Figure 14. a) Working theory of a polarimeter, b) Schematic of the 3D-printed polarimeter, originally published in [P11] (Bernard & Mendez, 2020b).

Using the measured rotation angle and equation (4) or (5), a substance's specific rotation can be calculated (Mickey, 1980).

$$[\alpha]_{\lambda}^{T} = \frac{\alpha}{l \cdot \rho} \qquad (4)$$

$$[\alpha]_{\lambda}^{T} = \frac{\alpha}{l \cdot c} \qquad (5)$$

Where:

l – path length in decimetres,
ρ – density in grams per millilitre (for a pure substance),
α – measured rotation in degrees,
c – concentration in grams per millilitre (for a solution).

A polarimeter can be used not only to measure the optical activity of a substance, but also for the introduction of optical activity phenomena, substance identification, or reaction kinetics monitoring (*e.g.* sugar mutarotation). In Fig. 15, measurement results for aqueous solutions of sucrose in the concentration range of 0.05÷0.35 g·mL for various colours of light (wavelengths) measured with a 3D-printed polarimeter are presented. Results for various colours are a great starting point for a discussion on optical rotatory dispersion phenomena. Moreover, the results marked with yellow colour in Fig. 15 were measured with a digital, fully automatic, commercial polarimeter using a 589 nm sodium lamp. It's clear that the precision and accuracy of the 3D-printed polarimeter are more than satisfactory.

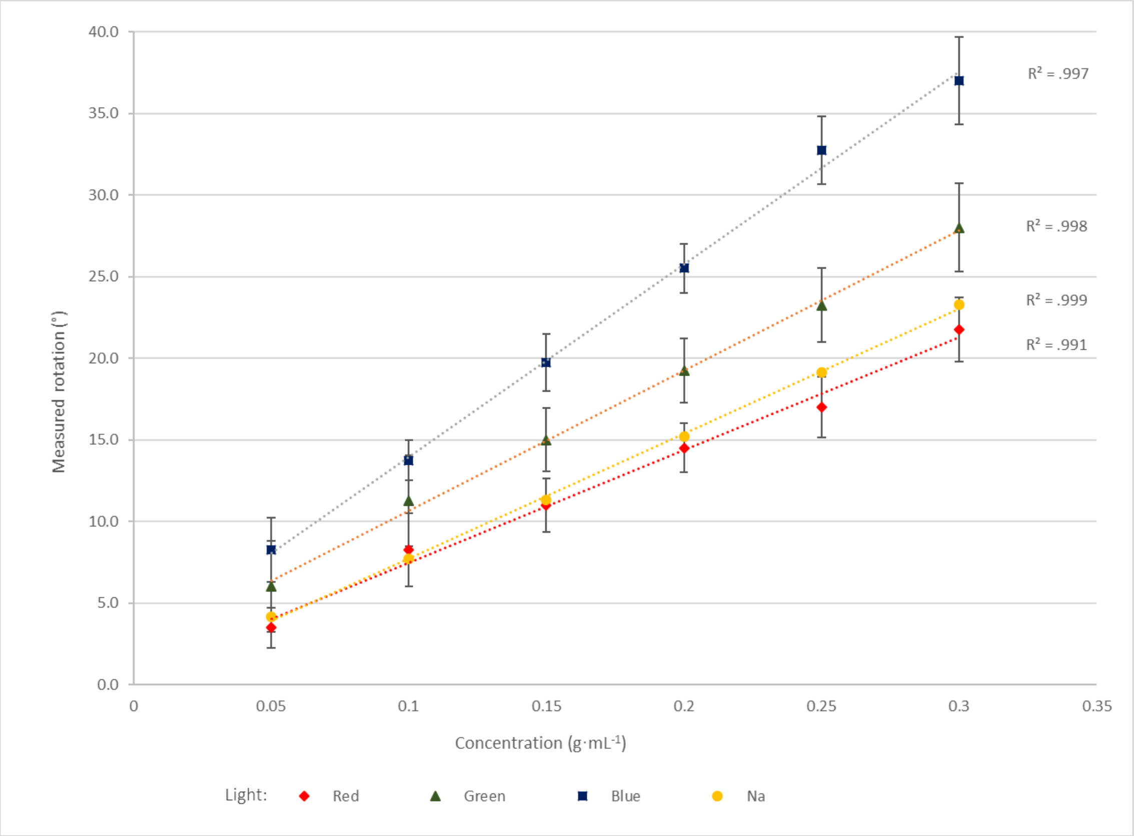

Fig. 15. Rotation angles measured with a 3D-printed polarimeter for aqueous solutions of sucrose in the concentration range of 0.05÷0.35 g·mL, series for various colours of light (red, green, blue) with error bars representing standard deviations of measurements, accompanied with results from commercial polarimeter with a 589 nm sodium lamp, originally published in [P11] (Bernard & Mendez, 2020b).

