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Pernaa, Johannes

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The Relevance of Radiochemistry: Perceptions of Future Radiochemists

Johannes Pernaa[1*], Gareth T. W. Law[2] and Sanjeev Ranjan[2,3*]

[1] The Unit of Chemistry Teacher Education, Department of Chemistry, Faculty of Science, University of Helsinki, A.I. Virtasen aukio 1, P.O. Box 55, FI-00014 University of Helsinki, Finland

[2] Radiochemistry Unit, Department of Chemistry, Faculty of Science, University of Helsinki, A.I. Virtasen aukio 1, P.O. Box 55, FI-00014 University of Helsinki, Finland

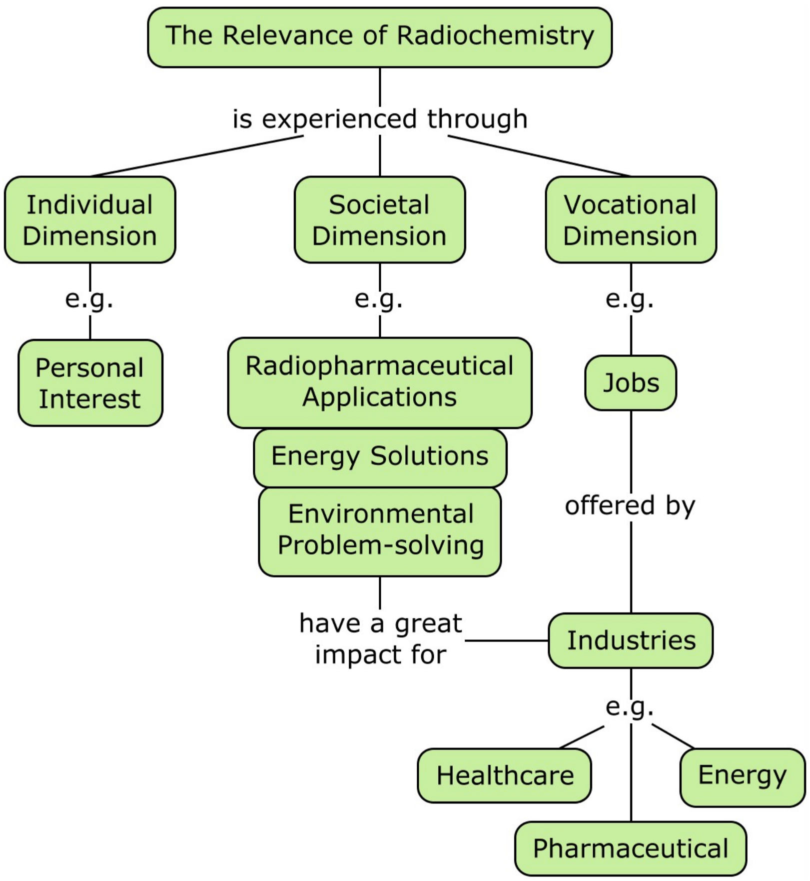
[3] Institute of Biomedicine, University of Eastern Finland, P.O. Box 1627, FI-70211, Kuopio, Finland

ABSTRACT

Radiochemistry faces a well-documented training and recruitment crisis. Older radiochemists are retiring, and fewer young people are studying radiochemistry. In turn, this is leading to a shortage in newly qualified radiochemists, as well as a loss of historical knowledge (as know-how is often not passed-on). Here, we analyzed the relevance of the study of radiochemistry in higher education through future radiochemists' perceptions. Our objective was to provide insights into future radiochemists' thinking and provide some clear examples on how to support relevance. A qualitative study was conducted through a research question: What perceptions of relevance do future radiochemists experience about radiochemistry studies and radiochemistry as a field? We used the relevance model of Stuckey et al. (2013) as the relevance framework. This was selected because it offers a comprehensive definition of relevance including individual, societal, and vocational dimensions. The data were gathered from post-graduate radiochemistry students (masters and PhD level) through use of a qualitative questionnaire that was designed using the selected relevance framework. In total, 15 future radiochemists participated in the study. The data were analyzed through theory-based content analysis using the selected relevance framework. According to our data, future radiochemists experience their university study and the chemistry field as being highly relevant. They experienced that radiochemistry topics are interesting (individual relevance), the field has great societal impact through radiopharmaceuticals, energy solutions, and environmental problem-solving

(societal relevance), and that their professional future was clear e.g. a job in the nuclear industry (vocational relevance). These results can be used in student recruitment and in developing radiochemistry teaching towards a more relevance-oriented direction.

