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Sohair Sakhnini & Ron Blonder

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Nanotechnology applications as a context for teaching the essential concepts of NST

Sohair Sakhnini and Ron Blonder

Department of Science Teaching, Weizmann Institute of Science, Rehovot, Israel

ABSTRACT

The goals of this study are to map applications of nanotechnology that are recommended to be taught in high-school science and to identify the 'need-to-know' essential nanoscale science and technology (NST) concepts for each of the selected nanotechnology applications. A Delphi study using a community of experts was used to address these goals. Five nanotechnology applications that should be taught in high-school science were found to be important and reached a consensus by the Delphi-study experts: (1) nanomedicine, (2) nanoelectronics, (3) photovoltaic cells, (4) nanobots, and (5) self-cleaning. It was found that teaching these five nanotechnology applications should be based on all seven NST concepts, and therefore, these applications can be used as an appealing context for teaching the essential NST concepts. The different recommendations between the two communities of experts emphasize the importance of involving teachers and scientists in the process of designing a scientific curriculum. Identifying the applications of nanotechnology that should be taught in high-school science and identifying the connections between the applications and the essential NST concepts constitute an important step that supports designing a context-based nanotechnology program before it is integrated into a high-school science curriculum.

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Introduction

Nanotechnology education programs have been developed in many countries and in different settings (Jones et al., 2013). Most of the programs include appealing nanotechnology applications (e.g. Blonder & Dinur, 2011; Delgado, Stevens, Shin, & Krajcik, 2015; Dori, Dangur, Avargil, & Peskin, 2014; Hutchinson, Bodner, & Bryan, 2011). Choosing the different applications for each program was based on the perceived relevance of the application usually by the program designer or based on students' interest (Hutchinson et al., 2011). The current research was designed to identify the recommended nanotechnology applications to be taught in high-school science based on two communities of experts: science teachers and nanoscience researchers. After the identification stage, the recommended nanotechnology applications are examined to serve as a context for teaching nanoscale science and technology (NST) essential concepts (Sakhnini & Blonder,

CONTACT Ron Blonder ron.blonder@weizmann.ac.il Department of Science Teaching, Weizmann Institute of Science, Rehovot 76100, Israel

2015). These two stages of the research are based on a Delphi-study methodology that will be described. This study resulted in research-based guidelines for building context-based NST programs in which nanotechnology applications can be used as learning context for teaching the essential concepts of NST.

Background

Over the decades, science education, in general, and chemical education, in particular, has faced many challenges (e.g. overloaded curricula, isolated facts, low engagement, and lack of relevance) (Gilbert, 2006; Pilot & Bulte, 2006a, 2006b) and it has undergone many changes as a result. A major effort to address these challenges has been through the use of 'context' as the basis for curriculum design and classroom teaching (Elster, 2009; Gilbert, 2006). According to Whitelegg and Parry (1999), context refers to the social and cultural environment in which the learning is situated. Overman, Vermunt, Meijer, Bulte, and Brekelmans (2014) suggest that a context-based approach is characterized by the use of societal, technical, or scientific contexts as the starting point for developing chemical understanding, with the intent of making chemical content more relevant to today's students.

Using a context-based learning approach influences students' interest and increases their motivation to study science as a product of contexts that are seen relevant to students' lives (Bennett, Lubben, & Hogarth, 2007; Eilks & Hofstein, 2015; Elster, 2009). Elster (2009) suggests that using context-based teaching and learning in biology transforms the biological contents that are provided to the learners to everyday experiences. The same notion was stressed for chemistry education (Bennett et al., 2007; Gilbert, 2006; King, 2012) and physics (Kortland, 2005; Whitelegg & Parry, 1999).

Consequently, upon initiating the context-based learning approach, many changes have taken place in science education instruction. A wide range of materials have been developed, using contexts and applications as a starting point for creating an understanding of scientific ideas and concepts (e.g. De Putter-Smits, Taconis, & Jochims, 2013). The literature is rich in descriptions of context-based programs and the accompanying educational research (Bennette et al., 2007; Eilks & Hofstein, 2015). ChiK, a context-based chemistry course developed in Germany, describes context as a question or issue that is considered relevant to students (Nentwing, Parchmann, Demuth, Gräsel, & Ralle, 2005). In PLON, a Dutch physics-context-based curriculum, 'the curricula were context-based in [the] sense that the students' "life-world" was taken as a starting point' (Kortland, 2005, p. 67). The Salters approach, a context-based chemistry course for upper high-school students, defined context 'as born from a perception that school science needed to be more relevant to young people's interest and their daily lives' (Bennett, Holman, Lubben, Nicolson, & Otter, 2005, p. 123). Pilot and Bulte (2006a, 2006b) developed criteria for using contexts within chemistry education. The main criterion refers to the learning setting: 'It must clearly arise from [the] everyday lives of the students, or social issue and industrial situations' (Pilot & Bulte, 2006b, p. 1090). Nentwing et al. (2005) described the demands from the context in context-based programs: 'It should be embedded in authentic and rich environments, which are perceived as relevant by the learners. Learning environments are considered authentic, when

International Journal of Science Education 2016.38:521-538.

learners acquire knowledge and competence in dealing with an issue of interest and relevance to them' (p. 161).