The device was tested by 50 upper secondary school students (K11) in Poland, and 15 chemistry university students majoring in organic chemistry in the US. Students were acquainted with polarimetry principles and device schema, and they carried out several measurements. Students performed measurements with pure liquid first – (R)-limonene, and next with various concentrations of fructose and sucrose solutions. Finally, they carried out measurements using various colours of light (wavelengths). The measurements were followed by a discussion on the optical activity of substances, and the introduction of optical rotatory dispersion phenomena. Calculations of specific rotation of the substances was a homework, checked by the teacher during subsequent classes.

As the design of the 3D printed polarimeter is intended for self-assembly by teachers, constructing the device was also tested. The instructions provided with the design were used by 16 pre-service teachers, chemistry students realizing a Chemistry Didactics course in Poland, and by 4 undergraduate chemistry students in the US. None of the students had previous experience in constructing electronics or building measuring devices.

They worked in pairs following provided instructions, and after approximately 45-60 minutes, all groups constructed fully operational devices. After the assembly, students carried out test measurements. The devices built were used later during classes with school students described above. Assembly of measurement devices has also a high didactic value (Porter et al., 2016), the measurements are no longer performed in a "black box", which affects understanding of the method and measured phenomena positively. Therefore, 3D-printed polarimeter can be used not only for various inquiry-based investigations, but its assembly can be organized and run as an inquiry itself.

14. Using 3D printer pens to draw chemical models

Chemistry involves macroscopic, submacroscopic, and symbolic domains (Johnstone, 1991), thus models play an important role in chemical education, visualising structures invisible to the naked eye. Therefore, it's not a surprise that the application of 3D printing technology in chemical education is not limited to construction of measuring devices but involves modelling. This technology provides an opportunity to design, personalize and produce various types of models. Especially useful and interesting are models of atoms (Smiar & Mendez, 2016), orbitals (Carroll & Blauch, 2017; de Cataldo, Griffith, & Fogarty, 2018; Griffith, Cataldo, & Fogarty, 2016; Robertson & Jorgensen, 2015), crystal unit cells (Rodenbough, Vanti, & Chan, 2015; Scalfani & Vaid, 2014), nanostructures (Scalfani, Turner, Rupar, Jenkins, & Bara, 2015), steric interactions (Carroll & Blauch, 2018; Diaz-Allen & Sibbald, 2016), proteins (da Veiga Beltrame et al., 2017; Meyer, 2015), DNA (Roberts, Hagedorn, Dillenburg, Patrick, & Herman, 2006) and even potential energy surfaces (Lolur & Dawes, 2014). Although these new models are useful, 3D printing process is time-consuming (takes up to several hours to complete) and that is why preparation of the models must take place outside of regular school hours, and students work with reusable kits prepared by the teacher, which they have to return after classes.

The solution can consist in using 3D pens (hand-held 3D printers) which allow users for instant 3D modelling. Unfortunately, precise drawing directly in 3D is almost impossible and even small models of molecules are not accurate enough for educational purposes. Therefore, guides used so far instructed the user to draw flat objects first, using 2D paper printed templates, and then assemble flat elements into a 3D structure (Dean, 2016). The invention presented in [P12] (Bernard & Mendez, 2020a) consists of 3D templates that can be printed with a classical 3D printer, and assist the user in drawing directly in 3D. Templates for drawing molecules are built like puzzles using basic modules representing atoms with the required geometry (presented in Fig. 16). Templates assure proper direction, length, and angles between drawn lines representing bonds.

