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Young Raw Matters Ambassadors: High School Students Act as Science Communicators

Mariaconcetta Canino[1], Alberto Zanelli[2], Mirko Seri[2], Alessandra Degli Esposti[2] and Armida Torreggiani[2]*

[1]Institute for Microelectronics and Microsystems, National Research Council of Italy, Bologna, Italy, [2]Institute for Organic Synthesis and Photoreactivity, National Research Council of Italy, Bologna, Italy

Nowadays communication skills are essential for the successful future career of undergraduate students, as well as to develop a mindset able to face new challenges linked to a sustainable development and to adopt sustainable strategies with respect to finite resources on Earth allowing the transition to the circular economy (CE) model. Here we present the experience of seven classes of teenagers involved in learning paths linked to researches in the field of material science aiming at developing more sustainable materials. The expected output was oriented toward the common goal of creating a communication tool targeting an external audience. The paths were proposed as a work-based experience in the framework of Raw Matters Ambassadors at Schools (RM@ Schools), a European project which aims at raising awareness on the sustainable use of raw materials as well as increasing the interest in STEM disciplines, able to allow the future transition toward a low-carbon society. By using a combination of approaches such as open discussion, learning by doing, and peer-to-peer education, students are involved in an experiential learning process to develop communication competencies and increase their awareness about sustainability development.

Keywords: school, work-based learning, science education, science communication, career orientation, raw materials in electronics, public engagement with science

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Correspondence:
Mariaconcetta Canino
canino@bo.imm.cnr.it

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INTRODUCTION

The importance of nontechnical skills can be sometimes underestimated in the fields of science, technology, engineering, and mathematics (STEM). However, professional skills are no longer enough in the competitive STEM sector (OECD, 2013; Nugent and Lindburg, 2015), while a set of personal skills, often referred to as 21st century skills (Binkley et al., 2010), are considered key elements for a successful career (American Management Association, 2010; Davidson, 2016). Communication skills, problem solving, critical thinking, and use of digital tools to retrieve or convey information are considered as important as technical skills in the evolving labor market.

In order to fill the gap between the output of education and the expectations of employers, the Italian Ministry of Education established the School-Work Alternation (SWA) in 2015 (Italian Ministry of Education on SWA, 2015) and then it was replaced by the Transversal Skills and Orientation Programs in 2018 (Italian Ministry of Education on PCTOs, 2018) for students from 16 to 19 years old. It consists of an experience which requires students to apply both their technical and personal skills in real job situations proposed by one actor of the civil society (e.g., company, association, and research center) that can be adopted by a school as a part of its training offer

(Italian Ministry of Education "Carta dei diritti e dei doveri" 2017). SWA represents a link between school education and a career in a local productive environment, since students are expected to use the knowledge acquired in their studies to contribute to the achievement of a task. Moreover, collaborations between research centers (Bertelli et al., 2019) or universities (Pugliese et al., 2019) and schools can give rise to a significant relationship between theory and practice, able to develop benefits in providing an environment which can foster professional growth and progressive methods of instructions (Allsopp et al., 2006).

Moreover, in the learning paths for undergraduate students that are the next generation of professionals it is important to integrate a participatory vision on sustainability (Glasser, 2018), in agreement with the Principles of Responsible Management Education established by United Nations which promote responsibility and sustainability as broad concepts within the curricula (UNESCO 2016). In fact, addressing pressing sustainability challenges, such as a sustainable use of Earth resources, requires changes in our way of thinking and acting, that is, changes in the collective mindsets (UNESCO 2017; Scoones et al., 2018). Education is the most important tool to reshape worldviews and values and has enormous potential to address the sustainability challenges facing humanity (IIASA 2018; Kioupi and Voulvoulis, 2019). Thus, it is important to empower learners with the knowledge, skills, and values needed to promote a sustainable society (UNESCO 2014). On the other side, UNESCO's International Institute for Educational Planning, debating the role of education in promoting the Sustainable Development Goals (SDGs), declared that the highly silo-structured nature of education is a significant impediment to realize its potential contribution (UNESCO 2016).

The raw material value chain has been identified by Europe as a sector requiring education of highly skilled professionals because the supply of a certain group of raw materials (RMs) is a major concern for the growth of the European industry (European Commission, 2020). In fact, several countries are implementing green strategies and rapidly switching to clean energy technologies, as the focus on climate change increases. RMs are essential to secure a transition to green energy technologies and to meet the future energy demand through renewable energy sources; the power sector will face a massive deployment of wind and solar photovoltaic (PV) technologies. This is leading to an increase in demand for materials used to manufacture key components of such technologies necessary for a transition to a low-carbon economy. Thus, it is important to create a strategic plan to face this challenge by integrating better exploitation of resources, more efficient material processing, substitution of critical or toxic elements in products and for optimized performance, and design of products and services to help the transition from linear to circular economy.

