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How to promote chemical literacy? On-line question posing and communicating with scientists

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Facilitating students' chemical literacy is a focal point of current science education. This study examines views of chemists and chemistry teachers on chemical literacy and, more broadly, on scientific literacy of four kinds of stakeholders: scientists, teachers, STEM students, and the educated public. We explored the views of 347 participants, representing the four stakeholder groups with diversified scientific literacy, and an *Ask-a-Scientist* public website as a communication channel for facilitating chemical literacy through posing questions. Research tools included interviews, open-ended questionnaires, and questions retrieved from the website. We found that the questions posed on the website expressed a range of levels of chemical literacy that the students had constructed. The stakeholder groups expressed diverse perspectives of their experiences using various types of communication channels, arguing for the need to encourage students to pose questions and receive scientists' responses. Our study is placed in the larger context of scientific literacy and communication channels, as it takes the example of chemical literacy, with a focus on communications among scientists and chemistry teachers in the context of an *Ask-a-Scientist* website. It has established a link between responses of various stakeholders and the literature definitions regarding scientific literacy with focus on chemical literacy. From a practical viewpoint, the study presents a productive communication channel for posing questions in the context of chemistry and other sciences. Methodologically, this study includes the design of tools for analyzing both the views of different stakeholders and for evaluating the complexity level of chemistry questions, which might serve chemistry educators.

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Introduction

Science education standards (*e.g.*, AAAS, 2013; NGSS Lead States, 2013; NRC, 2012, 2013) in USA and chemical educators around the world (*e.g.*, Dori and Herscovitz, 1999; Dori and Sasson, 2008; Talanquer and Sevian, 2013; Sjöström and Eilks, 2018) underscore the need for developing K-12 students' scientific literacy in general and chemical literacy in particular. The need for scientific and chemical literacy amongst K-12 students is justified by three reasons: economic and political involvement, practical personal reasons, and cultural reasons relating to ideals, values, and norms (Avargil *et al.*, 2013). The ability to understand, and critically evaluate ideas and arguments in the media pertaining to chemistry content, enables one to cope with situations that citizens are likely to encounter in real-life scientific and technological contexts which surround them (Baram-Tsabari and Segev, 2011; Hofstein *et al.*, 2011; Shea, 2015; Pabuccu and Erduran, 2016). Formal science education provides the basis for scientific literacy in general, and chemical literary in particular (Gilbert and Treagust, 2008). Yet, formal science education in school and university settings may be insufficient to attain broader scientific and chemical literacy for all students, leaving them ill prepared to face societal challenges as future citizens (Herscovitz *et al.*, 2012; Tal and Dierking, 2014; Kohen and Dori, 2019).

Responding to the need for students to understand chemistry and its many implications for daily life, the US National Research Council—NRC (2013) Framework for K-12 Science Education calls for educators worldwide to be aware of opportunities to supplement formal classroom instruction *via* informal communication channels. Engaging in science through dialogue and interaction with science professionals can be valuable to students, as it enables them to understand the role of science and chemistry in their daily lives (Besley *et al.*, 2015). Indeed, in recent years, with rapidly advancing scientific developments and mass media outlets having become the dominant purveyors of information, we have witnessed a shift of scientists from only practicing science to becoming significant distributors of

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scientific information to different science stakeholders through the mass media in its various forms (Brossard, 2013). In the context of chemistry, researchers have pointed to the importance of associating chemistry knowledge with daily life phenomena in order to make abstract chemical concepts more concrete (*e.g.*, Pabuccu and Erduran, 2016; Sevian *et al.*, 2018). This raises the need for reliable channels of communicating science to the public. According to previous research, active participation *via* various communication channels which provides an opportunity to be in direct contact with scientists, has the potential to promote scientific literacy (McCallie *et al.*, 2009; Ogawa, 2011).

A keyword-based literature review, conducted by Kohen and Dori (2019), which explored the literature of science communication and science education, pointed to disparities that highlight the need for and importance of narrowing the gap between the two communities. This review provides the basis for establishing three themes that are common to the two disciplines: (a) attitudes towards the importance of science communication, (b) communication channel types, and (c) scientific knowledge construction. The current study focuses on the last two themes with the elaboration of scientific knowledge construction to the dimension of scientific literacy and particularly chemical literacy. In this study, we elaborate on the concept of scientific knowledge construction as a dimension of scientific literacy with focus on chemical literacy. According to our literature review (Kohen and Dori, 2019), scientific knowledge is seen as a product of a dialogue between scientists and other stakeholders who are interested in gaining scientific knowledge. Ogawa (2006) has designated the scientists, science educators, science communicators, and pro-science public as 'pro-science' groups. In this study, we targeted four kinds of stakeholders: scientists, teachers, STEM students, and the educated public.

Moreover, productive communication suggests understanding of various stakeholders' views about the effectiveness of the activities that a communication channel offers (Schibeci and Williams, 2014). Therefore, the current study aims to explore various stakeholder views regarding scientific and chemical literacy that are communicated *via* informal communication channels. We then explore the effectiveness of posing questions to scientists by teachers, STEM students, and the educated public *via* an *Ask-a-Scientist* website on developing their scientific and chemical literacy. We explore an *Ask-a-Scientist* website, called *At-the-Gate* (In Hebrew: "*BaSha'ar*", http://www.bashaar.org.il/). This website is a communication channel created by scientists for the facilitation of scientific literacy of the public at-large. It enables students and the STEM-oriented public to pose questions to vetted scientists, who respond reliably and clearly to these questions, promoting scientific literacy in topics such as hybrid cars, immunizations, and air pollution. In this study, we investigated (a) questions posed by chemistry teachers to promote their students and their own chemical literacy, and (b) views on chemical literacy held by chemists, chemistry teachers, STEM students, and the educated public.

Theoretical and conceptual framework

In what follows, we provide an overview of scientific literacy and chemical literacy. We then present literature concerning communication with scientists as a means for promoting scientific literacy, specifically using the *Ask-a-Scientist* communication channel type. We conclude with the literature on how to facilitate chemical literacy *via* question posing.

Scientific literacy

Scientific literacy and its construction are motivated by the need of citizens to become more knowledgeable about how to judge science-related issues in order to be able to make scientifically-informed decisions in a wide range of matters that impact daily lives (Ryder, 2001; Roberts, 2007; Dijk, 2011; Tal and Dierking, 2014). In the Framework for PISA 2015, De Jong (2012) refers to the required knowledge as "not just knowledge of the concepts and theories of science, but also a knowledge of the common procedures and practices associated with scientific enquiry and how these enable science to advance" (pp. 3–4). Researchers (*e.g.*, Miller, 1983; Norris and Phillips, 2003; Shwartz *et al.*, 2006) emphasize the necessity for using scientific knowledge for reaching high levels of scientific literacy. They define *scientific literacy* as being constructed from the following components: (1) understanding the core concepts of the natural sciences, (2) the ability to understand and critically evaluate scientific content, and (3) enabling members of society to cope with situations they are likely to encounter in real-life scientific and technological contexts (Roberts, 2007; Shea, 2015). The OECD (2006) underscores the significance of promoting scientific literacy, especially for young students, who will be the future citizens; by aligning the scientific skills and knowledge that are needed by citizens with those that schools actually teach.

Chemical literacy

Chemical literacy encompasses knowledge of chemistry and the skills needed for chemistry-based understanding of socio-scientific issues. It is comprised of three components: (1) key concepts in basic chemistry, such as elements, symbols, processes, and models, (2) understanding what professional chemists in academia and industry do, and (3) societal context—placing chemistry in real-world contexts (Holman, 2002; Shwartz *et al.*, 2013; Dori *et al.*, 2018). Shwartz *et al.* (2006) added to chemical literacy the affective component, which refers to expressing interest in chemistry-related issues. Other researchers (Avargil *et al.*, 2013; Dori *et al.*, 2018) argued for students and the general public need to gain chemical literacy, as it impacts civic, societal, and individual decision making. Yet, most chemical educators continue to emphasize teaching of rudimentary facts and theories, rather than fostering the skills and concepts that enable students to understand the significance of science in their daily lives. By fostering chemical literacy, students understand better the role of chemistry in their lives and society and acquire the skills to actively participate in the relevant civic and political debates (Bolte, 2008; Seery and McDonnell, 2013).