GRAPHICAL ABSTRACT



KEYWORDS

Second-Year Undergraduate, Upper-Division Undergraduate, Graduate Education, Chemical Education Research, Nuclear/Radiochemistry

INTRODUCTION

Radiochemistry faces a training and recruitment crisis. Older radiochemists are retiring from the nuclear industry and from other radiochemistry fields. This is resulting in a serious shortage in radiochemistry expertise (e.g. in Australia, Europe, Japan and the US).[1–3]

Even though radiochemistry has been an integral part of general chemistry knowledge for several decades[4], knowledge of this critical discipline is currently decreasing as radiochemistry is not widely taught in high-schools or at universities, further, younger generations seem to avoid the subject when it is included on a syllabus. Reasons for this avoidance include negative perceptions about nuclear weapons and the nuclear industry; radiochemistry research being perceived as "not a modern field of chemistry"; and radioactivity itself being seen as inherently frightening[1]. Clearly, many students don't understand the real importance of radiochemistry or the issues faced in the discipline and its associated industries. Radiochemistry expertise is vital in a wide range of areas. For example, in radiopharmacy, radiochemistry knowledge is applied across a diverse range of applications, including drug development, oncology, image-guided drug delivery, neurology, and radiation therapy. In the nuclear industry, radiochemistry knowledge is critical across the entire nuclear fuel cycle, especially in areas like spent fuel management and recycling, nuclear waste disposal, and nuclear decommissioning[5,6]. Radiochemists also make vital contributions to the environmental sciences (e.g. radioecology, the management of contaminated nuclear sites etc.), industry, and in work-place safety (e.g. mitigating against the build-up and impacts of ionizing radiation in the workplace). Fundamental radiochemistry research is also at the vanguard of modern chemistry research (e.g. assessing co-valency by probing the behavior of the f-block elements). More information about the diverse careers offered in the field of radiochemistry is available from the Careers section of American Chemical Society's homepage[7].

The need for new radiochemists is significant, urgent, and well documented[1–4]. From a future radiochemist's (student) point of view, the demand for expertise means that the graduates don't have trouble gaining employment. This should be a positive thing and encourage young chemists to choose radiochemistry as their chemistry major. But even though the professional future of radiochemistry seems quite secure, why don't chemistry students specialize in this field?

One major reason is that there are not enough chemistry students in the first place. The small number of graduates is a much broader issue concerning all science, technology, engineering, and mathematics (STEM) fields, not just in chemistry or more precisely radiochemistry. Applicants are few and there is a problem with a large number of dropouts.[8] In Europe, the dropout rate of science students has been reported to be ~30%[9–11]. According to Astin and Astin[12], in the US, ~40% of science, mathematics, and engineering students will drop out or change their major during their undergraduate years. The dropout rate is especially high in chemistry. For example, Heublein and Schmelzer[13] reported that in Germany the dropout rate has been over 40% in chemistry bachelor's programs[13]. The drop-out students often transfer into other closely related fields like pharmacy or medical school, or leaving higher-education entirely[10].

In terms of dropout numbers, chemistry higher education needs to recruit more motivated students who will graduate and students inside the pipeline need more support to help them to finish their degree. From radiochemistry's point of view, it is crucial to first get young people inside the chemistry pipeline, and then inspire and support them during their bachelor's degree so they can enroll in a radiochemistry master's program.

According to the latest research, continuous guidance has a significant impact in supporting student's persistence in chemistry, but the challenge is what kind of guidance do students need?[11] In order to understand the reasons behind the high dropout rate, we need to explore students' reasons for choosing a science career (particularly chemistry) and factors that keep them motivated at university. If the reasons and motivational factors are known, it is possible to offer specific needs-based support and reduce drop-out rates.