Education and social awareness are mandatory elements in the actuation of such strategy. For this reason, the European Commission, through the European Institute of Innovation and Technology (EIT) in the sector of raw materials (EIT RawMaterials, n.d.), the largest consortium in the raw materials sector worldwide, has funded a pool of educational projects, where actors from business and science sectors are brought together with educators, with the aim of increasing the public awareness about the use of natural resources, explaining the RM value chain, and training the next generation of innovators. Raw Matters Ambassadors at Schools (RM@Schools) (RM@Schools, 2016) is the flagship project in the Wider Society Learning segment of the EIT RawMaterials and, since 2016, proposes to schools active learning pathways linked to sustainable challenges, solutions explored by research, and improvement of students' technical and nontechnical skills. The paths have a modular structure, including lessons, experiments with RM-related hands-on educational kits and visits to industries, museums and research centers, and a final step focused on the communication work (Torreggiani et al., 2020; Torreggiani et al., 2021). In fact, the students are then asked to become Young RM Ambassadors, i.e., science communicators, by creating dissemination products focused on issues related to RM in both their native and English language. Science communication can offer successful engagement strategies to reignite interest to science education (Baram-Tsabari and Osborne, 2015). Previous research has called this joining-of-forces a third space (Stocklmayer et al., 2010) where formal and informal science education systems work together in order to promote science engagement and literacy (de Vries and van der Sanden, 2016). **Table 1** shows a schematic representation of the activities that can be included in a learning pathway proposed in Italy by the National Research Council (CNR). This path represents a multilearning experience for youngsters linked to the sustainability challenges as well as a case-study for socioconstructivist principles in science classroom since students are actively involved in their own process of learning. **Table 1** shows an attempt to identify in the proposed learning path the phases of learning described by the 5E model of constructivism in science classroom. The 5"Es" model proposed by Roger Bybee employs for Engage, Explore, Explain, Elaborate, and Evaluate. Each of the 5 "Es" describes a phase of learning. In our case the last one, consisting in the moment when the learners are encouraged to assess their understanding and abilities, is favored by the engagement of society (Singh and Yaduvanshi, 2015).

The activities proposed in RM@Schools merge industry-relevant scientific contents with teamwork and creativity-training tasks, which will be useful for students to develop flexibility and ability to handle changes in their future work (Kind and Kind, 2007). The realization of multimedia communication products represents a training in the use of Information and Communication Technologies (ICT) either in information retrieval or in transfer of knowledge. According to the teachers' choice some pathways can be complemented by classes on video-making, storytelling, and internet search tools. The use of two languages (the mother tongue and the English language) allows for the exploration of technical expressions in English. Taking part in live communication events at the national or international level engages students in mastering the scientific contents in order to face discussion. The strong correlation

TABLE 1 | Modular structure of a learning pathway proposed to develop communication competencies and increase their awareness about sustainable development. The columns represent the modules and each module includes independent optional activities.

Learning pathway modules					
	1 *Introduction to the RM-related topic*	**2** *Strengthening the link with research and labor market*	**3** *Strengthening/ widening of topic knowledge*	**4** *Creation*	**5** *Communication/dissemination*
Main Actor	Researcher	Researcher/Teacher	Student	Student	Student
Activity	Lesson	Hands-on experiment Lab visit Company visit Lesson	Individual research to retrieve more information from web	Communication product Experimental kit	Other schools Science fair EU conference Web/social media
Constructivist phase	ENGAGE	EXPLORE	EXPLAIN	ELABORATE	EVALUATE (engage society)
	Students become interested in the scientific topic linked to reality	Students discuss about the activity in the classroom or with external experts	Students redefine and increase their own understanding	Students practice multidisciplinary skills	Students self-evaluate his/her performance and the own progress by facing the public

TABLE 2 | Summary of the activities carried out by the seven classes involved in this case-study; the cognitive skills reached in each activity included the learning path are indicated in square brackets.

Class number	Activity 1 Lesson	Activity 2 Hands-on experiment/other Lesson	Activity 3 Creation Communication product	Activity 4 Science communication to Society	Activity 5 Other communication activity
1	Mobile Phone [U]	-	Video [A]	EU Conference for schools [C]	Raw Material Week 2016 [C]
2	Mobile Phone [U]	Lab on electrodes [Apply]	Experiment protocol [A]	Farmers' market [C] EU Conference for schools [C]	-
3	Mobile Phone [U]	Lab on electrodes [Apply]	Board game [A]	White night at school [C] EU Conference for schools [C]	Peer education in another school [C]
4	Mobile Phone [U]	Lab on electrodes [Apply]	Experiment setup [A] Video tutorial [A]	-	Peer education in the own school [C]
5	Mobile Phone [U]	Lab on electrodes [Apply] Power electronics in e-cars [U]	Digital games [A]	Open event in the own school [C]	-
6	Mobile Phone [U]	Power electronics in e-cars [U]	Video [A] Newspaper [A]	European Researchers Night 2019 [C]	Interaction with Industry [Apply]
7	Mobile Phone [U]	Materials for automotive [U]	Flyer [A] Newspaper [A]	Competition Scienza-E [C] EU Conference for schools [C]	-

Remember *[R]: recognizing or recalling knowledge from memory.*
Understand *[U]: constructing meaning from different types of functions like interpreting, exemplifying, summarizing, comparing, or explaining.*
Apply *[Apply]: carry out of using procedure through executing or implementing. Referred to situation where learned material is used through products like models, presentations, and interviews.*
Evaluate *[E]: making judgments based on criteria and standards.*
Create *[C]: putting elements together to form a coherent or functional whole; reorganizing elements into a new patter or structure.*

between these activities and the development of soft skills makes RM@Schools activities suitable for SWA and PCTOs for many kinds of schools.