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Students' communication with scientists—the Ask-a-Scientist forum

Communication channels concern various means that enable the process of communicating science, which serves the purpose of disseminating scientific information to different stakeholders, primarily the general public (Schibeci and Williams, 2014). A study by France and Bay (2010) revealed that K-12 students who had direct discussions with scientists developed both scientific literacy and positive views of science and scientists. The researchers explain these findings by asserting that students' *posing questions* by their own to scientists helped them to bridge the gap between acquiring scientific knowledge and understanding its application in a lab compared to what they do in the classroom. Additionally, by creating a connection between what they had thought a scientist looked like in their mind and what a 'real' scientist looks like, students begin to recognize the value of having scientists in our society and may consider becoming one.

Traditional forms of public engagement with science involve public lectures, science fairs, festivals, and cafes (Bultitude and Sardo, 2012). New formats and opportunities for engaging stakeholders with science, both online and in-person, are emerging. These include taking part in social networks, an increasingly popular format amongst individual scientists (Besley *et al.*, 2015).

In the educational context, web-based media channels and advanced online platforms such as massive open online courses (MOOCs—online multi-participants courses), social networking sites (SNSs), or *Ask-a-Scientist* websites, are available to members of the general public with access to the internet. These channels provide individuals with opportunities to address questions directly to leading scientists in their fields of expertise and get reliable answers, find scientific information, gain general scientific knowledge, and interact with scientists.

The mass media is a major intermediary between scientists and the public (Brossard, 2013). Scientific studies of interest are presented in a simplified version through the media, which may (or may not) facilitate public understanding of complex issues (Brossard, 2013). Scientists communicate *via* these channels to various stakeholders in order to increase the stakeholders' interest in science (Baram-Tsabari *et al.*, 2006) and scientific understanding (France and Bay, 2010; Norris and Phillips, 2012), or in order to disseminate higher education courses to large audiences (Zutshi *et al.*, 2013).

Studies that were conducted on *Ask-a-Scientist* sites revealed that the internet may allow populations which generally lack access to quality science learning environments an equal opportunity to access quality, formal science education. For example, Baram-Tsabari *et al.* (2006) analyzed 79 000 questions sent to *Ask-a-Scientist* site over a decade, according to the question-poser's age, gender, country of origin, and the year the question was sent. The study demonstrated a surprising dominance of questions from female K-12 students; this differs from offline (in-person) situations, in which questions are commonly characterized by males who are perceived to have a greater interest in science.

Question posing for promoting chemical literacy

Fostering students' question posing capabilities by asking for solutions to real-world problems is a strategy for improving K-12 students' chemical literacy (Santoso *et al.*, 2018; Sasson *et al.*, 2018). Specific scaffolding acts should be implemented to encourage and guide students to pose complex questions (Dori and Herscovitz, 1999; Sevian *et al.*, 2018). As students' question posing skills improve, the number and the level of complexity of the questions asked increases. Herscovitz *et al.* (2012) have examined the effect of fostering chemistry students to pose complex questions and understand embedded concepts in scientific articles through distinct reading strategies. In short, guiding students in posing questions at their own level of chemistry understanding improved their abilities to pose complex questions independently.

Complexity of questions is determined by (a) the *type of information* requested, meaning the nature of the question and the knowledge it generates, and (b) the question poser's *understanding level* reflected in the question. The *type of information* criterion describes the nature of the question and the knowledge its response generates. The three information types feature gradual increase of the cognitive level reflected by the question, as follows (Baram-Tsabari *et al.*, 2006; Kaberman & Dori, 2009; Gai, *et al.*, 2019): (a) factual/explanatory—understanding questions that can be answered by providing general information or simple explanations; (b) methodological information—questions that require information on application or deeper explanations; and (c) predictions—analysis, evaluation, or inference questions requesting results of experiments or open-ended answers, related to opinions, controversial issues, or moral or ethical issues, for which science has no one 'correct' answer. Prediction is considered as the highest cognitive level as it posits that a student has the ability to identify the strategies that he/she applied in order to provide justification to the question asked. The *chemistry understanding levels* criterion is a scale comprised of the four chemistry understanding levels, featuring increasing difficulty and complexity, as discussed in previous studies (Treagust *et al.*, 2003; Dori and Sasson, 2008; Gilbert and Treagust, 2008; Herscovitz *et al.*, 2012; Dori *et al.*, 2018). The chemistry understanding levels are: (a) the macroscopic level, which pertains to the observable phenomena; (b) the microscopic level (also known as sub-microscopic), in which the explanations are at the particle level; (c) the symbol level, which comprises formulae, equations, and graphs; and, (d) the process level, which demonstrates understanding of what substances react with each other, and explanations of the process between reactants to create new products in terms of one or more of the first three levels.

For this study, we added the *system level* as a fifth chemistry understanding level. This level pertains to phenomena involving explanations that include the specification of chemical objects (*e.g.*, elements, molecules, solutions,...) and chemical processes that transform them (*e.g.*, chemical reactions and conditions for their occurrence) as part of a whole system in chemistry, biology, food engineering, or any other scientific

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domain or cross-disciplinary domains. We added this fifth, system level to the previous four, as it enables the identification of systemic synthesis questions, which were found to foster students' higher order thinking in chemistry and biology classes (Hrin *et al.*, 2017; Labov *et al.*, 2010). Specifically, it facilitates the identification of interdisciplinary topics, where organizational or system levels are crucial (Mayr, 1997). In our study, we refer to the system level in explanations that relate to the cell or the organ levels, a whole-organism level, or even the level of entire ecological systems all the way to global systems.

Below is a question that we classified at three chemistry understanding levels: macroscopic, microscopic, and the system level, as it combines (a) a phenomenon we can see, (b) elements, and (c) a system of recycling, which involves both environment and chemistry domains: ''We are planning to use the water coming out of an air conditioner for watering plants. What elements should be added? Are elements such as N (nitrogen), K (potassium), and P (phosphorus) suitable?''

Research questions

We aimed to answer three research questions, of which the first and third relates to chemists and chemistry teachers, while the second—to the four stakeholder groups: scientists, teachers, STEM students, and the educated public. The educated public in this study is comprised of a subset of the public, liberal arts and social sciences undergraduate students, who are mostly not scientifically oriented.

RQ1: How do chemists and chemistry teachers who communicate with the public *via At-the-Gate* website view chemical literacy?

RQ2: What are the views of the four kinds of stakeholders on scientific literacy and communication?

RQ3: How do the questions chemistry teachers posed to the *At-the-Gate* website reflect their chemical literacy, as expressed *via* the scientific communication exchanges between them and the scientists?

Method

Research setting—the *At-the-Gate* website

At-the-Gate is an Israeli academic website that gives teachers, students, and anyone with access to the internet the opportunity to pose questions directly to leading science faculty and researchers in Israel in their respective fields of expertise. The director of the *At-the-Gate* website transfers the users' questions to the appropriate science experts. This process is described in Fig. 1. While this website is targeted at Hebrew speakers only, websites of a similar nature in English and other languages exist. We compare and contrast the *At-the-Gate* website to several other key websites targeted at English speakers (see Part B of the findings).

Over a decade, about 1800 questions were asked *via* the *At-the-Gate* website, in the fields of chemistry (N = 399), biology (N = 944), physics (N = 323), engineering (N = 28), and environmental sciences (N = 132). The current study focuses on the 399 posted questions that are chemistry-related, accounting for 23% of all the questions.