Nanotechnology applications are good candidates to be used as context for science education programs. They have clear connections to students' everyday lives (e.g. nanoelectronics that can improve their smartphone), they have industrial aspects because they all promise products that will be produced or already have been produced (e.g. antibacterial fabrics that are already being produced and are available in different products), and they all represent a rich environment that involves research, society, and industry. Indeed, the use of nanotechnology applications has been proposed as means of increasing students' interest in science (Chang, 2006; Foley & Hersam, 2006; Roco, 2003).

One of the nanoscale science and engineering (NSE) nine big ideas (Stevens, Sutherland, & Krajcik, 2009) refers to nanotechnology applications (nanoscience, technology and society). Researchers have argued that NST learning is a modern and interesting context for increasing students' interest and motivation to learn science and technology in general due to interesting and novel phenomena that occur at the nanoscale (Blonder & Dinur, 2011; Hutchinson et al., 2011). Hutchinson et al. (2007) investigated 7–12th grade students' interest and motivation in nanoscience concepts and phenomena. Students were introduced to several nanoscale topics and phenomena through four manipulative activities and a series of nanoscale driving questions. The research found that students were most interested in NST topics that related to their 'real world' and daily lives.

Delgado et al. (2015) developed a 12-hour instructional unit for size and scale, in a summer science camp for middle-school students. The unit was contextualized with a driving question dealing with: 'how can nanotechnology keep people from getting sick?' (p. 51). This context was productive and enabled the students to examine the size of surface features, bacteria and viruses. In addition, the context provided the students with the opportunity to be involved in the learning process. They found that students significantly increased their knowledge of the size of objects. They mentioned that the learning context made the students more involved and interested because the context is relevant to students' daily lives.

In Israel, two examples of using nanotechnology applications as a context for chemistry learning were reported. Dori, Dangur, Avargil, and Peskin (2014) designed a context-based module for teaching basic concepts of quantum chemistry for high-school students. The module adopts a context-based approach, which replaces mathematical derivations typically used in quantum mechanics and includes an interdisciplinary, real-life nanotechnology application called LED[1] (light-emitting diode). In order to understand how LEDs work, students need to learn qualitative quantum mechanics. The researchers found that the students understood the basic quantum mechanics, even though they did not have an advanced mathematics background. In a different module that was designed for middle-school students, the context of LED was used for teaching about light, colors, and the uniqueness of LEDs (Blonder & Dinur, 2011). In this study, those students who learned the module were found to have increased motivation to learn science. Using LED as a rich context for learning basic scientific concepts exemplifies the potential of using nanotechnology applications for context-based learning.

According to the presented studies, nanotechnology applications represent relevant contexts that can make science more relevant, interesting, and meaningful to students' lives and their daily experiences. Learning science through the context of nanotechnology applications provides students with the opportunity to learn how modern science works and the role that science and technology plays in finding solutions to everyday life problems (Jones et al., 2013).

Hutchinson et al. (2011) evaluated high-school science students' levels of interest in a variety of NSE phenomena and concepts using a three-point Likert-type scale survey. The survey covered 4 NST activities and a set of 11 intriguing questions. In addition to the questionnaire, they used students' interviews. They found that students were more likely to be interested in activities or questions if they involved: (1) real-world objects or events, (2) topics that were viewed as novel, and (3) physical manipulatives with which the students were actively involved. The least interesting activities for students were those that lack relevance to their lives or the students were not very actively involved during the activities or when they believed they knew the answers. These results suggest that students' interest in science might be increased by incorporating examples from NST into the classroom. They suggest that the advantage of using NST topics and phenomena for increasing student interest might be due to the following combination of factors: (1) their prominence in today's society in the form of consumer products, advertising, popular media, and books; (2) the perception that these topics are novel; and (3) the fact that students are unlikely to view these topics as having been learned in previous coursework.

The great potential of using nanotechnology applications as a context for science learning was demonstrated in the above studies. We wish to emphasize that there is a need to conduct a research-based selection of NST applications for educational purposes. This study should include researchers who develop NST applications, teachers who will use the applications as a teaching context, and students who will utilize the NST applications. In the current study we will discuss the first step in identifying NST applications that are recommended to provide a context for teaching NST concepts based on two communities of expert NST researchers and science teachers. Students' voices will be heard in the next step of the study. The current research was conducted to design guidelines for a context-based NST program in which nanotechnology applications will be employed as learning context for teaching the essential concepts of NST (Sakhnini & Blonder, 2015).

In a previous study, a three-round Delphi-study methodology was applied to reach a consensus between experts in nanotechnology regarding the essential NST concepts that should be taught in school science (Sakhnini & Blonder, 2015). Seven essential concepts of NST and the concepts' sub-categories, their definitions, and importance emerged from the Delphi study: (1) size-dependent properties, (2) innovation and application of nanotechnology, (3) size and scale, (4) characterization methods, (5) functionality, (6) classification of nanomaterials, and (7) fabrication approaches of nanomaterials (Sakhnini & Blonder, 2015).