Over the last two decades, these problems have been recognized and studied extensively in the science education field. Many scholars suggest that the lack of perceived relevance is the main reason why students don't choose chemistry or other science subjects[14]. Also, Hill et al.[15] have found that the perceived relevance of mathematics and science is one of the key components behind science career choices. Evaluating through the high dropout level, this observation seems to be one key explanatory factor from the chemistry education research perspective. Research has shown that chemistry is not only perceived as being one of the least interesting subjects, but it also is thought to lack vocational and societal relevance.[14,16,17]

In this study, we investigated future radiochemists' perceptions of the relevance of radiochemistry. In addition, we present practical examples to support the relevance. Our objective was to understand what motivates and inspires students who have chosen radiochemistry as their major and help others to develop their radiochemistry courses to address future radiochemists' needs. The specific research question guiding our research was: what perceptions of relevance do future radiochemists experience about radiochemistry studies and radiochemistry as a field? To the best of our knowledge, this has not been studied before, and we suggest that the knowledge obtained from this research will be useful for chemistry educators working in higher education, especially in the field of radiochemistry. It could be used in e.g. recruiting students into radiochemistry programmes and developing relevance-based curricula for undergraduate chemistry students in order to reduce the high dropout rate.

THE RELEVANCE OF CHEMISTRY STUDIES

As mentioned in the introduction, the lack of relevance has been raised as the main reason for low interest in science study and careers[14,16]. The focus of this article is the relevance of radiochemistry. In order to explore it, we need a clear definition of the concept of *relevance*.

In the past, the concept of relevance was often equated with interest[16]. However, in 2013, Stuckey et al.[14] argued that relevance should be addressed through a more detailed definition in order to develop curricula in a more relevance-oriented direction. They have presented a model of relevance that offers a comprehensive tool for analyzing the different dimensions of relevance. According to their relevance model, the experience of relevance may have individual, societal, and vocational features focused on the current state or in the future. The nature of experience may range from intrinsic to extrinsic, when looked at from the individual's perspective (see Figure 1).