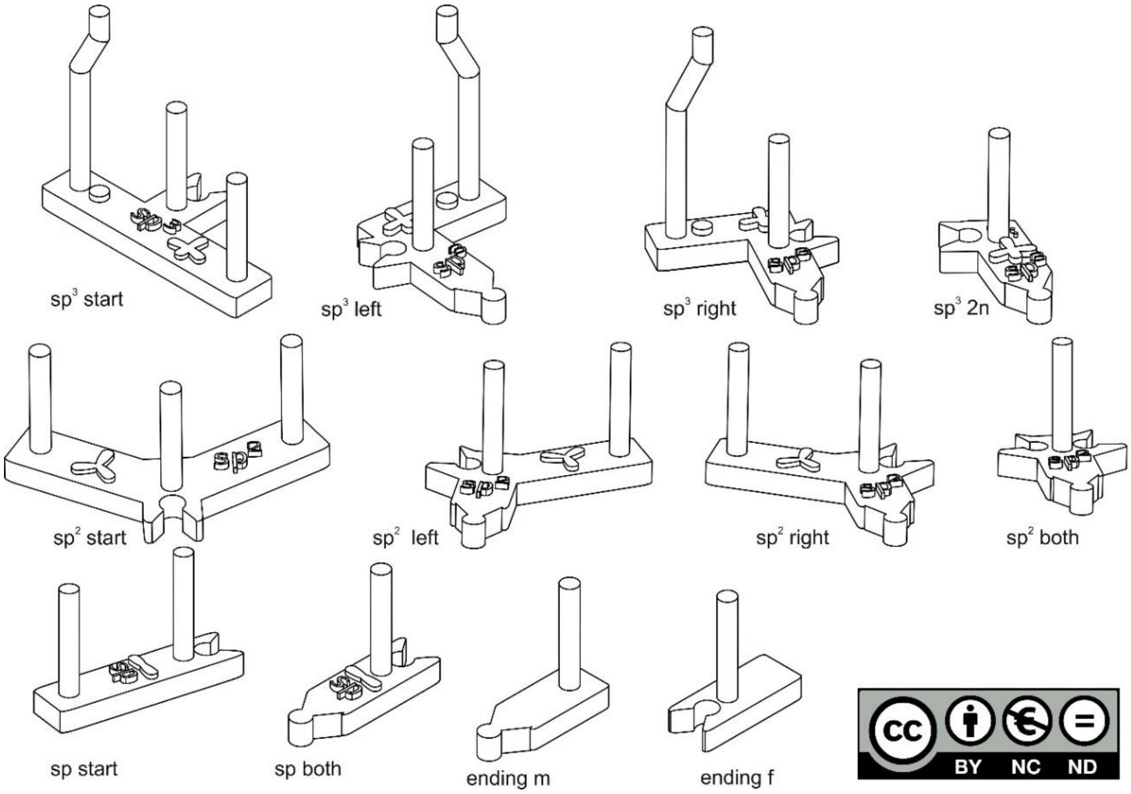

Fig. 16. Shapes of modules, originally published in [P12] (Bernard & Mendez, 2020a).

The product (drawing) is a wireframe molecular model (see Fig. 17 and Fig. 18), it can be drawn by a student in less than a minute. It means students can draw several models in real-time during classes and later take them home. However, not only the product is important, but also the process of drawing in 3D that along with classical 2D notes can help students develop spatial literacy and their ability to make 2D–3D transformations, as well as clarify mental models of molecules.

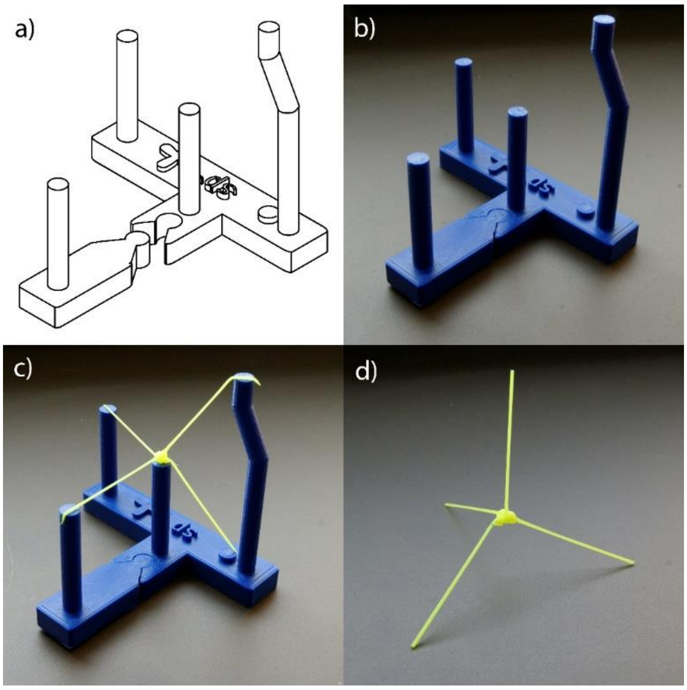

Fig. 17. Model of a methane molecule, a) scheme of the template; b) photo of the template; c) photo of the template with the structure drawn; d) model detached from the template, originally published in [P12] (Bernard & Mendez, 2020a).