The second essential concept that was agreed upon, namely, innovation and application of nanotechnology, was defined as: 'The potential applications and innovations of nanotechnology and included four parts: Current and future applications, mimicking nature, risks and benefits of nanotechnology, and tailoring nano-materials to the application' (Sakhnini & Blonder, 2015, p. 1708).

However, there are still several open questions regarding teaching this concept: What nanotechnology applications should be included in a high-school program? How are this concept and the other essential NST concepts connected? What specific nanotechnology applications could serve as a context for learning the other essential concepts? We will attempt to address these questions based on an additional Delphi study.

Methodology

Research goals and questions

The goals of the current study are to map applications of nanotechnology that should be taught in high-school science and to find the 'need-to-know' (Bulte, Westbroek, de Jong, & Pilot, 2006) NST concepts for each of the selected nanotechnology applications. More specifically, our research questions are as follows:

(1) What nanotechnology applications are perceived by science teachers and nanoscience researchers as important to be taught at school science level?
(2) What are the differences in how the two different communities of experts (nanoscience researchers and science teachers) perceived the importance of these applications?
(3) Which of the essential NST concepts are perceived by science teachers and nanoscience researchers as needed for teaching each of the identified applications?

Methods

A Delphi technique survey, which is used for collecting the opinions of experts on a particular subject and for reaching a consensus, was chosen as the research methodology (Hsu & Sandford, 2007). The Delphi-study methodology (Hsu & Sandford, 2007; Murray & Hammons, 1995) was chosen to collect the expert community's views regarding the nanotechnology applications that should be taught in school science. The Delphi technique is useful whenever policies, plans, or ideas have to be based on informed judgment in cases characterized by partial or primary knowledge about a new field (Skulmoski, Hartman, & Krahn, 2007). The Delphi technique is a multiple-iteration procedure for obtaining the most reliable consensus from a group of experts without the need for actual meeting of the expert group (Hsu & Sandford, 2007). The multiple-iteration procedure of the Delphi technique is accompanied with feedback from the experts' groups (Delbecq, Van de Ven, & Gustafson, 1975). The number of the experts that are needed for a reliable Delphi study will not be less than 10 (Cochran, 1983). As the group size increases, the reliability of the Delphi improves (Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003). In the current paper we will briefly present the Delphi methodology and design. More details regarding the three-round Delphi methodology are provided in a previous study (Sakhnini & Blonder, 2015).

Delphi process design and analysis

The Delphi process begins with an open-ended questionnaire in the first round. It serves as the cornerstone for exploring specific information about a content area from the Delphi participants (Custer, Scarcella, & Stewart, 1999). After receiving the participants' responses, researchers convert the collected information into a Likert-type questionnaire. This questionnaire is used as the qualitative instrument for the next rounds of data collection.

Participants

The first-round Delphi questionnaire was sent to 82 potential participants for the current study, from 2 groups of experts, 41 participants in each group. Twenty-one researchers who are experts in nanoscience ($n = 21$) out of the 41, and 21 teachers ($n = 21$) out of 41 science teachers that have knowledge in NST accepted the invitation to participate in the study and filled out the first-round Delphi questionnaire. All of these participants continued in rounds 2 and 3 of the study.

NST researchers in Israeli universities and industries constituted the first community of experts. The group composition reflected the interdisciplinary nature of NST because they had different scientific backgrounds (chemistry, materials and science engineering, physical chemistry, applied physics polymer physics, and physical organic chemistry). All researchers in the community of experts hold Ph.D. degrees. Thirteen of them are full professors in their field, and three researchers work in companies in the nanotechnology industry.

The second community of experts consisted of high-school science teachers who teach different science disciplines (chemistry, biology, biotechnology, and physics) and who have at least 15 years of teaching experience. They were chosen based on their solid background in NST from different sources: Some were involved in developing a NST curriculum in Israel from different science disciplines, some had taught the nanoethics module, others had taught nanobiotechnology, and some teachers had only informal experience in teaching nanotechnology, and others underwent a thorough course about NST and were defined as Nano literate (Blonder, 2011) and also possessed strong pedagogical content knowledge. Four of the teachers who participated in this research hold B.Sc. degrees, thirteen hold M. Sc. degrees, and four of them have Ph.D. degrees in science or science education.

We chose these two different communities of experts in order to combine the different aspects that characterized them, namely content and pedagogy. These factors, in our opinion, play a fundamental role in developing a new scientific curriculum and in particular, the emerging NST education field.

Data collection and analysis

Delphi pilot study

In the pilot stage, the researchers decided on the questions that would appear in the open-ended questionnaire and sent it to three participants of each community to determine (1) whether the questionnaire's phrasing influenced the participants' responses and (2) whether the phrasing of the questions was sufficiently clear for the participants. The participants were asked to suggest NST applications that are important and should be taught in school science, to provide a clear description of the suggested applications, and to justify why they find them important. Three nanoscience researchers and three science teachers completed the open-ended questionnaire in the pilot study, which confirmed that the questionnaire was clear, useful, and provided a wide variety of participants' answers.