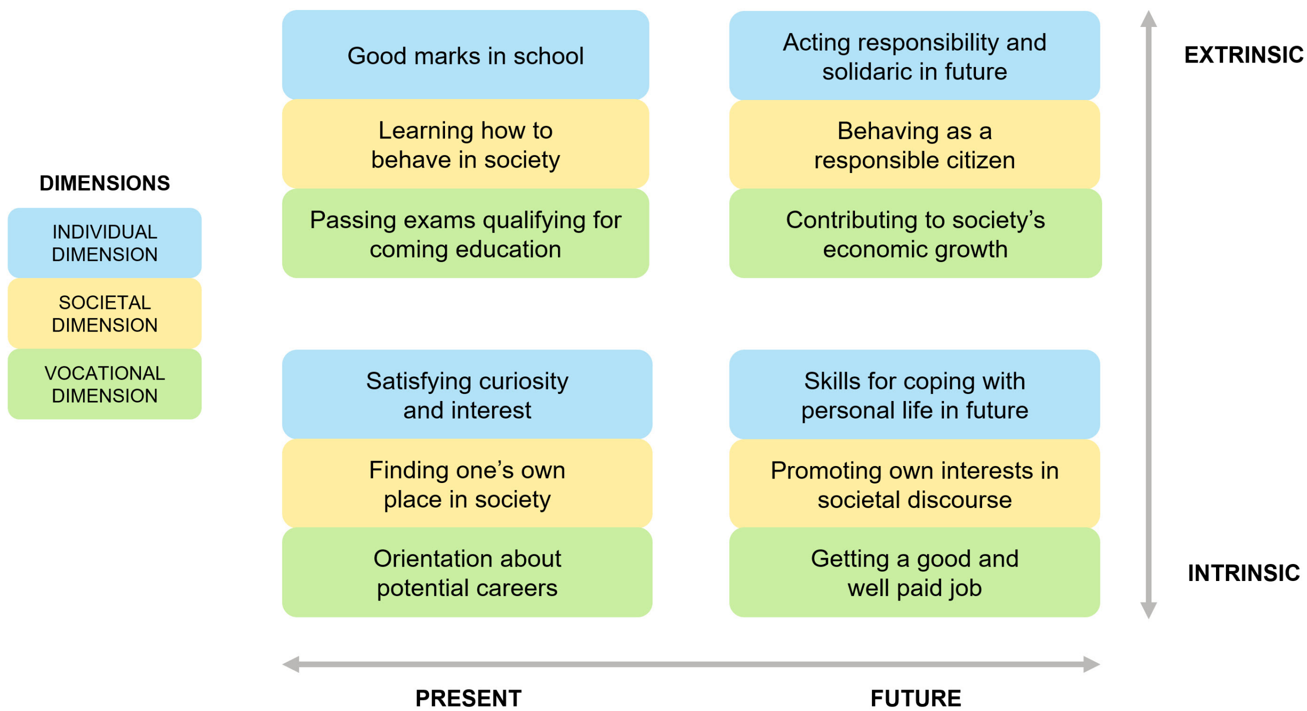


Figure 1. A model of relevance. Data are from Stuckey et al.[14].

Individual Perspective

In the Stuckey et al.[14] model, personal interest has a major role in the individual dimension. Interest can be defined and categorized in many ways, but one highly cited approach is a distinction between individual and intrinsic interest (e.g. curiosity in learning), and situational and extrinsic interest (e.g. status). Interest in science has been studied extensively at all education levels. The major challenges are why interest in science decreases with age, and why boys are more interested in science than girls.[18]

According to the Stuckey et al.[14] model, chemistry fulfils learners' curiosity and information needs. Chemistry students have an opportunity to learn skills and acquire the knowledge needed for their personal life in the future. In the chemistry education research literature, Ogunde et al.[19] argued that this dimension is crucial. They have found that intrinsic interest in chemistry is the predominant reason for choosing it. As far as interest is concerned, it is important to note that interest in chemistry arises in childhood during early school years. Positive school experiences and non-formal activities have a major role in attracting young people into chemistry.[18,20,21]

Societal Perspective

The societal dimension focuses on supporting students' scientific self-image in a societal context. For example, students become aware of their own role as members of society. In the chemistry context, they would acquire the knowledge needed in responsible research-based decision making and promoting sustainable development.[14] There has been little research on the societal dimension in chemistry education, but Marteel-Parrish and Lipchock[22] have suggested that understanding the societal role of chemistry is one of the key competencies for the 21st century.

Macášek[4] highlights the societal relevance of radiochemistry. The field is tightly connected to other chemistry fields and it provides applications from understanding nature through radioanalytical measurement techniques to energy solutions and medicine.

Vocational Perspective

The vocational dimension offers orientation for future professions and careers in chemistry. In Stuckey's model, the extrinsic motivation is to pass courses and graduate in order to get a satisfactory job. The job itself is classified as an intrinsic objective, but it leads into contributions to society's economic growth, which is an extrinsic outcome.[14]

According to the research, the vocational perspective is important in chemistry education. If students don't see the possible career opportunities, it decreases their will to choose chemistry.[23] The vocational perspective can be offered via individual career courses[24] or embedding career planning inside other courses[22]. Also, there is evidence that authentic research-based laboratory experiences support interest in chemistry careers[25].

Chemistry students' career aspirations have been studied a little. For example, Ogunde et al.[19] found that in general, students are aware that chemistry offers many career options. However, even though some individuals have a clear vision about their future dream job in chemistry[26], according to large international research data, only a few students choose to study chemistry in order to get a specific job[19].

According to scientific identity research, scientist stereotypes[27] and media images[28] have a strong effect students vocational self-image. A positive stereotype that one can identify with can serve as a role model to inspire in pursuing a career in a STEM field. On the other hand, if the stereotype is not identifiable, it can reduce the interest / increase drop-out rates. For example, a typical stereotype for a scientist is a white man with a highly educated background, which might reduce interest amongst women and people of color.[27] As a solution, Schinske et al.[29] suggest offering non-stereotypical examples of scientists for students. They discovered that it will lead to better study success in a diverse college study setting. Also Hill et al.[15] emphasizes the importance of role models in supporting the science career choice.