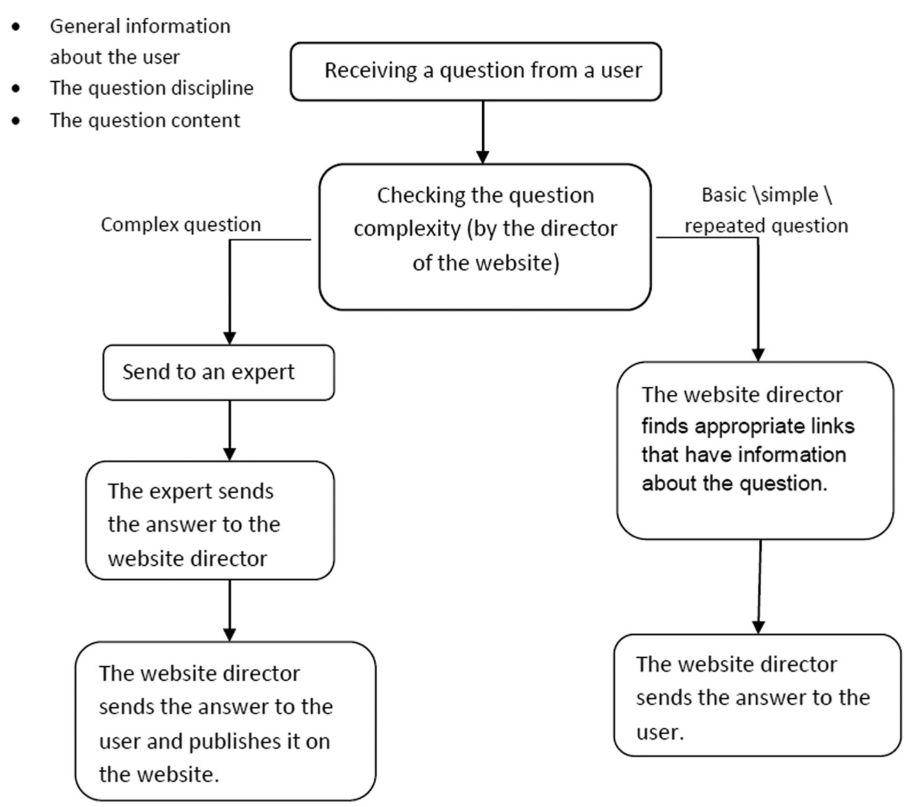

Fig. 1 The *At-the-Gate* website Q&A process (Abed, 2013).

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Research participants

We investigated four stakeholder groups, which included 347 participants. The stakeholders are: (1) scientists, (2) science, technology, engineering and mathematics (STEM) undergraduate students, (3) teachers, and (4) the educated public. Part of the scientists and the teachers (as following detailed) were experts in chemistry and active participants in the *At-the-Gate* website, thus served as the stakeholders for responding to the first research question. The participants within each stakeholder group were chosen to represent diversity of gender and years of experience, and where applicable, scientific discipline.

As noted, in addition to the interviews and questionnaires for the four research groups, another source of data collection in our study were the questions posed at the *At-the-Gate* website. These users of the website are provided with an opportunity to directly interact with scientists and ask questions regarding scientific issues. The questions are uploaded to the website anonymously, and only the website master has access to personal details of age, workplace, *etc.* The scientists' answers are not anonymous, so those who pose the questions can see who responded. For the current study, we received an approval from the Technion Research Ethics Committee for Behavioral Sciences (Institutional Review Board—IRB committee) for the data collected from the various stakeholders (ACCOR-2014). In addition, the *At-the-Gate* management board agreed to send the emails to their users and provide us with the data of the *At-the-Gate* website users without exposing any of their personal details. These details were only used to describe the question poser population at large, but not to identify each participant individually. Informed consent was obtained from all the study participants, including the *At-the-Gate* website director. Following is a description of each stakeholder group:

(1) *Scientists* (N = 27)—we use the term 'scientist' to refer to university faculty members or researchers. We sent emails to 40 scientists from six (out of the eight) major universities and the three top research institutes in Israel in diverse areas, so they represent the Israeli scientist population by workplace and domain. These scientists are experts in chemistry, physics, biology, agriculture, environmental science, medicine, engineering, and/or technology. They hold senior positions, and many of them have been involved in nationwide forecasting and science and engineering policy-making for higher education. Of the 40 scientists approached, we received responses from 27 (68% response rate), who indicated their willingness to participate in this study. Of these scientists, 74% were male university professors. About 50% of the scientists who participated were volunteers who actively contributed to the *At-the-Gate* website, one of whom was the website initiator. About 15% of the scientists were chemists. Those scientists who actively participated, responded to questions in their respective domain of expertise to questions posed *via* the site by K-12 students and teachers. Since scientists were the most difficult participants to recruit and were the smallest population, to ensure their participation, we interviewed most of them in person or by telephone, while the rest of the stakeholders responded to an online questionnaire.

(2) *STEM undergraduate students* (N = 146)—we sent an online questionnaire to undergraduate and graduate STEM students at a technological institute. About 20% of the students (N = 30) used the website frequently. Most of the students were single majors BSc students (83%), BSc double major students (15%), or MSc students (2%). About half were males (52%). The students' average age was 37 years (SD = 9.29). Of the questionnaires distributed, 88% responded.

(3) *Teachers* (N = 117)—we sent an online questionnaire to teachers, of whom one third (N = 43) were chemistry teachers and the rest were *At-the-Gate* website users—either STEM teachers or teachers of non-STEM subjects. About 60% of the teachers were MA students. About one quarter of the teachers were males. The teachers taught in elementary school (22%), junior high school (8%), and high school (61%). The rest of the responding teachers (9%) were not teaching at that time. Their average teaching experience was 12 years (SD = 8.2). Of the questionnaires distributed, 75% responded.

(4) *Educated public* (N = 57)—we sent an online questionnaire to first year undergraduate students who studied social science, specifically criminology and political science, at a liberal arts and science university. In this study, they represented the educated public, as they are more scientifically literate than the general public, with low or intermediate level of scientific literacy and their age was 25 years and up, with average age of 30 years (SD = 7.8). These were BSc students (83%) and MA (17%) students. About half (49%) were females. Their work experience ranged between beginners to 16 years, with an average of 4.5 years (SD = 3.8). The response rate to the questionnaires was 82%.

Research tools

Research tools included interviews and an open-ended questionnaire, as well as chemistry questions posed on the *At-the-Gate* website. The interviews and the open-ended questionnaire served to investigate the various stakeholders' views, while the questions in chemistry served to assess the facilitation of scientific literacy, and particularly chemical literacy (see elaboration in the data analysis section). Following the conceptual frameworks of scientific and chemical literacy (Miller, 1983; Holman, 2002; Norris and Phillips, 2003; Shwartz *et al.*, 2006, 2013) and scientific communication (Schibeci and Williams, 2014), the authors of this paper designed the interview protocol and the open-ended questionnaire to explore aspects of expert views on scientific communication, including engagement, knowledge and scientific literacy construction, communication, and research practice. Explanations about each aspect and an exemplary question from our interview protocol and questionnaire are presented below (see Appendix A for additional questions).

(a) *Scientific literacy construction*—the stakeholders were asked who should participate in constructing scientific literacy, why, and in what ways. One question for example was: *How should scientific literacy be constructed for better public understanding?*

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(b) *Communication channel types*—the stakeholders were asked questions relating to ways of engaging with stakeholders and the modes of communication used in these exchanges. Example: *Through what channels can communication between the scientists and the public be promoted?*

The chemists and the chemistry teachers who were users of the *At-the-Gate* website, were asked additional questions, including: *What do you think about the At-the-Gate website in terms of promoting academia-community relations?* [relating to *Communication channel types*] *What are the contributions of this website in terms of chemical literacy* [relating to *Scientific literacy construction*]?

Inter-judge content validation was conducted for these measures. Two science education experts were asked to express their opinion on the extent to which the questions in both the interview protocol and the questionnaire represent the conceptual frameworks that underlie this study. In this process, we modified and added some of the questions, until fully agreement on the exact phrasing of the questions was reached. Additionally, the interviews and questionnaire were tested in a pilot study with representative groups who were not among the participants of this study, in order to determine whether the questions and the vocabulary we used, were interpreted by the participants correctly and answered what was asked coherently.

In order to convey the questions and answers in the *At-the-Gate* website, as well as the questions in the interviews and the open-ended questionnaire, written originally in Hebrew, we translated them to English. To this end, we used the guidelines for reporting research data in a language other than English, published at the CERP journal (Taber, 2018). The quality of the translation was assessed by two professors, a chemist and a chemistry educator. Both are experts with more than 30-year experience in teaching chemistry at the undergraduate level and fluent in both Hebrew and English. Table 1 summarizes the research tools and their relations to the research questions and participants.

Data analysis

To answer the first and second research questions, we carried out content analysis of the open-ended responses for both the interview transcripts and the questionnaires. This analysis was based on Carey *et al.* (1996) and Hsieh and Shannon (2005) methodologies for data analysis. Based on the various stakeholder responses, we created a list of categories, which is also in line with the literature on chemical and scientific literacy. For RQ1, the chemists' responses yielded the following categories: (1) encouraging students to study science, (2) breaking down the barriers between academia and other stakeholders, and (3) contribution to teachers and students in their daily life and in their work or studies (Dori *et al.*, 2018; Shwartz *et al.*, 2006; Holman, 2002; Shwartz *et al.*, 2013). For RQ2, the responses of the four groups of stakeholders yielded the following categories: (1) expanding knowledge and understanding of core concepts, (2) gaining practical experience and understanding what professional chemists do, (3) getting different perspectives *via* placing chemistry in a real-world context, (4) promoting interest and confidence, and (5) personal involvement (Miller, 1983; Norris and Phillips, 2003; Shwartz *et al.*, 2006).