Delphi round 1

After the Delphi pilot stage, the same open-ended questionnaire was sent to all participants by mail. The completed questionnaires were analyzed according to categories.

Categories of the suggested applications were identified by the first researcher, who did not interfere with or change the wording that the participants used. The categories consisted of the names of the suggested NST applications or a broader field of the application. The process of identifying the emerging categories included discussions between the first author and her advisor (the second author who is an expert in nanotechnology and in science education research).

Upon completing the Delphi round 1 data collection, the percentage of teachers and researchers who suggested each of the (NST) applications was calculated (Table 1). A chi-square test was used to compare the relative frequencies of each application in the two communities of experts (nanoscience researchers and science teachers).

Delphi round 2

The second-round questionnaire was a 5-point Likert-type scale online questionnaire (Turoff & Hiltz, 1995). Participants were requested to rate the importance of each application that emerged from Delphi round 1, on a 5-point Likert-type scale (1 = not important; 5 = very important).

Median and the Interquartile range (IQR) for each application (using the rating given in the 5-point Likert scale) was calculated. Kruskal–Wallis non-parametric test was used to compare between the two communities of experts. A consensus regarding the importance of an application was obtained when the participants rated an application with a median ≥ 4.0 on the 5-point Likert scale and the IQR was ≤ 1.33 (Green, 1982; Heiko, 2012).

Delphi round 3

Generally, the final questionnaire in the Delphi study presents the titles, revised summaries, and representative anonymous supporting statements from participants for the top-rated themes from round 2, together with the medians and IQR (or mean and variance) calculations of the ratings for each theme. Participants are usually asked to rescore each theme.

In the current study, we decided to modify the third round. Based on the consensus results already obtained from the second round, we decided to cancel the additional

Table 1. First Delphi round: the percentage of teachers and researchers who suggested each of the NST applications.

Suggested applications	#	Teachers (%)	Researchers (%)
Nanomedicine	26	76.19	52.38
Nanoelectronics	17	42.86	47.62
Self-cleaning	12	42.86	19.05
Nano-composite	11	23.81	28.57
Nano-lubricants	10	23.81	28.57
Photovoltaic cells	9	19.05	23.81
Lighting display*	8	33.33	4.76
Diagnostics	7	19.05	14.29
Nano-filtering	6	14.29	14.29
Nano-lithography	5	4.76	19.05
Catalysis	5	4.76	14.29
Nanobots	3	9.52	4.76
Antiviral and antibacterial	2	0.00	9.52
Security	1	4.76	0.00

*$.01 < P < .05$.
#Number of participants who suggested the application in the first round.

rating of the applications. Instead, we designed an online questionnaire that presented the participants' consensus percentage regarding five of the applications that emerged from Delphi round 2. We included those applications that met the consensus conditions, at least by the communities of experts, namely median ≥ 4.0 on the Likert scale and when the IQR was ≤ 1.33. Nanomedicine was perceived as very important by both communities of experts. Nanobots, self-cleaning, and photovoltaic cells reached the highest consensus by the teachers' community, and nanoelectronics was perceived to be very important by the NST researchers' community. The other NST applications were not perceived as very important by any of the communities of experts.

The participants were asked to denote all the essential NST concepts (Sakhnini & Blonder, 2015) that are needed for teaching each of the suggested applications. Note that the participants were familiar with the meaning of the NST essential concepts, since they participated in defining and identifying them.

For this stage, a consensus was reached when at least 50% of the participants (Hasson, Keeney, & McKenna, 2000) indicated that an essential concept was needed for teaching each of the specific applications that emerged from the second round of the study.

Results

The results will be presented according to the first, second, and third rounds, respectively, of the Delphi process. The whole Delphi process led to a consensus regarding (1) the nanotechnology applications that should be taught in high-school science and (2) the connection between the essential concepts needed for understanding each of consensus applications.

Round 1

There was no significant difference ($P = .13$) regarding the average number of applications that were suggested by each group of participants (teachers and researchers). However, the teachers suggested ($M = 3.6$; SD = 2.3), on average, more applications than the researchers did ($M = 2.8$; SD = 1.7).

Fourteen different applications were suggested in the first round of the Delphi study. Table 1 presents the applications that emerged in the first round, the number of participants that denoted each application, and the percentage of teachers and researchers who suggested each of the nanotechnology applications. Only one significant difference was found between the teachers and researchers regarding the application 'lighting display' (LED) (Table 1). This application was suggested more by teachers ($P = .018$).

Round 2

In the second round, all the participants, from both expert communities, rated the importance of each application that was identified in round 1 (on a 5-point Likert-type scale). The median and IQR of each application by each group are presented in Table 2.

Significant differences between the two groups of experts (teachers and researchers) were found concerning most of the applications using the Kruskal–Wallis non-parametric test (Table 2). Therefore, we decided to use the experts' recommendations as two separate

Table 2. Delphi round 2: medians, means, and IQR of teachers and researchers for the NST applications. Differences between the two communities were tested using the Kruskal–Wallis non-parametric test. The table is organized according to the total median obtained for each application.