We present the experience of seven classes (about 160 students) involved in a learning path whose expected outcomes were an increased awareness about the importance of research in facing innovation challenges and the "transformation" of students into science communicators able to present to a general public some research topics in the field of material science.

METHODS

Activity Structure

The pathway proposed by RM@Schools has a modular structure. It begins by introducing students to relevant content knowledge about the advantages and issues coming from the use of certain materials in electronic technologies, as well as some solutions offered by the research for replacement materials. Then, students are engaged in another activity to support or extend their learning and their inquiry skills. Afterward, the students are asked to

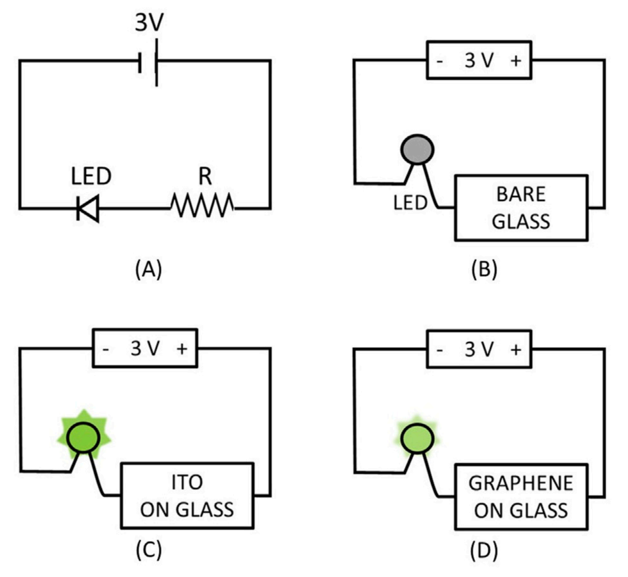

FIGURE 1 | Circuit scheme of the experiment on ITO substitution in transparent conductive coatings. **(A)** Switching on a light emitting diode (LED) inserted in a circuit made up of the LED itself, one battery, and one resistor. **(B–D)** The resistor is presented in the form of a glass platelet either uncoated **(B)** or coated with transparent conductive layers of different materials **(C,D)**. The light turns on only when the glass is coated by ITO **(C)** or graphene **(D)**.

communicate their learning by creating communication products, designed to promote dialogue around the key message that they have learned. Students work in small groups to develop their versions of the experiments and their communication products can take several forms: videos, lab experiments or serious games, lessons for younger pupils, and participation in public science dissemination events. The students were involved in the learning path described here for about six months. **Table 2** summarizes the activities carried out by the seven classes and the cognitive skills reached in each activity included in the learning path.

The case-study scientific theme presented in this contribution is focused on raw materials in emerging electronic technologies. It was presented to all the classes by a frontal lesson named "Don't Throw Away Your Mobile" (Canino Lecture, 2020) which gives an overview on the materials applied in emerging technologies and provides some links with school curricula in chemistry and physics. By starting from mobile phone, a device that is very attractive for youngsters, a reflection/discussion about elements/materials classified as critical because of their economic importance for many industrial applications and emerging technologies (i.e., Rare Earth Elements in high efficiency permanent magnets, Indium in flat panel displays and solar cells, etc.), but with a supply risk, was opened. Implementing novel, noncritical materials into electronic devices allows for substitution of the critical ones and can be a possible solution to the problem. Thus, the research on finding an alternative to Indium Tin Oxide (ITO), that is used as a transparent electrode in optoelectronic devices, e.g., in flat screens and solar cells (Pang et al., 2011), was presented to students. One possible substitute of ITO is graphene, a single layer of carbon atoms arranged in a two-dimensional hexagonal lattice. Graphene was first isolated from graphite in 2004 (Novoselov et al., 2004). Among its properties, high transparency, flexibility, and electrical conductivity make graphene a suitable candidate as a transparent electrode in electronic devices.

The connection of the scientific content with an object from daily life was highlighted with the aim of catching and maintaining students' interest toward RMs. Furthermore, the introductory lesson was followed by a second guided activity in order to enhance the students' ability to apply their knowledge to real situations (Perkins, 1993). The second step of the pathway consisted in an activity capable of supporting or extending the students' learning and their inquiry skills: carry on a hands-on experiment followed by the result discussion, or a lesson on the results obtained in a European research project, or a survey on the materials used in automotive over time.