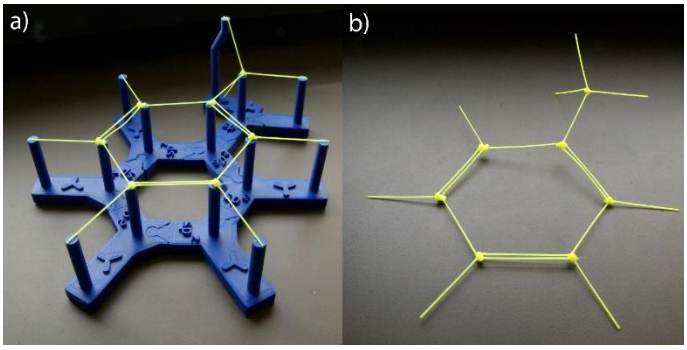

Fig. 18. Model of a toluene molecule a) photo of the template with the structure drawn; b) model detached from the template, originally published in [P12] (Bernard & Mendez, 2020a).

The system usability was tested with 4 groups of Polish students, two at the lower secondary school level (n = 24; K9; age: 16), and 2 groups at the upper secondary school level (n = 47; K11; age: 18). At the lower secondary level, during 90 minutes classes, students drew models of methane, ethane, propane, ethene, propene, ethyne, propyne, methanol, ethanol, methanoic acid, ethanoic acid, and ethyl ethanoate. At the upper secondary level students drew all the models from the lower secondary level and additionally but-1-ene, (2Z)-but-2-ene, 2E)-but-2-ene, methanal, ethanal, benzene, o-, m- and p-dichlorobenzene, and toluene, during 135 minutes (3 school periods). In all cases, classes had a review character. Students first wrote a molecular and structural formula of a given compound and draw the structure of the molecule on the paper. Next, following the instruction, students built the desired molecule template, and draw a 3D model using 3D pens. The research was based on a semi-structured group interview and the PMI – Pluses-Minuses-Interesting thinking tool (de Bono & British Broadcasting Corporation, 1985). The interview covered the questions about the used system concerning its usefulness, convenience of use, educational aspects, and ways of improvement. Finally, students were asked to classify their answers according to PMI channels.

Using the 3D pens accompanied with the templates occurred to be extremely easy for the students. All students were able to draw models of desired molecules. Moreover, students enjoyed the process, and they liked the most the possibility to see 3D models of molecules (see Fig. 19). Other positive aspects were the quickness and simplicity of drawing, using modern technology, and the process was considered as ‘fun’.