Further, we created a list of categories of scientists' communication ways with reference to relevant literature (Baram-Tsabari *et al.*, 2006; France and Bay, 2010; Schibeci and Williams, 2014). For RQ1, the following categories emerged from the chemistry teachers' responses that referred to communicating science *via* the *At-the-Gate* website: (1) general usefulness of the website, (2) satisfaction from the answer received, (3) the website benefits, and (4) suggestions for improvement of the website. For RQ2, the four stakeholder groups viewed communicating science through the following communication channel types: (1) using mass media, (2) writing popular articles, (3) being socially involved, (4) being available and willing to engage with the public, (5) sharing scientific materials, and (6) open discussions.

We assessed the reliability of these categories based on a selected portion (15%) of the responses. These were coded independently by three science and chemistry education experts, until achieving over 90% agreement after two coding rounds. Having achieved reliability of this encoding, the stakeholder responses were randomly divided and provided to the three experts, so each expert coded about one third of the responses. Since the questions in both the interview and the questionnaires were open-ended, some of the participants' responses related to just one category, while others—to more than one. We divided each response into segments, each representing an idea or a concept related to a specific category. We then counted the number of times each category appeared for each one of the stakeholder groups, calculated the percentage

Table 1 Research questions, tools, and participants of the research

Research questions	Tools	Participants
RQ1: How do chemists and chemistry teachers who communicate with the public *via At-the-Gate* website view chemical literacy?	• Interviews • Open-ended questionnaire	• Chemists from the academia • Chemistry teachers
RQ2: What are the views of the four kinds of stakeholders on scientific literacy and communication?	• Interviews • Open-ended questionnaire	• Scientists • STEM undergraduate students • Teachers • The educated public
RQ3: How do the questions chemistry teachers posed to the *At-the-Gate* website reflect their chemical literacy, as expressed *via* the scientific communication exchanges between them and the scientists?	• Chemistry questions posted on the *At-the-Gate* website	• Chemists from the academia • Chemistry teachers

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of segment appearances in each category, and compared the distribution of each stakeholder group with the other stakeholder groups based on these percentages.

Regarding the third research question and the analysis of the chemistry questions posted on the *At-the-Gate* website, we created a rubric by coding each question according to three criteria of question posing established in the literature for promoting chemical literacy (*e.g.*, Treagust *et al.*, 2003; Baram-Tsabari *et al.*, 2006; Dori and Sasson, 2008; Gilbert and Treagust, 2008): (a) discipline or a combination of disciplines—chemistry combined with biology, physics, industrial, or environmental science; (b) *type of information*—factual/explanatory, methodological, or prediction; and (c) *understanding level*—micro, macro, symbol, process, system, or some combination thereof. Criteria (b) and (c) indicate different aspects the question's complexity and difficulty levels.

Four science education experts, of whom two were chemistry education experts and two graduate students, assigned each question into the various categories. We assessed the reliability of these categories based on 15% of the questions in several rounds of coding and discussions, until over 90% agreement between all experts was achieved. Then, we assigned the chemistry-related questions posted on the *At-the-Gate* website randomly to the two graduate students, so each coded about half of the questions. We counted the number of times each category appeared and calculated the percentage of each category for all the posted chemistry-related questions.

In what follows, we present an example of a question, and the use of the rubric for the appropriate categorization. "*Is there a difference in conductivity of two easy-dissolving salts being in the same temperature and having the same concentration? If there is, what factors affect the conductivity of these salts? If there is no difference in conductivity, what is the reason?*" This question expresses the interaction between two science disciplines: chemistry and electrical engineering; the information included in the question expresses the prediction type of information, as it seeks to find the relationship between chemical properties such as solubility and their conduction, which is an electrical engineering feature, thus the understanding level expressed in this question refers to the micro and macro levels for type of information.

Findings

We present our findings in three parts. Part A includes findings pertaining to the first research question, regarding views about chemical literacy as reflected in the communication between chemists and chemistry teachers *via* the *At-the-Gate* website. Part B presents findings related to the second research question—the communication in the wider set of stakeholders, by classification of the views of the four stakeholder groups regarding *scientific literacy construction*. We also report the views of these stakeholder groups on *communication channels types*, to figure out where a website like *At-the-Gate* fits into the array of resources that different stakeholders use or trust for gaining scientific literacy. We also compare and contrast the *At-the-Gate* website with several websites of similar nature. Finally, Part C presents findings pertaining to the *types of questions* posed and answered in the communications between scientists (chemists) and chemistry teachers.

Part A: views of the At-the-Gate website as a communication channel for promoting chemical literacy

We asked chemists and chemistry teachers to describe their experiences with using the *At-the-Gate* website as a venue of communication for promoting chemical literacy. Analyzing the responses in view of the literature on chemical literacy, we identified different categories that arose from each stakeholder group's responses.

Regarding chemists' views, we found that scientists mostly capture the effectiveness of the website as a communication channel in three main categories: the first category mentioned by most of the scientists (about 75%) referred to encouraging students to study science, as one of the scientists said: "*One of the activities of 'At-the-Gate' is to give lectures to students in schools, because we want to influence them to study science and engineering. We focused on science lectures more than on humanities lectures*" [S3]. The second category referred to scientists' wishes to break down the barriers between the academy and the different set of stakeholders, *e.g.*, "*We sat together, college professors, and discussed what we should do with science education. We want to break down barriers and encourage high school students to meet professors. We want to break down the boarders that exist between 'students from periphery or minorities?' and 'professors', and to provide accessibility for academic people to the community. We hope that students will not be afraid to think about higher education*" [S1]. Another example statement involves the feedback received from teachers: "*We always receive feedback from teachers, in which they thank the 'At-the-Gate' website for supporting them. [The teachers] always mention that the answers helped them to understand certain issues and to expand their knowledge*" [T58]. The third category referred to the contribution of the website to teachers and students in their daily life and in their work or studies. In daily life, the website provides its users with explanations to simple phenomena they encounter; and, regarding their work or studies, the website gives them explanations of chemical phenomena. This communication process contributes to enhancing teachers' and students' chemical literacy. The following is an excerpt from an interview with one of the scientists: "*Teachers and students posed questions that arose from their daily life, some are basic level questions and others are high level questions. The basic level questions relate to phenomenon from daily life, while the high-level questions relate to scientific studies, such as phenomena that occur in outer space*" [S8].

Regarding the chemistry teachers, we found that their views spanned various categories of the website as a communication channel. The categories and the percentages associated with them are as followed: (a) general usefulness of the website (23%), *e.g.*, "*[The website] contains a wide range of questions*" [T43]; (b) satisfaction from the answer received (23%), *e.g.*,

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"*I received a detailed answer in short time*" [T67]; (c) the website benefits (43%), *e.g.*, "*It is very helpful for teachers and students, it makes the job of teachers easier*" [T78]; and (d) suggestion to improve the website (11%), *e.g.*, "*The website can be promoted also by developing a website chat between the user and the expert*" [T12]. We also ascertained that the chemistry teachers' views were divided regarding the contribution of the website to improving their professional development, or to enhancing their chemical literacy. About 60% of the teachers indicated that the *At-the-Gate* website contributed to their chemical literacy to a small extent (see Appendix A for the full research tool). These views were demonstrated in statements such as, "*There is no relationship between the question and my profession*" [T34], or "*I have received an answer to a very specific question*" [T97]. While other teachers (about 40%) referred to high effectiveness of the website as promoting their chemical literacy, *e.g.*, "*Now my knowledge is more accurate and more complete*" [T40] or, "*Now I have a framework that provides me with answers to questions related to my profession; previously I had no source to turn to*" [T75].

Part B: analysis of four stakeholder groups' views of scientific communication

In Part B, we present two sections: (1) scientific literacy construction, and (2) communication channel types. Here, we extend our investigation from chemical literacy to scientific literacy as we expand the participants' number and diversity. For each of the stakeholder groups, in each section, we show the distribution of responses corresponding to the aspects or categories that arose from the content analysis of the interviews and the open-ended questionnaire and provide examples.