The proposed hands-on experiment consists in switching on a light emitting diode (LED) inserted in a circuit with one battery (**Figure 1A**). The circuit can be closed on three different glass platelets: one uncoated, one coated with a transparent conductive layer of 100 nm thick ITO, and one coated with single-layer graphene (**Figure 1B**). The students verify that the light turns on when the glass is coated by ITO or graphene (**Figures 1C,D**) although the light becomes fainter with graphene. After the experiment, a brief discussion about the pros and cons of the substitution of ITO by graphene (i.e., pros: devices could be flexible; cons: battery would discharge faster) was opened with the class. This debate can also lead to discussing the difference between commercial and laboratory-scale materials, introducing additional concepts such as technology scaling-up and transfer. The hands-on activity complemented the pathways of four classes (**Table 2**).

Two classes went deeper into the research in material science by following a seminar on the results of a research project called "Challenge" (Challenge, 2017), funded under Horizon 2020 and aimed at modifying the production of silicon carbide (SiC) which is a semiconductor using the set of appliances that must sustain high voltages, such as the ones that control electric cars, industrial equipment, and energy plants (Spaziani and Lu, 2018). By using simple words, the tutor introduced Frontier knowledge such as physical properties of semiconductors, defects in native SiC, material manufacturing processes, and cost. Analogously to the hands-on experiment, the seminar provided an example of substitution in the field of raw materials aimed at reducing the material cost, and not related to the need of replacing scarce elements in technical applications, as shown during hands-on experiments. In particular, for SiC the replacement can be operated by using a material constituted by the same elements but differently arranged in space (Canino et al., 2021).

One class, Class 7, attended a lesson about the materials used in automotive: from steel and bronze of the first cars, to the Rare Earth Elements (REE) used in the current electric motors, and the platinum group metals in the catalytic converters of the 1980s. Automotive is an interesting topic for 16-year-old students and an important industrial sector in the area where students of Class 7 live, that is, Emilia-Romagna Region, n.a., the region hosting famous sport-car and motorbike brands such as Ferrari, Lamborghini, Maserati, Pagani Zonda, and Ducati.

Then all the classes were involved in the Step 3 of the learning path that consist in the creation of communication products aimed at disseminating the key messages to different targets, such as younger pupils, peers, or a general public. These products were used in Step 4 to support the communication work of student events in schools or in open-spaces (**Table 2**).

The creation of original content is the pedagogical core of the activity. In accomplishing this task, students internalize the acquired scientific concepts by coconstructing and negotiating ideas through meaningful interaction with peers and, where necessary, with their teachers and tutors (Solomon, 1987). Acting as science communicators builds on the concept of situated learning (Lave and Wenger, 1991), with students having the opportunity to engage socially in the scientific community, by sharing some of the tasks (Driver et al., 1994) and language (Singer et al., 2000) of researchers.

Participants

The participants comprised the teachers and students in seven adolescent classes from five schools in Italy. The number of students involved was about 160. All the classes were from Scientific High School with the exception of two classes attending a Technical School (Class 4 and Class 5). This paper summarizes the results collected along three years.

Materials

Didactic material was made available to all the classes, included a set of references complementing the seminars/lesson.

Students were allowed to use their own additional ICT devices for information retrieval and to realize communication videos. The classes received different assignments in agreement with the specific regular curriculum in order to strengthen the bridge among SWA and school curriculum and to test the use of different skills.

Teachers and students were provided with some test circuits (battery + LEDs), glass, ITO/glass, and graphene/glass slides. In technical schools, students were able to assemble their own circuits within the school facilities.

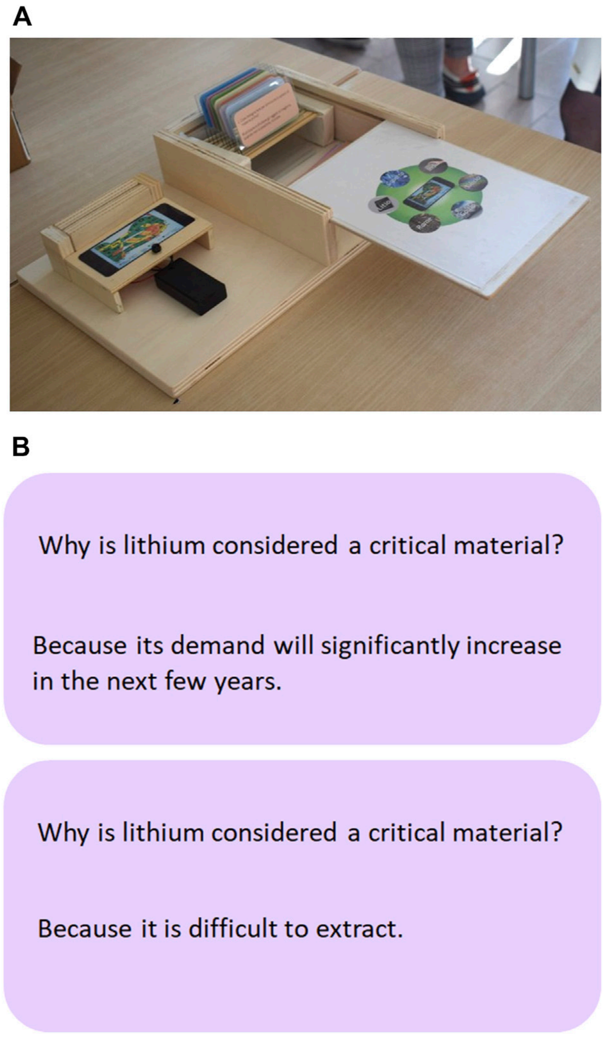

FIGURE 2 | (A) Board game realized by students of Class 3: the circuit is on the **left** while the box, containing the glass platelets where the questions are printed, is on the **right**. **(B)** Example of labels where the question is followed either by the correct answer **(top)** or by the wrong answer **(bottom)**.