Group applications	Total median (mean) IQR	Teachers median (mean) IQR	Researchers median (mean) IQR	(K–W) χ^2
Nanomedicine	4.1 (4.03) 0.84	4.23 (4.19) 0.79	4.0 (3.86) 0.88	2.53
Nanoelectronics	4.0 (3.95) 1.32	3.8 (3.81) 1.36	4.2 (4.1) 1.14	1.24
Nanobots	3.8 (3.53) 1.58	4.2 (4.19) 0.76	2.9 (2.86) 1.84	15.29***
Photovoltaic cells	3.7 (3.67) 1.34	4.04 (3.76) 0.75	3.5 (3.57) 1.34	0.54
Self-cleaning	3.7 (3.41) 1.54	4.1 (4.05) 0.80	2.9 (2.76) 1.94	14.07***
Catalysis	3.6 (3.55) 1.34	3.9 (3.81) 1.07	3.3 (3.29) 1.23	3.62
Diagnostics	3.5 (3.43) 1.36	3.9 (3.76) 1.07	3.1 (3.1) 1.04	6.37*
Nano-lithography	3.4 (3.43) 1.34	3.2 (3.33) 1.08	3.7 (3.53) 1.5	0.73
Nano-composite	3.4 (3.36) 1.36	3.6 (3.57) 1.17	3.3 (3.14) 1.72	1.37
Lighting display	3.4 (3.21) 1.44	3.9 (3.76) 0.81	2.9 (2.67) 1.46	19.76***
Antiviral and antibacterial	3.2 (3.19) 1.5	3.8 (3.76) 1.36	2.7 (2.62) 1.47	11.37***
Nano-lubricants	3.2 (3.19) 1.24	3.6 (3.55) 1.23	2.9 (2.86) 1.07	5.44*
Nano-filtering	3.1 (3.07) 1.53	3.8 (3.67) 1.23	2.7 (2.48) 1.61	12.33***
Security	3.1 (2.93) 1.72	3.7 (3.57) 1.16	2.6 (2.29) 1.76	13.62***

*.01<P<.05.
***P<.001.

groups and not to combine them into one general group (Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003). Four of the 14 applications were rated by the teachers as important (nanomedicine, nanobots, photovoltaic cells, self-cleaning) to be taught at the high-school science level (median ≥ 4.0 and IQR ≤ 1.33) as presented in Table 2. The researchers' group ranked only two applications: Nanomedicine (median = 4.0, IQR = 0.88) and Nanoelectronics (median = 4.2, IQR = 1.14) as important to be taught.

For most of the applications, the IQR within the researchers' group was higher than the IQR within the teachers' group and the medians were lower than 4.0. It is important to mention that the researchers in our study have heterogeneous scientific backgrounds and differ in their research interests. We found that some of the researchers highly recommended those applications that were specifically related to their research area and rated the other applications lower.

An additional qualitative difference between the two communities was found when we analyzed the justifications for teaching the different applications. Most of the justifications given by the researchers emphasized the universal importance of the application. For example: 'This application is very important, due to the lack of energy in the current era and due to the need to produce green and clean energy' (a researcher). The teachers' community, however, gave more attention to pedagogical aspects related to the application or possible connections to the existing science curriculum. For example: 'It is important because it can help teachers to teach about proteins and hydrocarbons that are part of the chemistry curriculum in Israel' (a teacher). 'Nanoelectronics is a natural continuation of the LED topic that is part of the chemistry curriculum for 12 graders in Israel' (a teacher).

The next section presents the five recommended applications, (four applications selected by teachers, two from researchers, with one application selected by both groups), their definitions, and importance, formulated by integrating explanations and comments from different participants in the Delphi study.

(I) *Nanomedicine* refers to applications of nanotechnology, including medical treatment and diagnosis. There are two kinds of nanomedicine applications: *in vivo* and *ex vivo* medical treatment and diagnosis. *Ex vivo* refers to using nanosensors outside the living organism and *in vivo* refers to using nanomaterials within a living organism. Diagnosis is made by monitoring the change in the optical/physical/electrical/chemical signals of the nanomaterials upon binding to the targeted (disease) site/organ. Medical treatment and drug delivery are concerned with the use of nanomaterials, such as liposomes and polymer micelles and/or Nano-electro-mechanical (NEM) systems for drug delivery into specific organs or disease sites.

Some examples of the importance of teaching this application according to the participants are as follows:

> The technique is non-invasive, safe, can be applied at home or in an office, does not require expertise, is inexpensive, portable, etc. Additionally, this technique can serve as a health monitoring tool (or a warning system) on a daily basis, thus allowing one to detect the disease at its very early stages. (a researcher)

'The treatment with this technique is minimally invasive, compared with the current surgical procedures. Additionally, this treatment is more selective than the currently available treatment procedures'. 'This is arguably the field that will benefit the most from nanotechnology' (a researcher). 'Nanomedicine applications stress the importance of nanotechnology to humanity and encourage students to learn science' (a teacher). 'Nanomedicine spurs the students' interest to learn science' (a teacher). 'It is important because it can help teachers to teach about proteins and hydrocarbons that are part of the chemistry curriculum in Israel' (a teacher).