Scientific literacy construction

We asked stakeholders to describe their experiences and characterize the scientific literacy that should be shared and constructed by the public. Analyzing the responses in light of the literature on scientific literacy with focus on chemical literacy, we identified five *scientific literacy construction* categories: (1) expanding knowledge and understanding core concepts; (2) gaining practical experience and understanding what professional chemists do; (3) getting different perspectives *via* placing chemistry in a real-world context; (4) promoting interest and confidence; and (5) personal involvement. The first three categories focus on the cognitive components of learning science, while the last two categories refer to the affective components. Fig. 2 presents the distribution of categories within the *scientific literacy construction* aspect, which emerged from the stakeholders' responses.

Within the *scientific literacy construction* aspect—when comparing the stakeholders' views regarding the cognitive and affective components for sharing and constructing scientific literacy—we discovered that the STEM students valued almost equally the cognitive components (53%) and the affective components (47%). However, the affective components of scientific literacy construction were less favored by the teachers (40%) and even less by the scientists (27%) or the educated public (25%).

In order to examine the distribution of the different segments for the cognitive and affective components, we performed Chi-square tests of independence. The distribution of the cognitive

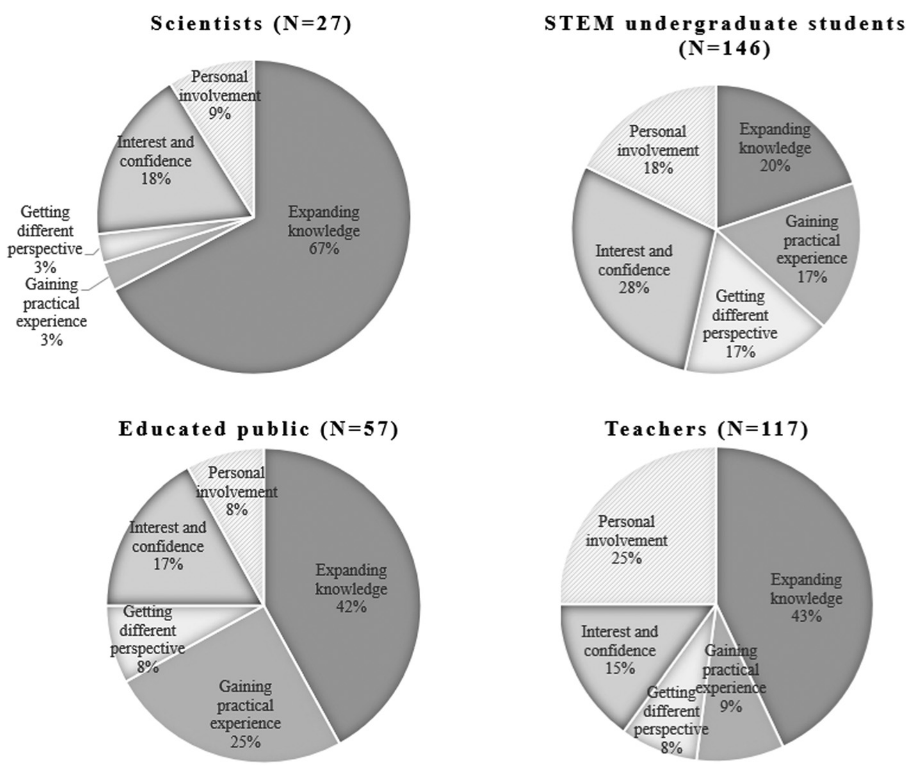

Fig. 2 Distribution of categories within the aspect of *scientific literacy construction*.

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components was significant ($\chi^2(6)$ = 23.91, p < 0.001). STEM students were in favor of diversifying the ways of *scientific literacy construction*, while the educated public (42%), teachers (43%) and even more so scientists (67%), preferred mostly the basic category, *expanding knowledge and understanding core concepts*. One physicist's response is exemplary of a common theme among the scientists surveyed: "*The knowledge gap between scientists and the public today is clear, and this gap will increase with time. The public should trust the experts in their fields... scientists should give access to the information responsibly and objectively*" [S23]. This quote demonstrates scientists' desire for the public to understand core concepts as a key part of their scientific literacy. The literacy component pertaining to the *gaining practical experience and understanding what professional chemists do* was emphasized mostly by the undergraduate students. For example, one of the educated publics wrote: "*Scientists have the ability to provide me with the tools I need for my professional development*" [SS42]. The category of *getting different perspective via placing chemistry in a real-world context* was almost completely ignored by the scientists, the teachers, and the educated public, with percent ranging from three to eight per cent. However, 17% of the STEM students perceived it as important to scientific literacy construction, as one of them said: "*A relationship with a scientist has the potential to develop the ability to cope with difficulties, learning what is important, and what are independent learning and critical thinking...*" [SS42]

The distribution of the affective components of scientific literacy construction was not significant ($\chi^3(3)$ = 3.88, p > 0.05), indicating a similar distribution of the categories among the different stakeholders. Yet, excluding the teachers, who presented the opposing views of the affective components, mostly the STEM students, favored more the way of *promoting interest and confidence*, rather than *personal involvement*. One of the science education experts interviewed said, "*our job is to do everything in order to provide access to science to the general public and especially to students, including those who did not choose to major in science. There should be a focus in the curriculum on the relevance of science to daily life for encouraging students to be interested in science and understand that everything around us is science...*" [S20].

As for the teachers who also discussed the *personal involvement* category as an important factor in the construction of scientific literacy, one of them wrote: "*Communicating with scientists can contribute personally, as scientists might be role models for me*" [T14].

Communication channel types

We asked stakeholders to express their views toward what types of communication channels can be used for communicating science to different stakeholders. Analyzing the stakeholders' responses, we identified the following six categories for *communication channel types*: (1) using mass media, (2) writing popular articles, (3) being socially involved, (4) being available and willing to engage with the public, (5) sharing of scientific materials, and (6) open discussions. We classified a segment (of a response) expressed by a stakeholder as referring to using mass media (category 1) only if the term *media* was explicitly mentioned, otherwise, the segment was classified as describing one of the other channel categories. Fig. 3 shows the distribution of categories within the *communication channel types* aspect by the four stakeholder groups.

Calculating the average number of segments related to communication channels per stakeholder within each group, we found that scientists had the highest average number of segments (M = 1.3, SD = 0.63), while teachers had the lowest (M = 0.85, SD = 0.46). STEM students (M = 1.1, SD = 0.74). The educated public (M = 1.1, SD = 0.77) had a similar average number. Overall, we found a significant difference in the average number of segments between the four stakeholder groups for this aspect (F(3,338) = 5.85, p < 0.001), implying that the scientists were most aware of the variety of channels for communicating with the public. However, exploring the scientists' preferred communication channels, we discovered that, like the other stakeholders, the *open discussions* category was their most favorable way of communicating science (40%). An example of applying this channel of communication is the following quote by a scientist: "*I don't think that there is one-channel of communication between scientists and the public. For example, in the Researchers' Night, many people came to my stand and to my lab and asked questions. Anyone who was interested in science could have come and ask for information and we discussed it together*" [S10].

The second most preferred communication channel among the scientists was mass media (23%). An educational technology expert said: "*The media nowadays is the largest resource and the most available channel for reaching the public. I realized that if you are not in the 'media' it means you do not exist... Scientists should use the television and the radio channels in addition to all the popular websites, such as YouTube, Facebook and LinkedIn, for creating maximum exposure of the public to news of science and engineering*" [S20]. This type of channel was less preferred by the STEM students and was almost ignored by the teachers and the educated public.

Another category that was prevalent among both the scientists and the STEM students was *sharing of scientific materials*. One of the STEM students commented that: "*Professors and students in advanced degrees should display their most recent studies so the public can realize that it is applicative or relevant to the industry*" [ST39].

A communication channel that was prevalent mostly in teachers was *being available and willing to engage with the public* (41%). Expressing their opinions regarding this category, one teacher wrote "[the scientists should make themselves] ...*available to the public: The researchers from academia should give the public access to*... [their studies and] *the public should feel comfortable to contact them*" [T11].

Finally, *writing popular articles*, *e.g.*, publication of plain language studies and *being socially involved*, *e.g.*, shared cultural activities, were the least mentioned communication channels, with less than 15% relating responses.

These findings suggest that the various stakeholder groups distinguish between different types of communication channel.