RESULTS

Communication Products Realized by Students

Videos

Class 1 realized four short movies, each focusing on a different aspect concerning RMs in mobile phones: geopolitical and ethical aspects concerning the supply chain of certain materials which can be found in mobile phones; the consumer habits in purchase and disposal of mobile phones (consumerism); the history of the miniaturization of electronic technologies; and the substitution of critical raw materials by other materials such as graphene (for more detail see **Supplementary Table 1**).

The variety of topics, declined as a mix of social values and science, allowed for the exploitation of different skills connected to the different interests the students had (i.e., human rights, science, videogames). These products were then presented by students at the Raw Materials Week in Brussels.

A video on SiC devices in electric cars was realized by Class 6 (**Supplementary Table 1**). The research in the field of SiC material development was explained by using nice images (some drawn by the students themselves) and a witty use of the language, culminating in the pun in the movie title. The use of specialist terminology, instead of loading the speech, resulted in a clear and precise description of the situation. This movie was projected during the European Researchers Night held in Bologna in 2019.

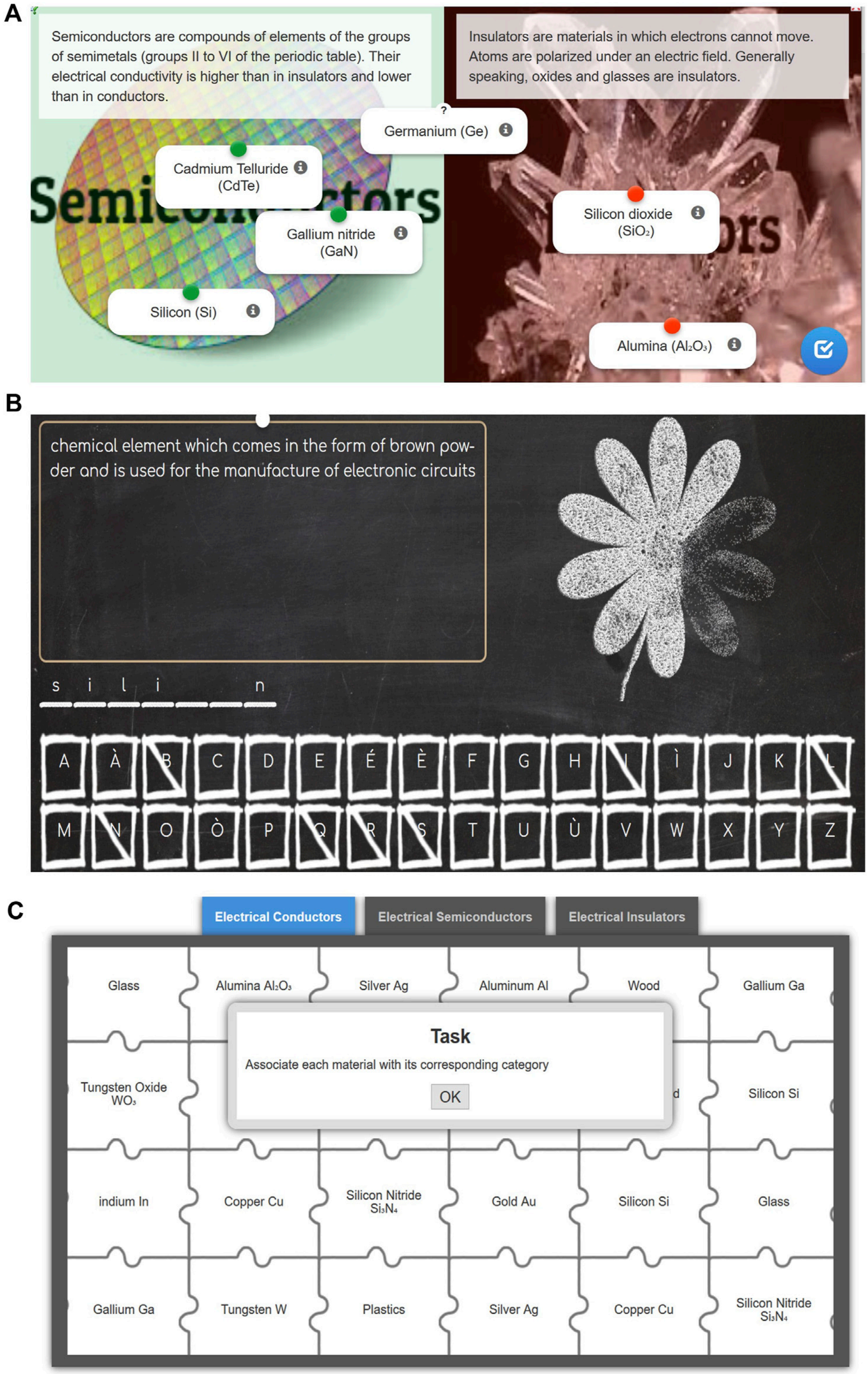

FIGURE 3 | Screenshots of the digital games created by students of Class 5: **(A)** the "semiconductor or insulator?" quiz; **(B)** the "hangman game"; **(C)** a puzzle associating each material to the corresponding category.