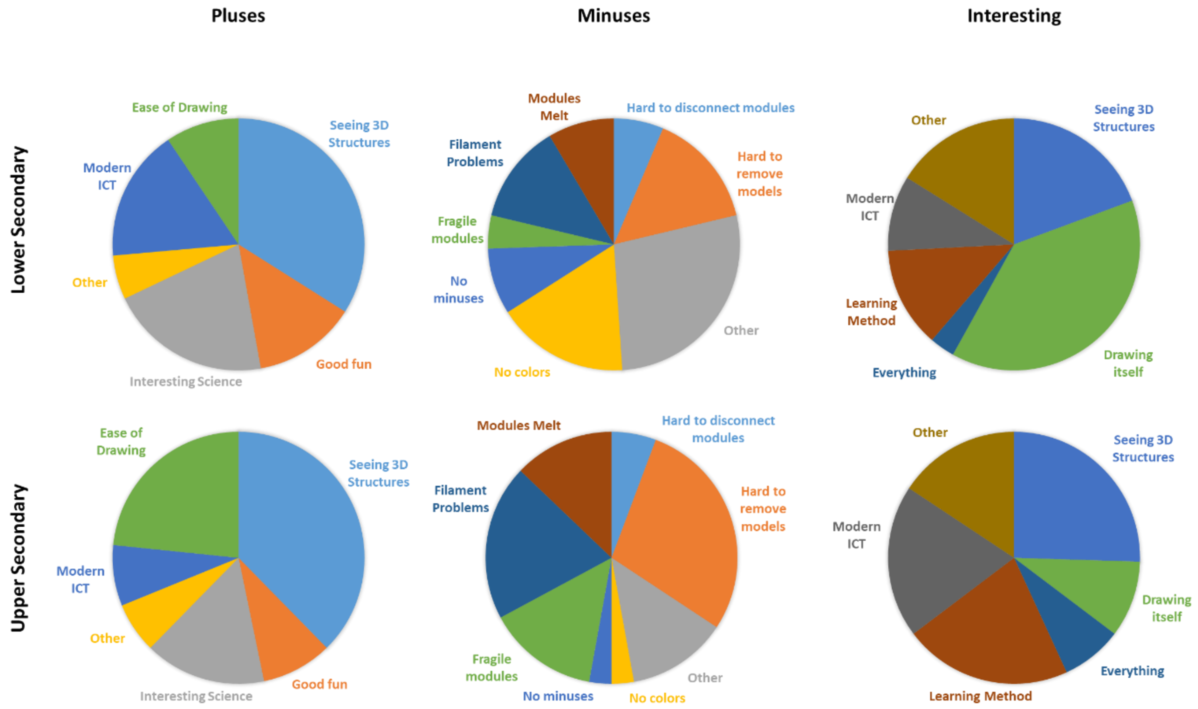

Fig. 19. Results of the Pluses-Minuses-Interesting (PMI) thinking tool, originally published in [P12] (Bernard & Mendez, 2020a).

The results also indicated an area for improvement for the invention. The most common issue was the difficulty of detaching models from the templates, caused by using the same filament – acrylonitrile butadiene styrene (ABS) for the templates and in the 3D pens. The problem can be eliminated using a filament with a lower melting point *e.g.* polylactic acid (PLA) with the 3D pens, which would also solve the problem of “plastic” smell during drawing, reported by several students. Later tests showed that using PLA solves these problems but drawing with it is a bit more difficult.

The developed invention can be used by chemistry teachers as a supplement to traditional ball-and-stick modelling kits. The frame models drawn can be taken home and used for further learning. The students can essentially take 3D notes from these chemistry lessons. The invention is free for personal/educational use but restricted for commercial application by a patent application (Bernard & Mendez, 2018).

Summary of the main scientific achievements

The most significant outcome of the presented studies is a professional development programme in IBL with embedded assessment for in-service teachers. The PD programme was created for Polish chemistry/science teachers basing on their beliefs and attitudes. Studies accompanying the PD application let enrich not only the methodology of the teacher training in IBL but also the general methodology of inquiry-based teaching and learning with embedded assessment. Moreover, the influence of the developed PD programme on teachers school practice was tested and its' high efficiency was proved. The PD programme was developed and applied first during the realization of the FP7 ESTABLISH project (2010-2013), and expanded within the framework of the FP7 SAILS project (2012-2015), moreover, it was further used in FP7 IRRESISTIBLE project (2013-2016). The parallel version of the training aimed for pre-service teachers has become a part of the regular training for chemistry students at Jagiellonian University who apply for chemistry teaching certify and is still in use. Moreover, a massive open online course (MOOC) was developed and based on the mentioned PD programmes, within the framework of the 'Shaping research abilities of children and adolescents' project (2020-2022). This course is addressed not only to science teachers but also to teachers of kindergarten and early education, as well as the general public, including parents having children in school age. This project is meant not only to train in IBL but also to popularize this method, and increase its understanding in Polish society.

Teachers introducing IBL into school practice expect not only methodological and practical knowledge from trainers, but also teaching materials prepared for the method that can be used directly in the classroom. The presented tools and scenarios are well-suited for various levels of education, from lower secondary school to graduate studies, and use various types of inquiry, from interactive demonstration to open-ended inquiry. These tools are based on areas indeed problematic for teachers or/and current and urgent chemical issues like sustainable development and environmental protection. Important outcomes of completed studies include, apart from ready to use didactic tools, a scientific and technological workshop for the application of 3D printing in chemical education. It let not only design and create new didactic tools, but also use the latest available designs, and involve the use of 3D printing technology in chemistry pre-service teachers training at Jagiellonian University, as a part of the 'ICT in chemical education' course. Moreover, a dedicated course entitled '3D printing in chemical education' was developed and run *i.a.* for students of Charles University in Prague in 2018 and Pavol Jozef Šafárik University in Košice in 2019.