METHODS

The data for this qualitative research[30] was gathered in two cycles. The first data gathering cycle was carried out during the *Radionuclide production and tracer techniques* course (5 ECTS) in the autumn 2017 at the University of Helsinki, Finland. The second data cycle was performed in spring 2020 through an email query send to radiochemistry students from the UK and Finland. As mentioned, the objective was to map students' experiences of the relevance of radiochemistry. Their perceptions were gathered using an electronic questionnaire that included three open ended questions. Questions were designed via the relevance model from Stuckey et al.[14]:

1. Consider whether the knowledge acquired, and skills learned in the course/studies are relevant to you from a personal point of view (e.g. grades, personal interest, learning outcomes, or anything else). (Individual dimension)
2. Consider whether the knowledge acquired, and skills learned are relevant to you from a societal point of view (e.g. you find your own place in society, promote your own views in society, help you behave responsibly in society, or something else). (Societal dimension)

3. Consider whether the knowledge acquired, and skills learned are relevant to you from a professional perspective (e.g. obtaining a degree, supporting the country's economic growth, preparing for work or helping to get a good job, or something else). (Vocational dimension)

During the first data gathering cycle, one author worked as one of the instructors in the course and delivered the questionnaire to students at the end of course. The response time expired in January 2018. Six out of thirteen students (46%) participated voluntarily in the study. Students enrolled in the course were first- or second-year master's level radiochemistry students. The second data gathering cycle was performed by the second author, who sent an email query to current masters and PhD level radiochemistry students (nine total respondents).

Altogether 15 respondents (abbreviated as R in the result section) answered all three questions which produced 45 descriptions of perceived relevance from different relevance dimensions. Data were gathered and processed anonymously without any indication of gender or ethnicity. The process was designed anonymously to meet privacy requirements related to qualitative research. We also hoped that it would encourage respondents to provide more detailed and critical reflections. Students were free to choose the language of their choice: either Finnish or English. Data were analyzed using theory-based content analysis[31] using the relevance model from Stuckey et al.[14] in categorizing the perceptions of relevance.

RESULTS AND DISCUSSION

In this section, we present first the findings of questionnaire data, and then we give authentic case examples how to support the relevance of radiochemistry studies on multiple levels.

Perceptions of the Individual Dimension

As radiochemistry master or PhD students, it is clear all respondents have found radiochemistry somewhat interesting. Some stated that radiochemistry is interesting in general and others gave more specific descriptions. Compared to the relevance model, personal interest is an intrinsic perception of relevance in the present state. From the extrinsic perspective, some respondents mentioned that they don't care about grades, but others mentioned they matter.[14,18]

> "Yes, definitely. I find the area of radiochemistry to be very interesting personally. When I first learned that radiochemistry was a thing, I immediately wanted to study it. I don't give too much attention to the grades I get, but I've found all the radiochemistry courses that I've done extremely interesting." (R10)

> "I found the course content interesting for me. At the master's level, we can choose interesting courses and include them in our degree. That's why I am aiming for good grades overall." (R1)

Examples from more detailed descriptions are of interest towards multidisciplinary problem-solving, nuclear history, environmental radiochemistry, and radiopharmaceuticals. For respondent 5, radiopharmaceuticals were the reason to apply to a radiochemistry program in the first place.

> "The knowledge and skills acquired have i) inspired me to pursue a career in radiochemistry, ii) it instilled an interest in the area, this led to taking courses on the history of 'the nuclear age' and also got me reading books, listening to podcasts and watching documentaries about radiochemistry." (R14)

> "The radiochemistry studies were interesting to me as it incorporated a multidisciplinary approach in problem solving. As someone formally in physics, the courses allowed me to gain more insight into the chemistry in radiation work. For example, we learnt about different separation techniques employed to analyze specific radionuclides effectively." (R15)

> "The skills I acquired were relevant from a personal point of view. I was lucky enough to start the courses included in my master studies on the year when all the environmental radiochemistry courses were organized. They only run the courses every other year." (R11)

> "The skills and knowledge learned during the course are relevant to me for several reasons. I am very interested in radiopharmaceuticals, so I saw this course as an important introduction to the topic. The reason why I applied to study radiochemistry was to study radiopharmaceuticals." (R5)

Perceptions of the Societal Dimension

According to two respondents, radiochemistry has a clear extrinsic societal impact through radiopharmaceutical knowledge, the healthcare industry and energy solutions.