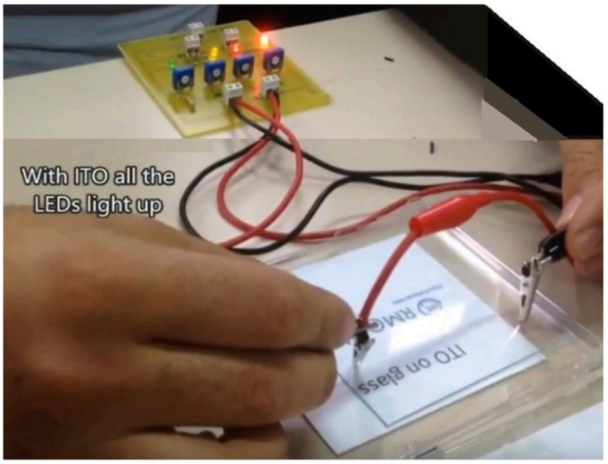

FIGURE 4 | Experiment on ITO substitution carried out with the printed circuit board realized by Class 4 and Class 5. This image is obtained by juxtaposing and matching two photograms of the movie (circuits in **Supplementary Table 1** in Supplementary Info).

Educational Games

In order to reach peers and convey information about RMs and the materials used in electronic devices, the gamification approach was chosen by Class 3 and Class 5, who realized a board game and a set of digital games, respectively. The working principle of the board game reproduced the circuit fabricated in the lab experiment. It consisted in a quiz made up of ten forced-choice questions, printed on two labels: on one label it was followed by the correct answer and on the other by the wrong one. The labels were glued on the two sides of an ITO-coated glass platelet with the right answer on the ITO-coated side. The circuit, composed of a battery and a red LED, was inserted in a wooden structure able to lodge a coated glass. The role of the ITO coating was to close the circuit allowing for the LED lighting up if the player chose the correct answer; otherwise, the LED did not light up. **Figure 2** shows the board game and a sample question. This tool was then used during an open-access event organized in the school, the White Night.

The set of digital games focuses on materials and techniques used in electronic, power electronic, and optoelectronic device fabrication (**Figure 3** and **Supplementary Table 1**). It served as a playful final during the open event organized in the Technical School, attended by more than 80 participants.

By playing these games, students can recall knowledge about names and electrical properties of the materials dealt about in the pathway, and the public of the open events could reinforce the key messages conveyed by the seminars.

Experimental Tools

The students of the Technical School (Class 4 and Class 5) were asked to fabricate a circuit where a scale of LEDs allows for a visual comparison between the resistivity of ITO and graphene coatings, accompanied by a video tutorial to explain the phases of the work (**Figure 4** and **Supplementary Table 1**). A special focus was given to the ability to explain the scientific content related to the experience and the fabrication techniques in order to present the work to the commissioners in the final examination for the diploma. The whole workflow was carried out in autonomy under the supervision of the teachers.

Another class (Class 2) outlined a tutorial containing instructions to make an experiment replicable in the physics laboratory of a high school. Two types of tutorial were produced: a written document and a video (**Table 2**). The work was carried out in both Italian and English. Much attention was devoted to the use of correct scientific terms in English because the class had the achievement of the IGCSE (International General of Secondary Education) certification among its objectives.

Newspaper Articles

Class 6 wrote science dissemination articles which were published in a local newspaper. They deal with the advantages of controlling electric motors by using high performance electronic devices, production, processing, and disposal of silicon carbide devices, and the issues in integrating innovation with established production routes (**Supplementary Table 1**). The articles give a fresh outline of pros and cons as perceived by the students themselves and represents a good proof of the enhancement in science communication skills among youngsters, that is one of the aims of RM@Schools.

Science Communication Experiences

Once the product has been developed (i.e., video, lab activity, game, etc.), students are expected to share their learning. The pathway leads them to communicate within their school or into the community at large. School-based communication aims at promoting the knowledge of the topic among peers by presenting, for example, an event in their own school or by running a lesson for younger pupils; otherwise, students can engage with society outside their school by taking part in existing public events such as science fairs. The communication experiences carried out by the students were many and of different types.