As we were also interested in figuring out whether the *At-the-Gate* website represents a well-established communication channel venue, we compared and contrasted it with several websites of a similar nature, including *Newton Network*, *NASA Network*, and

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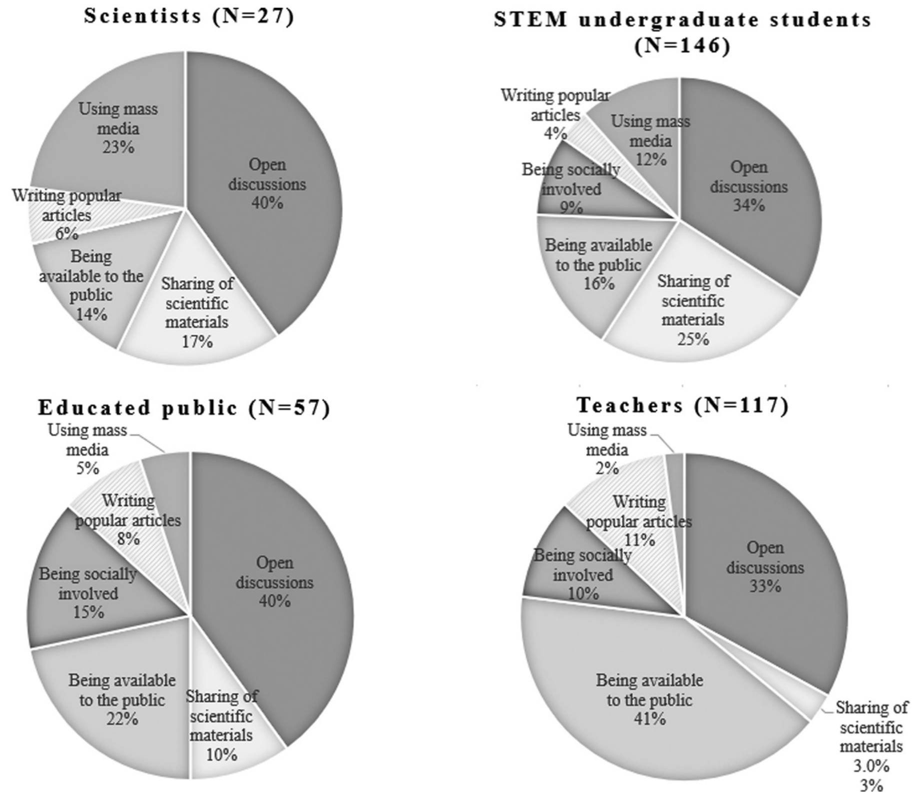

Fig. 3 Distribution of categories within the aspect of *communication channel types*.

Science Answers Network (see Appendix B). Key characteristics included (a) voluntary connections between users at different scientific and seniority levels, (b) coverage of various scientific domains and medicine, (c) request for basic information from the person submitting the question while the scientists usually identified themselves, and (d) additional activities beyond scientific question posing. Focusing on these characteristics, we have observed that the *At-the-Gate* website shares similar properties as other *Ask-a-Scientist* websites. One common property was that the responses to answers in the *At-the-Gate*, *Newton Network*, and *NASA Network* websites are provided by scientists in their respective fields of expertise, suggesting that the answers are reliable. Another is that the *At-the-Gate* and *NASA Network* websites offer additional activities beyond the asking scientists questions.

Part C: promoting chemical literacy *via* question posing in the At-the-Gate website: types of question posed

As Table 2 shows, we analyzed 399 chemistry questions posted on the *At-the-Gate* website between 2003 and 2012 and coded according to our rubric based on the following criteria: disciplines that the question involved, type of information requested, and the understanding levels required in the answer.

Table 2 shows that questions posted to the website exhibit different levels of chemical literacy, as represented in different types of information and understanding levels. About 50% of the questions were blended with other science fields, which points to the broad perspective of the question poser. The following examples are a variety of questions that represent the criteria described in the above table. We added the scientists' answers for each question to demonstrate the process of obtaining a reliable answer from scientists, as well as the validity of our criteria, as the scientists' responses related to these criteria.

Table 3 presents three examples of questions posted on the *At-the-Gate* website, their analysis according to the rubric in Table 2, and the answers that three chemists provided.

The first question in Table 3 is a basic-level [Factual] one, which relates to two literacy components: (a) *understanding*

Table 2 Frequency of chemistry questions according to different criteria (N = 399)

Discipline		Type of information		Understanding level	
Chemistry (Ch) only	320 (54%)	Factual/explanatory	372 (89%)	Micro & Macro	46 (12%)
Ch + Biology	62 (10%)	Methodological	23 (6%)	Symbol	224 (56%)
Ch + Physics	67 (11%)	Predictions	19 (5%)	Process	81 (20%)
Ch + Industry	28 (5%)			System	48 (12%)
Ch + Environmental science	122 (20%)				

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core concepts and (b) *getting different perspectives via placing chemistry in a real-world context*. It was posted by a teacher who wished to explain to her students an unexpected phenomenon in the behavior of elements in the periodic table. This chemistry topic is studied in high school, and therefore the teacher asked the scientist for more information. The scientist made an effort to adapt the complex answer to student's level of understanding, as the explanation contains no equations. However, his explanation is related to issues that are beyond the framework of chemistry classes in high school (Einstein's theory of relativity and Bohr model), thus is considered as a very high-level response.

The second question, also posted by a teacher, refers to the methodology of teaching chemistry, but at a higher level than the first one, as it involves the methodological, rather than the factual, description of chemical bonding. This question calls for promoting interest in chemistry as an example of an *affective* component *of chemical literacy*. The scientist's answer included a relatively simple and clear response, as well as a clarification question, since the scientist did not fully understand what compounds the teacher was referring to.

An early-career teacher, who was interested in understanding a daily-life question involving both chemistry and biology, asked the third question in this table. The scientist's answer was brief and required a low level of understanding. The chemical explanation was simplistic, as it referred only to the concept of oxidants and did not involve the processes at the molecular level. The second part of the question, pertaining to disinfection, remained unanswered. While answering this question could raise *chemical literacy in* the aspect of *real-world context*, it remained at the level of *core concepts literacy.*

Discussion

In this study, we have investigated the relation between the two dimensions of scientific literacy and communication among scientists and the public. In what follows, we discuss the views on chemical literacy of chemists and chemistry teachers who communicate *via* the *At-the-Gate* website scientific communication channel, as well as the broader views related to *scientific literacy construction* and *communication channel types* of four kinds of stakeholders. In our discussion of chemists' and chemistry teachers' views, we also discuss the *At-the-Gate* website as an established venue of communication *via* question posing.

Views of chemists and chemistry teachers as related to question posing for chemical literacy

For investigating the *At-the-Gate* website as a case in point for examining the relations between scientific literacy and communication among scientists and the public, we explored the

Table 3 Examples of questions posted in the *At-the-Gate* website, their analysis and scientists' answers

Question posted to the *At-the-Gate* website	Question analysis	Scientist answer
[T13] How can I explain to my students the fact that the chemical elements: gold and silver, appear in the same column in the periodic table (the gold is under the silver) but differ in their chemical activity, as gold hardly reacts with other substances? For example, a silver ring gets tarnished when exposed to air while a gold ring does not react this way.	Discipline: *Chemistry* Type of information: *Factual/explanatory* Understanding level: *Micro, Macro, & Symbol* [Bohr model]	Gold has a different chemical activity than could be expected from its neighboring elements within its group. Similar phenomena appear in other groups in the periodic table. This is due to influence of relativity. The Bohr model can give some explanation, according to the model, an electron spins around the nucleus in an orbit which is determined by the balance between its attraction to the nucleus and the centrifugal force. Calculating the electron velocity shows that in heavy atoms, the velocity is a significant part of the speed of light so relativity is of great significance in this process. According to Einstein's equations, the mass of a particle moving in increased velocity, causes, according to Bohr model, a reduction of the electron spin radius, so it is found closer to the nucleus, and thus will be more difficult to ionize. As a result, the Gold will be less chemically active than Silver.
[T37] Can you suggest an interesting way of showing students what chemical ionic and covalent bonds look like?	Discipline: *Chemistry* Type of information: *Methodology* Understanding level: *Micro & Macro*	I can think of, for example, regarding the difference in polarity, this is not a general case, but can help in more specific cases. More polar salts won't advance on TLC silica or alumina surfaces. In many covalent compounds there will be progress in the separation of the materials, but this is not always the case because there are many covalent compounds that are very polar (organic salts, *etc.*). Also, in many cases solubility in water or organic solvents, such as butanol, can help. The question should be more specific, for example: What are the types of compounds that you are thinking about?
[T56] I would like to know why iodine is used for disinfecting and what is the process involved?	Discipline: *Chemistry + Biology* Type of information: *Factual/explanatory* Understanding level: *Micro & Macro & Process*	Halogens are elemental oxidants that harm microorganisms. Bromine and Chlorine are strong oxidizers, in contrast to the iodine, which is much weaker oxidizer. Therefore, we use iodine for disinfection. It can be used for external injuries to prevent growth of bacteria.