> "The societal perspective depends on many things. I believe the contents of this course have an important role in the development of diagnostics and drug therapies in the healthcare industry. Of course, the course is useful if you end up working as an expert in the healthcare industry." (R1)

> "I believe that the knowledge and skills learned will help me find my place in society because of the prominent role of radiopharmaceutical research and drug development in general in our society." (R5)

> "I have a better understanding of the implications on the use of nuclear power and power plant incidents." (R9)

In addition to pharmaceutical applications, radiochemistry knowledge in general has a clear extrinsic societal role in general and from the environmental perspective. For example, respondent R6 wrote that many people wonder about the dangers of radioactivity. The respondent suggested that all people should know the basics of radiochemistry in order to trust the solutions that the field provides.

> "I think that every sort of knowledge is in some way meaningful and important for society. Personally, lots of people ask me about the dangerousness of radioactivity. Trying to understand (to some level) every subsection of radiochemistry and sharing the knowledge to the people that know literally nothing about it might be huge benefit for society since people will trust radioactive entities, not fear them." (R6)

In addition, respondents said that radiochemistry has an important role in environmental sciences. For example, respondent 9 said that radiochemistry knowledge has complemented the environmental chemistry expertise. And according to respondent 15, nuclear safety is an important part of it.

"Before studying radiochemistry, I was an environmental chemist. The radiochemistry study sort of "patched up" my knowledge hole with regards to radiation, radiation protection, and more importantly safe utilization of nuclear energy. That has helped shape my general view towards the society, towards the carbon reduction, and towards my personal behavior." (R9)

"During my studies here, I had the opportunity to enter the Chernobyl exclusion zone. My experience made me a staunch believer in the importance of keeping nuclear power safe. As a result, I am more driven to contribute to society in this aspect." (R15)

"I think my studies have enabled me to develop an informed and balanced point of view on relevant societal issues regarding the broad area of radiochemistry. It's allowed me to critically assess information in the area of radiochemistry that's presented in the media and in scientific circles whilst having the added benefit of making myself aware of my own lack of knowledge in other areas of science. I suppose it's also helped me find my place in society as I'd always hoped to become useful and beneficial to society in some respect and I believe doing research into radiochemistry on some tough environmental problems is one way of doing that." (R13)

Perceptions of the Vocational Dimension

According to data, the intrinsic vocational relevance of the course was very clear. All respondents argued that they felt that the studies would support their future employment. For example, they provide vital skills and knowledge, confidence and learning skills. In addition, one respondent (R11) mentioned that the studies could include more basic laboratory skills.

"Every time I work with some instrument, I am becoming more and more confident while using it; also, the more we work with instruments the more we understand them. Moreover, we start to think about other issues. That is a big plus. Having such confidence might be needed while getting a job." (R6)

"The skills learned during the course are important to me. Not only that you get a course grade, but also that you learn something new from the radiochemistry field that was not covered in other courses. I believe that in the future, I will be using skills and knowledge learned from the course e.g. in research tasks. The fact that I completed the course with a good grade will have a positive impact on the average level of study and thus improve future job opportunities." (R2)

“Courses usually consist of basic skill sets and I believe more skills are learnt during practical work (e.g. research work). And it is more about teaching you “how to learn” and give you a sturdy basis for you to build upon. In this respect, I would say they are highly relevant professionally.” (R9)

“Yes. The skills that I acquired has been relevant for my professional life and I have managed to find a good job and later a PhD position. Although, many people have told me that radiochemists should also learn basic laboratory skills, like quality control.” (R11)

There was a connection between vocational and individual relevance. A few students felt that they found the studies interesting but also saw that it supported their professional objective to work in the pharmaceutical industry after graduation.