(II) *Nanoelectronics* is the use of nanotechnology in manufacturing electronic components. It is related to the miniaturization of electronic devices.

> Carbon nanotubes or silicon nanowires can be integrated into electronic devices and/or circuits to regulate the transfer of electrons from one side of the device to the other (i.e. these nanomaterials can be used as precise electrical switches or diodes). These devices can then be integrated as the main parts of super-computers, and might revolutionize computing power.

Some examples of the importance of teaching this application are as follows:

> It is important to be taught because it illustrates how the type and size of a specific material would increase the performance of the electrical devices available in the current era. Also, it is important to show that miniaturization of devices would allow putting more devices per unit area, and, therefore, more 'uses' per unit area. (a researcher)

'Nanoelectronics is relevant to students' lives' (a teacher). 'It provides connections to things that the students use every day, like computers and cellular phones' (a researcher). 'Nano-electronics is a natural continuation of the LED topic that is part of the chemistry curriculum for 12 graders in Israel' (a teacher).

(III) *Photovoltaic cells* that are based on Nanomaterials (such as Titanium oxide nanoparticles) can be integrated within the components of conventional solar cells (either within the materials themselves or as separate films) to increase the efficiency of the devices because of their enormous surface area. Additionally, the integration of nanomaterials within solar cells increases their sensitivity to the optimal wavelengths of the sun light.

The importance of teaching this application: 'This application will demonstrate the utility of nanomaterials for increasing the efficiency of the solar cells, decreasing the cost of the solar cells, and allowing miniaturization of the solar cells' (a researcher). 'This application is very important, due to the lack of energy in the current era and due to the need to produce green and clean energy' (a researcher). 'Students should be educated in the direction of alternative energy since this is the future of our planets' energy supplies and the students will be part of that future' (a researcher).

> It is important to expose students to this application, and its related scientific knowledge. To engage them with the environment's educational and ethical issues and to teach them how to be responsible to their planet's future. In addition the application of nanotechnology in photovoltaic cells can be easily demonstrated at the school level. (a teacher)

(IV) *Nanobots* refer to the nanotechnology engineering discipline of designing and building nanorobots, with devices ranging in size from 0.1 to 10 micrometers that are constructed of nanoscale or molecular components.

The importance of teaching this application: 'Nanobots demonstrate the future of nanomotion. They demonstrate the relationship among chemistry, materials science, and nanoengineering' (a researcher). 'Nanobots enrich students' knowledge by exposing them to new and challenging scientific topics. In addition, nanobots stimulate the students' imagination and connect them to scientific ethical issues by thinking about different consequences of nanobots in our daily life' (a teacher).

(V) *Self-cleaning*. In the responses, we found two different kinds of self-cleaning nanotechnology applications that are based on different nanomaterials and different principles: (1) use of nanomaterials as a self-cleaning agent. Applying TiO_2 nanoparticles as thin films on glass, eye glasses, buildings, paintings, cloth, etc. induces photocatalytic behavior. In this process, the (sun) light induces oxygen species on the surface of the TiO_2 nanoparticles or thin films, which, in turn, attack organic contaminants adsorbed on the surface. In other processes, the same material can be used as an anti-fog agent. In this way, entities that are coated with this material remain clean for a long time. (2) The use of super hydrophobic surfaces based on nanoparticles is a good example of a commercially available nanotechnology product that is widely used today, and its scientific principles are easy to grasp.

The importance of teaching this application: 'It demonstrates the utility of nanomaterials for maintaining a green environment' (a researcher). 'It demonstrates the principle that changes in nanoscale can have a useful effect on daily life activities' (a teacher). 'Self-cleaning materials already exist in commercial markets; therefore, customers should know about their characteristics and understand the scientific principles behind their unique activity' (a teacher).

Round 3

The third-round Delphi questionnaire included the five top-rated nanotechnology applications presented before, along with data regarding the consensus percentage obtained from the second round. The participants were asked to indicate the NST essential concepts needed for understanding each application. Seven essential NST concepts that were found

Table 3. Delphi round 3: the consensus percentage (%) for the essential NST concepts that are needed for teaching each of the top-rated NST applications according to all Delphi participants.

Categories of applications/ essential concepts	Size-dependent properties	Size and scale	Fabrication approaches of nanomaterials	Characterization methods	Innovation and application of nanotechnology	Classification of nanomaterials	Functionality
(1) Nanomedicine	83.3#	83.3#	45.2	78.6#	71.4#	31.0	42.9
(2) Nanoelectronics	81.0#	95.2#	71.4#	66.7#	71.4#	50.0#	54.8#
(3) Photovoltaic cells	81.0#	81.0#	52.4#	73.8#	71.4#	38.0	54.8#
(4) Nanobots	83.3#	57.0#	21.4	59.5#	50.0#	21.4	42.9
(5) Self-cleaning	69.0#	73.8#	40.5	78.6#	54.8#	35.7	38.0

#Agreement among participants regarding the needed of the NST essential concept is ≥ 50%.

in a previous study were given to the participants in the third Delphi round: (1) size-dependent properties, (2) innovation and application of nanotechnology, (3) size and scale, (4) characterization methods, (5) functionality, (6) classification of nanomaterials, and (7) fabrication approaches for nanomaterials.