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views of two stakeholder groups, who were active users of the website. The scientists we interviewed expressed a positive attitude toward the contribution of the *At-the-Gate* website to the benefit of facilitating teachers and K-12 students' chemical literacy both in their daily life and in their work or studies, meaning the opportunity of the website as providing sufficient chemistry knowledge, *i.e.*, the explanations of a phenomenon that is needed when encountered during implementation of a formal curriculum. This finding is encouraging, as the scientists succeeded to refer to current perspectives of chemical literacy. The scientists expressed views of the importance that various stakeholders (a) better understand what professional chemists do, (b) be aware of the societal context of chemistry within real-world contexts, and (c) be interested in chemistry-related issues, the role of scientists and their contribution to the community (Holman, 2002; Shwartz *et al.*, 2006; Shwartz *et al.*, 2013; Dori *et al.*, 2018). In order to achieve these goals, chemistry curricula should consider not just students' attainment of chemistry understanding, but also the knowledge of how to incorporate chemistry into daily lives in ways that members of the broader society are able to participate in discourse revolving around authentic chemistry, interest and needs (Baram-Tsabari and Segev, 2011; Hofstein *et al.*, 2011; Blanco-López *et al.*, 2015; Dori *et al.*, 2018).

The scientists emphasized the benefits of using the website for encouraging students to study and for breaking down the barriers between academia and the community. Specifically, this platform provides populations lacking access to quality formal science education an opportunity to be exposed to science (Seery and McDonnell, 2013). Indeed, France and Bay (2010) argued that relationships between academia and the community are necessary in negotiating and providing opportunities for teachers and K-12 students to connect with the world of science and with scientists.

The teachers who participated in our study and were active users of the *At-the-Gate* website expressed views on both the *Ask-a-Scientist* forum as a communication enabler with scientists (Baram-Tsabari *et al.*, 2006) and its benefits for expanding their knowledge and professional development (France and Bay, 2010; Norris and Phillips, 2012). Although their views regarding the benefits varied, they nonetheless expressed appreciation for the usefulness and benefits of the website as a communication channel. Some of the negative attitudes can be explained also by the overly high level of an expert answer, which made it difficult for some teachers to benefit from it. Indeed, researchers have agreed that scientists should undergo training in order for them to improve their ability to explain scientific phenomena and to better appreciate the discourse, thus being able to engage in dialogue with the public more (McCallie *et al.*, 2009). As future research, we suggest more in-depth exploration of scientists' engagement in informal communication channels. One way of such exploration can be analysis of scientists' responses posted on *Ask-a-Scientist* websites. Such analysis can serve as a basis for devising guidelines for valuable communication with various population groups.

The value of question posing to students' scientific literacy has been established in previous studies (*e.g.*, Sasson *et al.*, 2018). Question-posing activity in chemistry is reflected in students' inquiry learning, such as the ability to ask questions that explain, evaluate or justify their understanding (Kaberman and Dori, 2009; Santoso *et al.*, 2018). Yet, students' ability to pose complex questions that reflect high-level thinking is not trivial and requires support. The current study suggests that using an *Ask-a-Scientist* website as a science communication channel encourages students to pose questions. Our comparison of the *At-the-Gate* website with other *Ask-a-Scientist* websites of similar nature confirms that *At-the-Gate* is a well-established and useful communication channel.

The current study responds to the calls of the US National Research Council—NRC (2012, 2013) for engagement in science *via* informal communication channels. Indeed, we have shown that questions posted on the website represent different understanding levels and responses to the various question kinds require different types of information. This finding is in line with the literature on question posing as a promoter of chemical literacy (*e.g.*, Dori and Sasson, 2008; Gilbert and Treagust, 2008; Treagust *et al.*, 2003; Baram-Tsabari *et al.*, 2006). Since the questions were posed in informal settings, the question posing process in and of itself, even before getting the answer, has the potential of promoting the questioners' chemical literacy. The type of question and understanding level criteria we used to analyze questions in the current study play an important role in understanding how to advance chemical literacy of various population groups. This finding supports previous studies (*e.g.*, Kaberman and Dori, 2009; Herscovitz *et al.*, 2012), which concluded that as students' question posing skills improve, the complexity of the questions asked increases.

Analysis of scientific literacy construction and communication channels

Examining our findings regarding the experiences of four stakeholder groups with diversified scientific literacy—Scientists, STEM undergraduate students, teachers, and the educated public—we found that the various stakeholders have different views on scientific literacy and science communication. In what follows, we characterize the views of each stakeholder group.

(1) *Scientists*—among the stakeholders, scientists were most aware of the variety of channels for communicating with the public. Similar to the other stakeholders, their most favorable and prevalent ways to communicate science were *open discussions* and *using the mass media*. Engaging science through mass media is often challenging, due to lack of guidance for using various types of media for their curricular needs (McClune & Jarman, 2012). Our findings on the benefit of the *Ask-a-Scientist* website as a mass media science communication channel might motivate scientists' willingness to interact with other stakeholders (Besley, Dudo, & Storksdieck, 2015).

(2) *Teachers*—analysis of the teachers' responses exposed that they were the strongest proponents of *being available and willing to engage with the public*, specifically *via personal involvement*. This is in contrast to the other stakeholders who valued more *expanding of knowledge*. Influenced by the need to stick to

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the curriculum and teaching 'to the test', teachers are constantly struggling for more time, so their top priority is promoting knowledge. Yet, they are unable or not interested in gaining deep scientific understanding. Researchers (*e.g.*, Ryder, 2001, 2002) explain that teachers are aware of their own limited scientific knowledge, so they are likely to embrace the opportunity to get support from authoritative senior scientists. This points to the need to support teachers emotionally and encourage them to acquire sufficient knowledge in order for them to be more self-confident when they transmit their scientific knowledge to their students.

(3) *STEM undergraduate students*—the STEM students in our study were the ones who considered diverse ways in which scientific literacy should be constructed, both cognitively and affectively. We attribute these views to the STEM students' continuous interactions with scientists, who are also their professors, and to the associations these students often make between theory and practice in STEM subjects. Specifically, their exposure to different scientists' perspectives helps them require high levels of scientific literacy that demand a broad viewpoint, beyond knowledge of concepts and theories of science (De Jong, 2012). A similar exposure to direct interactions with scientists *via Ask-a-Scientist* websites, such as the one investigated in the current study, might contribute not just to the enhancement of scientific literacy, but also to more positive affective views toward sciences and scientists (France and Bay, 2010). As these STEM students might become future scientists, it is important to develop approaches that encourage them to retain their positive views.

(4) *Educated public*—the educated public views were similar to those of the other stakeholders regarding the importance of *open discussions*. These correspond with the traditional and still more common approaches of engagement through communication channels, such as public lectures, compared to new forms for engaging stakeholders with science. Like other stakeholders (except for the teachers) they favored *promoting interest and confidence* more than personal involvement. These findings can be explained by the fact that the public in our study also is comprised in part of undergraduate STEM students, who are exposed to practical exercises as part of their studies.

Research limitations and recommendations

We investigated the *At-the-Gate* website, according to scientists and teachers' questions posed, and views. There are other potential and actual users of this website, such as pre-service teachers, K-12 students and the public at large. For the second research goal, we have explored the views of four stakeholder groups whose scientific knowledge ranges on several levels. Our study included neither K-12 students nor laypeople. The group with the lowest scientific knowledge was comprised of social science undergraduate students, who represent the educated public—the 'pro-science'' party (Ogawa, 2011)—that is mindful and supportive of STEM. This research limitation stems from the difficulty of reaching and investigating laypeople. Yet, we can assume that even educated members of the society, whose qualifications are other than STEM, will have limited understanding of science relative to scientists or engineers (Bromme and Goldman, 2014). K-12 students are important stakeholders. Due to their being the focus of most of the research in science education, we did not include them in this study. We are aware to the issue of generalizability of our findings that stem from the sampling strategy. We therefore suggest expanding our study by exploring the views of a wider array of population groups in different countries.