The videos realized by Class 1 were appreciated by the EIT RawMaterials who invited a delegation of 12 students to present their work in Brussels during the Raw Material Week (Raw Material week, 2016), an international event organized by the European Commission with specialists from academia, industry, and research (**Table 2**). Similarly, the video realized by Class 6 was shared with a general public during the European Researchers Night held in Bologna on Sept 27, 2019 (EU Researchers Night, 2019), at the stand of the “Challenge” project. The students assisted the public in playing some games developed for two age ranges and answered questions about scientific issues with the support of a poster and their movie. As the students themselves commented, the experience was interesting and engaging (**Supplementary Table 1**).

Other students (Class 2) gave a presentation in a local farmers’ market hosted by an environmental association (Public event in San Lazzaro di Savena, 2017). The topic was the discussion of the different possible approaches to face the problem of raw materials in electronic devices. Reduction of consumption and recycling of electronic waste were illustrated and discussed under the guidance of the teacher of philosophy, while the issues

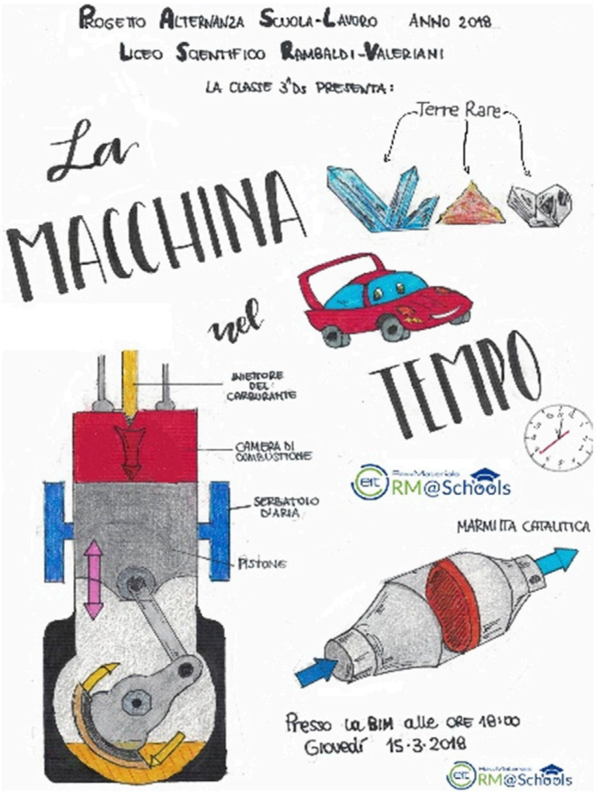

FIGURE 5 | Hand-drawn flyer of the live event "The time machine" presented by Class 7 at Scienza-E.

connected to the substitution of scarce materials and need for technology transfer, i.e., optimization of material and device processing from research to industrial scale, were discussed and exemplified by the experiment of ITO substitution in transparent electrodes. This experience represented an example of multidisciplinary activity based on contemporary science. As the seminar took place six months after the laboratory experience, the students demonstrated their ability to describe and reproduce the experiment and present their findings over time.

Class 3 contributed to the "White Night" public event hosted by the own school open both to the families and to the citizen of the municipality (RM@Schools-White Night for Science in Lissone, Italy, 2019) and was involved in peer education toward younger students of another school. The latter activity of science communication is of value. In fact, students who spend time in teaching what they have learned show better understanding and knowledge retention than students who simply spend the same time in restudying (Cohen et al., 1982). Class 5 contributed to the success of an open event organized at school and assisted the public in playing their games. Class 7 took part in the science festival Scienza-E (Scienza-E, 2018) with a presentation about the role of materials in the evolution of motors over time (in **Figure 5** the flyer to advertise the event is reported). The presentation arose an animated discussion within the public. Furthermore, one of these students was awarded with the first prize at the competition "5 min of science" with a short pitch about electric motors. This activity was not anticipated and denotes the ability of this student to adapt the speech to a different context in only 3 days.

Differently from the other undergraduate students, the teenagers of Class 6 were involved in further communication experience addressing a local company which produces electric vehicles. A very fruitful discussion session was open with professionals: students discussed the advantages and limitations of introducing SiC inverters in electric vehicle production and an innovation manager explained to them that cost and reliability of components are the key elements guiding the choice of companies, highlighting the need for further research in the improvement in the SiC material quality and processing technology.

Finally, three classes took part in the European Conference, annually organized for schools by the RM@Schools project, which involves delegates from 18 European countries and about 500 participants (**Table 2**) (EU RM@Schools Conference 2019). The project European Conference plays pivotal role in training science communication skills. It is not only a very important celebration of the work done by students but it also gives young people the opportunity to meet their peers from the other countries and explain by themselves on the stage what they have created in the framework of the project.

DISCUSSION

Studies suggest that learners chose whether to pursue a career in science, or not, as adolescents (12–17 years old) (Tai et al., 2006). Those who report more positive experience with school science are far more likely to continue in science after this age (Shirazi, 2017). Focusing on the development of engaging experiences in the science classroom may be a good strategy to encourage students to stay in science.