Table 3 presents the resulting connections among each of the five chosen nanotechnology applications and the essential NST concepts. Based on Hasson et al. (2000), a consensus is reached when at least 50% of the participants indicated that a specific NST concept is needed for teaching the application. Accordingly, these concepts can be integrated later on as pillars for teaching each of the chosen applications. The connection between the essential NST concepts and the nanotechnology application will provide the basis for developing a context-based program for teaching NST.

Discussion

The discussion is based on integrating the results obtained from the different Delphi rounds, and it will be presented according to each research question.

> (1) What nanotechnology applications are perceived by science teachers and nanoscience researchers as important to be taught at school science level?

Five nanotechnology applications (nanomedicine, nanoelectronics, photovoltaic cells, nanobots, and self-cleaning) that should be taught in high school (Table 2) were found to be important (median ≥ 4.0 and IQR ≤ 1). Nanomedicine reached a consensus by both expert groups. Another three applications reached a consensus within the teachers' group only; however, there was no consensus regarding their importance within the researchers' group. Nanoelectronics was found to be important by the researchers' group. We decided, as mentioned before, to separate the teachers' and the researchers' input in this educational research study. The five chosen applications by both research groups are as follows: (1) nanomedicine, (2) nanoelectronics, (3) photovoltaic cells, (4) nanobots, and (5) self-cleaning.

These five top-rated applications were also considered important in other studies. Many nanotechnology programs that were already developed included several nanotechnology applications. The importance of each of the recommended applications was highlighted in the literature, as will be described next.

Nanomedicine applications were found to be the most recommended application to be taught at the high-school level. This application received the highest consensus reached by all participants (Table 2). In a thorough review of nano education programs, Jones et al. (2013, p. 7) mentioned that 'biomedical applications [are] perhaps the most important application of nanoscience'. According to Roco, Mirkin, and Hersam (2010), nanomedicine will revolutionize the way one diagnoses and treats people, and in most cases, it substantially lowers the cost of health care. Personalized and point-of-use diagnostic systems will be used extensively to quickly determine the health of patients and their ability to be treated with specific therapeutics. Regarding the therapeutic side, nanomaterials will be the key to enabling gene therapies for widespread use and will serve as an effective means of dealing with antibiotic resistance and the so-called superbugs.

Nanoelectronics applications reached a consensus regarding their importance to be taught in high school by both groups of experts (Table 2). The participants explained that nanoelectronics is important for increasing the performance of electrical devices because of the changes in the size-dependent properties of a specific material. Roco et al. (2010) stressed that 'nanoelectronics has arguably been the primary driver (both economically and technologically) for increasing one's ability to control material at the nanoscale' (p. 284). Soon there will be no choice but to embrace the new nanoscale phenomena and focus on how to utilize them to achieve new functionality. This will not only mean taking advantage of new nanoelectronic phenomena, but will also involve manipulating many properties of a matter at the nanoscale for computation and new forms of data storage. Moreover, this new functionality will not only improve our existing products, it will provide us with new application areas, such as new sensors, new ultralow power devices, and new flexible electronics. This will result in wider uses of applications based on semiconductor nanoelectronics beyond those used in our current daily life such as today's laptops, smartphones and others (Roco et al., 2010).

The *photovoltaic* cell applications reached a consensus regarding their importance (Table 2) only by the teachers' group of experts. However, representatives from both groups believed that students should learn that nanomaterials can be used to produce green and clean energy resources and that nanomaterials can contribute to increasing the efficiency of solar cells, decreasing their cost, and allowing the solar cells to be miniaturized, as reflected from their reasons for selecting this application. Roco et al. (2010) mentioned that nanotechnology applications in the field of renewable energy will be transformed from the research lab to consumer use by 2020. Photovoltaic devices will feature very low-cost, long-life devices, with high efficiency as well as affordable high-performance devices (Ginley & Cahen, 2011).

The selection of teaching *nanobots* reached a consensus only in the teachers' group. Teachers rated this application as important (median = 4.2, IQR = 0.76). The nanobots application is predicted to be used in almost all fields of technology, making life very easy (Drexler, 2013). The fields of security, industry, and medicine will benefit the most from nanorobotics and will be able to realize many tasks that are not presently possible. Nanobots have dimensions comparable to those of biological cells and are expected to have remarkable applications in health care and environmental monitoring (Requecha, Koel, & Thompson, 2003). Nanobots are also described in science fiction stories and films and therefore can appeal to high-school students, and can serve as a basis for developing nanoethics discussions with students (Berne & Schummer, 2005).

The *Self-cleaning* application importance also reached a consensus by the teachers' group only. Teachers rated this application as important (median = 4.1, IQR = 0.80). The *Self-cleaning* application is included in many educational nanotechnology programs. Jones et al. (2013) indicated that this application is an example of a 'smart' material that holds promise for achieving a more efficient world. Teaching students about these advancements has the potential to capture their imagination and excite them about future careers in science (Jones et al., 2013), and it was used in many nanoeducational projects (such as: NanoYou http://nanoyou.eu/en/nano-educators.html)

As was demonstrated above, the applications that were selected in the current study were already recognized and used in different nanoeducation programs. However, the inclusion of all five chosen applications has an added value because they represent a spectrum of different applications and were chosen by considering the different perspectives of two communities of experts in a research-based manner.