“The skills learned during the course, such as practical skills in laboratory work, as well as knowledge skills obtained from lectures and the research lab visit have been very important to me as I took the course out of my own interest, not for compulsion. Grades are also important to me, but I'd love to see the course as a way to get to work with radiopharmaceuticals after graduation. Personally, I want a meaningful job that this course could help achieve.” (R4)

“Absolutely. I want to include in my degree as many courses that I find useful from my professional interest point of view. I hope that after graduation I can work on radiopharmaceutical research in one way or another. This kind of courses improve my chances the chances of fulfilling this wish. (R5)

“I think radiochemistry (especially environmental radiochemistry) is so multidisciplinary it inherently opens doors to you in the future for careers as you become equipped with basic knowledge of the industry (which covers socio-economic issues as well as scientific ones) as well as different areas of science that you become more expert in, such as chemistry, mineralogy and microbiology.” (R13)

Case Example 1: Fostering a Wider Interest in Radiochemistry

Training future radiochemists is one of the most important tasks of the Radiochemistry Unit at the University of Helsinki. We try to get students interested in radiochemistry by emphasizing why the subject is important to society as well as the student. We reach out to students by actively advertising our courses to our undergraduates and masters candidates through presentations, posters, and emails. We have seen uptake grow from ~35 (2018) students, to 50 (2019), and now > 60 (2020). In lectures on our basic course (open to undergraduates and masters students) we try to make the learning and theory relevant to the student (e.g. by including topical case-studies, real world examples etc.). We also invite guest lecturers from industry and government to talk about life as a radiochemist and what role radiochemistry plays in industry, society etc. For example, this year we had talks from Posiva (a Finnish expert organization responsible for the final disposal of spent nuclear fuel of the owners) and STUK (a Radiation and Nuclear Safety Authority operating under the Finnish government). We also include short presentations from our in-house researchers so that the students can see all possibilities in the field and not only learn the basics. We also conduct laboratory tours where we explain the safety aspects of working with radioactivity. In essence, the idea of the course is to teach the basics but inspire the students to take up our further radiochemistry study (i.e. masters level). We thus make clear what we offer at the University of Helsinki should they want to choose radiochemistry as a course package in their Masters. This model engages students through all relevance dimensions emphasizing its relevance for society and showing potential career options[14,19].

Case Example 2: Radionuclide Production and Tracer Techniques Course

For a practical level example, how to support the relevance, we present an example syllabus from a course called *Radionuclide Production and Tracer Techniques*. This 5 ECTS course belongs to the master's program in Chemistry and Molecular Sciences at the University of Helsinki, and it is an optional course in the Radiochemistry subdiscipline. The prerequisites for the course were that every student needed to have studied radiochemistry to a basic level (which is offered to bachelor students and new masters students at the University).

The objectives of the course were: 1) students can explain the different ways to produce radionuclides and to pick up a suitable production method for a specific radionuclide;
2) explain how radiotracers can be used in biomedical applications and drug discovery; 3) choose the optimal radionuclide for tracer studies.

The course included lectures, hands-on experience with research methods, reading assignments, group work, and individual experimental data analysis. At the end of the course, students wrote a learning reflection on the whole course. All activities and tasks were designed to support the learning of professional modern research skills and practices.

One of the course's main themes was to learn both the old and the modern research methods in radiopharmacy. In radiochemistry, autoradiography is a technique that is used widely to study the local distribution of radioactive isotopes. The distribution of the isotopes in different objects and organs was studied by exposing it to X-ray films. Further, to improve image quality and the quantitative analysis of radioisotope distribution, digital autoradiography methods were developed based on the phosphor imaging plate, a two-dimensional (2D) radiation detection, and recording medium. Digital autoradiography image intensity is measured as a dimensionless quantity, photostimulated luminescence (PSL) that is linearly proportional to radiation dose and improves image quantification.

A new advanced technique in autoradiography is digital real-time autoradiography[32,33]. BeaQuant – real-time autoradiography gives radiochemists freedom to measure radioactivity distribution in real-time with very high resolution and sensitivity with much shorter exposure time.

Students' were introduced to these different methods through hands-on exercises, and they had to write a report in which they were asked to consider and compare two research methods for their reliability, opportunities, and challenges.

Applications of autoradiography are relevant in preclinical research like whole-body autoradiography and micro-autoradiography as well as in clinical research related to PET and SPECT diagnostic imaging. Radiopharmaceutical chemistry education is highly vocational relevant in developing new radiologic diagnostics and therapy.