Referring to our focus on the chemistry domain, we noticed that throughout the *At-the-Gate* website activity, the number of questions asked in biology has been greater than the number of questions in all the other domains. This can be attributed to the large number of K-12 students who study biology compared to those who learn chemistry or physics. Another reason is that biology teachers and K-12 students were more aware of the website because of the inquiry unit in biology, which requires planning experiments and explaining their results. Motivating students to engage in posing chemistry-related questions and learning chemistry in context may encourage them to pursue and complete studies in chemistry (Borrego and Henderson, 2014; Pabuccu and Erduran, 2016; Dori *et al.*, 2018). This recommendation might help countering the decline of choice in the chemistry field in the last two decades (Aikenhead, 2003), which still exists in Israel (Dori *et al.*, 2019).

Summary and contributions of study

The current study supports the view that chemical literacy in a form that involves communicating science in informal settings is effective. The study is placed in the larger context of scientific literacy and communication channels, as it takes the chemical literacy with focus on communications among scientists and chemistry teachers in the context of an *Ask-a-Scientist* website as a case in point. Through the analysis of questions posed on the *At-the-Gate* website, our aim was to expand its potential impact on inspiring different stakeholders to enhance their engagement and collaboration on the website, thereby promoting chemical literacy. We explored this issue by identifying categories within chemical literacy that should be embraced, enhanced, and promoted for the benefit of different science stakeholders that are or should be involved in communicating science (Kohen and Dori, 2019). We suggest to further explore the views of non-users or former users of *Ask-a-Scientist* websites. This might shed light on why various stakeholders do not value such websites for meeting science literacy goals and on how to enhance the engagement of various stakeholders in such websites and other informal communication channels.

Our findings highlight the different emphases on science literacy placed by different stakeholders, which need to be taken into consideration when developing communication channels that connect stakeholder groups in formal or informal learning contexts. More specifically, the different views of the stakeholder groups in our study about scientific literacy that should be shared and constructed by the public demonstrate the importance of understanding what constitutes productive communication (Schibeci and Williams, 2014).

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Formal communication in science education is based on teacher-student interaction that does not regularly involve dialogue with science communicators in informal settings. The current research investigates the experiences of the four stakeholder groups with diverse scientific literacy, ranging from low—the educated public, to high—the scientists. The classification of categories within chemical and scientific literacy construction is aligned with the definitions of chemical and scientific literacy in the literature. This match is important especially for STEM-oriented stakeholders, notably science teachers and scientists, since their awareness of both cognitive and affective components of scientific literacy might raise the prospects of increasing literacy among the public. The investigation of the *At-the-Gate* website supplemented this view by presenting views of both chemists and chemistry teachers who were involved in this communication channel and supported the effectiveness of the website in facilitating chemistry literacy *via* their engagement of questions posing.

As much of the focus of science education is on developing K-12 students' chemical literacy (NRC, 2012, 2013; AAAS, 2013; NGSS Lead States, 2013), raising awareness towards science communication has the potential to increase students' choice of chemistry studies and careers. Many high school chemistry teachers are driven by the desire to motivate their students to consider studying chemistry in college. Yet, K-12 students are not sufficiently familiar with what chemistry entails. If students cannot appreciate the rich culture of chemistry and its relation to various situations surrounding them, they will likely not choose this as a field of study (Zavrel, 2011). The current study strengthens this implication and suggests supplementing formal classroom instruction *via* informal communication channels, particularly through direct contact with scientists (Besley *et al.*, 2015).

This research has theoretical, practical and methodological contributions. From the theoretical aspect, our study has established a link between the two dimensions of scientific literacy and communication among scientists and the public, *via* the responses of various STEM and non-STEM stakeholders on one hand and the definitions that exist in the literature regarding scientific literacy with focus on chemical literacy on the other hand. The links we found might help closing the gap between science education and science communication (Kohen and Dori, 2019). From a practical viewpoint, the study underscores the importance of communicating science to various stakeholders. The positive responses of the scientists and specifically the chemists in our study regarding their role in communicating science to the public suggests that scientists should be encouraged to spend more time and attention for improving communication of their scientific work to the public in order to expand citizens' scientific literacy. The study presents a productive communication channel which offers a site for posing questions in the context of chemistry and other sciences, classified into different levels of chemical literacy. This form of engagement with science through direct dialogue and interaction with scientists can be valuable to various stakeholders who wish to expand their scientific knowledge or to gain practical experience on how to cope with real-life situations in scientific and technological contexts. The methodological contribution of this study is the design of the questionnaire for examining views of different stakeholders on scientific literacy and communication channels. The questionnaire can serve as a basis for developing additional tools to enable further analysis of the communication process between scientists, teachers and students in general, and *via Ask-a-Scientist* websites in particular. Finally, the rubric for analyzing questions posted in this type of website, which we developed and used in this research, might serve chemistry educators as an assessment tool for evaluating the complexity level of teachers' and students' own questions aimed at improving their scientific literacy.

Conflicts of interest

There are no conflicts to declare.

Appendix A: additional questions from the open-ended questionnaire

Part A—questions common to all the stakeholders

Reviewing studies in the domain of science communication highlights the argument that the 'public' lacks understanding, especially in fields where there is a considerable public engagement, such as the resistance of UK public to engineered food. Some people suggest that it is the role of scientists to communicate with the public. What is your opinion about the role of scientists in communicating with the public? Through what channels can communication between the scientists and the public be promoted? What are your preferred channels of communication between scientists and the public? Should the communication with the public be different in various scientific fields? Are there any challenges in communicating technical information and concepts? In what ways can communication between scientists and the public contribute to scientific literacy? Can you envision a situation in which the public will play a role in shaping scientific research? Why or why not? If yes, how?

Part B—stakeholder-specific questions

[Scientists]—We are interested in how and why scientists interact with the public in the scope of their research projects. Have you had such an interaction? If so, please describe the aims of this interaction and the type of research you present. Who do you communicate with and why? What is your experience with this communication?

[Teachers]—Are you familiar with the *At-the-Gate* organization? If so, what is your motivation for using the *At-the-Gate* website? What is its contribution to scientific literacy of teachers and students? What is its contribution to you (personally, professionally, *etc.*)?

[STEM undergraduate students and the educated public]—Have you interacted with an academic scholar or a researcher? If so, how was this interaction made possible and did it contribute to you (personally, professionally, *etc.*)?

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Appendix B: comparison of websites that enable posing questions and receiving responses from scientists

Website	*At-the-Gate*	*Newton network*	*NASA network*	Science answers
Established	2003	1991	N/A	2010
Operated by	Volunteers from universities and research institutions	The Educational Programs of Argonne National Laboratory (University of Chicago, USA)	Nation's science community, sponsors and scientific research. (Washington, DC)	Group of Scientists (Global)
Website objectives	Increasing the participation in public discourse and social action within academia	Providing a place to practice telecommunications; retrieving useful information; contacting research scientists from all over the world; and opening communications between classroom teachers	Developing and deploying satellites and probes in collaboration with NASA's partners around the world; answering fundamental questions requiring the view from and into space	Aiding in finding and publishing the best and most accurate scientific information available
Motivational factors	Encouraging students to pursue STEM professions; providing local communities, also from rural areas, access to high-level academia; providing a framework that can address complex questions when needed	Offspring of a 1990–1991 NSF initiative at Argonne for middle school science teachers to enhance their classroom instruction by surveying the numerous projects and programs at FermiLab as well as Argonne	Exploring the universe in order to uncover new knowledge and apply it to the benefit of all mankind	None
Question are answered by	Leading faculty members in their respective fields of expertise	Volunteer scientists	Published scientific research	Experts
Field of questions the website serves	Questions within the Humanities, Sciences and Medicine	Math, Computers and Science	Astrophysics, Heliophysics and Earth Science	Science
Activities	Lectures given by scientists	Teacher seminars and monthly gatherings	NASA's Science Mission Directorate (SMD) sponsors independent peer reviews	None
	Summer camp	Summer programs	NASA Wavelength: an online catalog of NASA earth and space science resources	
	"Science gate" and "Citizenship gate"—a collection of science articles	A collection of articles	Earth & Space Science Explorers: a monthly series that introduces people to NASA Earth Explorers	

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