(2) What are the differences in how the two different communities of experts (nanoscience researchers and science teachers) perceived the importance of these applications?

In the first round of the Delphi study, the teachers and researchers did not significantly differ regarding the number of nanotechnology applications that they suggested (Table 1). In addition, no significant differences were found between the two different communities of experts (teachers and researchers) regarding the applications they suggested. The only exception was the 'lighting display' application, which was suggested by more teachers. About 33.3% of the teachers suggested this application in contrast to only 4.8% of the researchers (Table 1). This difference can be explained by a program that was introduced to the Israeli school chemistry curriculum that includes the 'lighting display' application (Dori et al., 2014) and a program for junior high school (Blonder & Dinur, 2011). In addition, the lighting display is a popular everyday application that is commonly used in Israel.

In the second round of the Delphi study (Table 2), significant differences were obtained between the two groups of experts (teachers and researchers) regarding ranking the importance of most of the applications. In this aspect, the teachers behaved as a homogenous group although they consisted of high-school science teachers who teach different science disciplines (chemistry, biology biotechnology, and physics). Science teachers experience the need to make science education more relevant to students' lives (Blonder, Mamlok-Naaman, Kipnis, & Hofstein, 2008) and encourage teachers to demonstrate the relevance of nanotechnology to their students' lives. As Gilbert (2006) noted, applications can serve as a science-context-based learning environment that enhances their motivation to learn basic scientific concepts (Bennett et al., 2007; King, 2012).

In contrast to the teachers' group, the researchers' group was heterogeneous in the second Delphi round. They have different scientific backgrounds as well as varied research interests. We found that the researchers suggested applications that are connected to their own research discipline. They considered them as important to be taught and important for humanity and therefore, for most of the applications, a consensus was not reached.

(3) Which of the essential NST concepts are perceived by science teachers and nanoscience researchers as needed for teaching each of the identified applications?

Based on the results of the study, the five selected applications constitute a context-based learning platform for teaching the NST essential concepts. In the third round of the Delphi study, we identified which of the essential NST concepts are needed for teaching each of the nanotechnology applications (Table 3). The nanoelectronics application mapped onto all seven essential NST concepts, and photovoltaic cells mapped onto all NST concepts, except classification of nanomaterials. The other three applications (nanomedicine, nanobots, and self-cleaning) mapped onto four essential NST concepts (size-dependent properties, size and scale, characterization methods, innovation and application of nanotechnology. The resulting connection between the essential NST concepts and each of the suggested applications indicates that the suggested applications can serve as natural and authentic contexts for teaching the essential concepts of NST. Thus, including these applications constitutes an important step toward designing a context-based NST program before it is integrated into the high-school science curriculum. Importantly, the applications will support students' understanding of the field, and enhance their interest in science (Gilbert, 2006), although there is still a need to study students' actual interest in the suggested applications. The connection between the applications as contexts and the NST concepts is a coherent 'need-to-know' basis that makes the students' learning intrinsically meaningful (Bulte et al., 2006). The applications engage the students in mechanistic thinking (Bryan, Magana, & Sederberg, 2015) and support the development of understanding NST concepts in order to explain the nanotechnology applications. Although the NST concepts are abstract, the need to learn them arises from the desire to better understand how the nanotechnology applications work. Therefore, nanotechnology applications serve as an effective context for teaching NST essential concepts.

Implications and further research

Although no significant difference was found between the teachers and researchers regarding the applications they suggested (except one) in the first round of the Delphi study, differences arose between the teachers and nanoscience researchers regarding the importance of the denoted applications and the different factors that should be considered in teaching the applications (in the second round). This raised an important issue regarding the stakeholders who influence the process of curriculum design: Who should decide what should be taught in high-school science? Whose voice should be involved in the discussion? The current study emphasizes that a combination of both teachers and scientists is vital for including different viewpoints when a new curriculum is planned.

However, we believe that an additional study is needed before a context-based NST high-school curriculum is developed. In order to choose a context that is relevant to the students, one needs to include students' voices (Jenkins, 2006), which Hutchinson et al. (2011) have already started to do. Another step that would support the integration of nanotechnology concepts and applications in the existing science curriculum is finding the insertion points of NST concepts in the curriculum and using the identified nanotechnology applications as the context for teaching the NST concepts.

Note

1. Light-emitting diode (LED) is a semiconductor light source.

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Notes on contributors

Sohair Sakhnini is a PhD student in the Department of Science Teaching at the Weizmann Institute of Science, Rehovot, Israel. She is also a chemistry and environmental sciences teacher, at the Italian School in Haifa, Israel.

Dr. Ron Blonder is a Senior Researcher the Department of Science Teaching at the Weizmann Institute of Science, Rehovot Israel.

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