This case supports vocational level relevance if the student intends to seek a radiopharmaceutical career. Societal relevance is clear because health and medical industries are essential for society. On the individual level, students' who enroll in this class already find radiochemistry quite interesting.[14]

CONCLUSIONS

Our study indicates future radiochemists experienced their study field as a highly relevant chemistry field (see Table 1). They felt that radiochemistry topics are interesting (individual relevance), the field has a great societal impact through e.g. radiopharmaceuticals, energy solutions, and environmental safety (societal relevance), and their professional future is clear e.g. a job in the industry (vocational relevance). Our results differed from the findings of Ogunde et al.[19]. This may reflect that fact that respondents in this study were mainly master's level students. In Ogunde's research, participants were bachelor's-level chemistry students and their professional self-image was not as clear as it becomes at the master's or PhD levels.

The individual dimension can be supported by selecting topics that students find interesting[18]. The described radionuclide production and tracer techniques course at the University of Helsinki is an example of a study context that students experienced as being relevant. One potential solution for developing relevant contexts could be constructing study settings that can be experienced as relevant in multiple ways at the same time. For example, using authentic and topical research cases that are societally relevant whilst also presenting a clear radiochemistry career option.

According to our data, both the vocational and societal relevance dimensions were clear in radiochemistry. Future radiochemists experienced that the industrial and environmental perspectives are important for society and they will offer clear career options after graduation. Both dimensions can be supported through real life case examples e.g. using environmental problem examples or techniques used in the industry. Knowledge of different careers can also be strengthened by inviting expert talks from academia, industry, and government. Speakers from different backgrounds could be invited to the courses so that as many students as possible could identify with the role models[27,29].

These two aspects could be useful in student recruiting and supporting study persistence / reducing drop-out rates. As Marteel-Parrish & Lipchock[22] mentioned, understanding the societal role of chemistry will be an essential skill in the future and future radiochemists clearly appreciate the contribution of the field to the healthcare, pharmaceutical, and energy industries. If students better understand radiochemistry and its relevance during their bachelor's degree, and that radiochemistry offer clear and secure jobs for chemists, it could motivate them to enroll in the further radiochemistry studys[19,24]. In turn, this may help address the radiochemistry recruitment crisis.

Table 1. Summary: The Relevance of Radiochemistry Studies.

Dimension	Perspective	Description	How to support?
Individual	Intrinsic	- Radiochemistry and radiopharmaceutical research are interesting, modern chemistry. - Important, wide-ranging knowledge (e.g. theories and laboratory techniques) can be gained.	- Choose interesting subject materials with topical context. - Show modern research techniques / instrumentation.
	Extrinsic	Aiming to good grades.	
Societal	Extrinsic	- Radiopharmaceuticals have a great societal impact through the healthcare and pharmaceutical industries. - Radiochemistry knowledge is important in solving energy and environment nexus and for supporting nuclear safety.	- Invite guest lecturers. - Conduct field trips, and make sure companies and governmental radiation agencies are represented. - Introduce authentic research examples in areas of major societal importance (e.g. nuclear accident response or radioactive waste disposal).
Vocational	Intrinsic	Many industries offer job opportunities for radiochemists.	- Support students' networking towards industry.

From the data point of view, the reliability of this research is acceptable, because the observed perceptions of relevance seemed to saturate during the analysis. However, the instrumental validity of the research could have been strengthened via in-depth interviews. When the findings of this qualitative study are applied in different settings, it should be noted that they are applicable only in this university-specific case setting and should not be generalized. For future research, we recommend that these perceptions of relevance are used in designing relevant radiochemistry learning environments and courses. These designs can be used as the research context for investigating if they have a positive effect on bachelor's level chemistry students' motivation for choosing radiochemistry as their chemistry major. There is also need for more research on the perceptions of experienced relevance with a larger data using quantitative methods. Through the quantitative research setting it would be possible to measure the statistical significance of the findings made in this qualitative research. Perceptions could be gathered from bachelor's level students to radiochemists in their early career. Research should be conducted in multiple countries and universities, because all universities have some specific focus on their radiochemistry research program and teaching which will impact on the experienced relevance.

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AUTHOR INFORMATION

Corresponding Authors

*E-mail: johannes.pernaa@helsinki.fi and sanjeev.ranjan@uef.fi

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