The case-study discussed in this paper presents the results of a work-based experience for teenagers combined with their involvement in science communication actions. It suggests how a form of work-based learning can create a unifying vision for action and does so across multiple disciplinary and identity boundaries. The proposed pathway was integrated into existing curricula of different kinds of schools with broad focus in terms of multiple disciplinary resources as well as personal skills. Contrary to the predominantly fragmented and disciplinary bounded approaches to sustainability, forms of work-based learning such as the one in our case-study are able to cross the conceptual boundaries and act as a catalyst for a wider cultural change, in agreement with the literature (Sun and Kang, 2015; Wall, 2017; Wall et al., 2017). The project-generated actions toward peers, besides the creative ideas for delivering messages on sustainability and the importance of research to society, provide an illustrative example of how a learning path can have transformative impacts in changing the students' societal perceptions of sustainability from "indifference" to "involvement and responsibility."

The learning path starts from the mobile phone which contains many of the materials classified as critical and some considered conflict metals. The connection with a useful object from real life is meant to catch the students' interest (Perkins, 1993). In order to maintain and consolidate knowledge, the classroom is guided to make considerations on sustainable use of Earth resources, environmental and sociopolitical issues, and personal and social responsibility that involve the whole lifecycle of this device. Basing on the student prior knowledge and wider interests to create knowledge recalls Dewey's pedagogy (Dewey, 1938). Thus, depending on the school curriculum and the interest shown by the class, this topic was developed in different ways. While Class 1 analyzed in more detail the provenience of the materials that can be found in a mobile phone and discussed some of the geopolitical issues connected to it, Class 2 reflected about possible solutions by comparing two approaches to reduce waste, including e-waste: either by reducing personal consumption (degrowth) or by progressing through research. Other classes focused on automotive due to the clear manufacturing vocation of their geographical location and worked about the application of novel materials or processing routes in electronic device fabrication. Independently on the different viewpoint toward the sustainability challenge, the works of all the classes highlighted the personal responsibility of consumers, which testifies students' commitment to give a prompt contribution.

Table 2 summarizes the activity modules of the learning path proposed to the classes and the learning outcomes that can be obtained in each module on the basis of taxonomies of cognitive domain (Andreson and Krathwol, 2001). The level of cognitive skills was qualitatively evaluated on the basis of the revised Bloom's Cognitive domain which has a hierarchy of categories that capture the process of learning, from simply remembering information to creating something new: Remember, Understand, Apply, Analyze, Evaluate, and Create. Each module of the learning paths proposed to the classes is intended to favor the achievement of one of them.

The variety of communication products realized by students involved in the RM@Schools project, analyzed in detail by Canino et al. (Canino et al., 2020), shows how science communication can offer successful engagement strategies to science education to reignite interest, in agreement with the literature (Baram-Tsabari and Osborne 2015). Moreover, it reflects some of the key principles which are themselves relevant to sustainability, such as the need to work across the boundaries of disciplines, subdisciplines, or organizational structures.

In order to create original content, each class retrieved more information on the web and selected the material according to the themes that the students found most interesting (**Table 1**). Some students (i.e., from classes 2, 4, and 6) also asked further information to experts, and this discussion resulted in a higher level of scientific correctness in the realized product and an enhanced critical thinking among students. It was observed that though the researcher's availability to be contacted was offered to all the classes, actual contacts mainly occurred when the students were involved in public events, mostly in the approaching of the event. Consequently, we find that the expectation of the public speech is an effective tool to stimulate the students to deepen their knowledge in order to achieve legitimate peripheral participation (Lave and Wenger, 1991) in the research community.

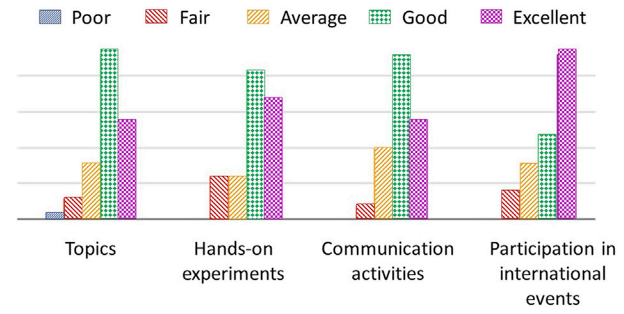

FIGURE 6 | Student evaluation of four aspects of the RM@Schools project: topics, hands-on experiments, communication activities, and participation in international events. The survey was completed by more than 20 classes, i.e., more than 500 students.

Students described that part of what made the learning path fun and exciting was developing communication products and getting to express their learning, creativity, and humor. For example, through the storytelling experience in creating a video, students felt that they could enjoy the content they were learning throughout the process of researching and producing their videos. We argue that it was the process of film making that allowed students to revise and learn material in a new way that aided their understanding and enjoyment of learning.

The creation of material to support live communication showed to be a successful step to recollect and elaborate on the treated scientific topics; it has additional impact on some of the 21st century skills: creativity, through the seek for original production; information literacy, through the search of further information; decision making, through the selection of the topics; communication and collaboration, through teamwork; critical thinking, because the outcome of research is not obvious. In particular, we observed that students' participation in live dissemination events enhances the results obtained by creating communication materials, the depth of the scientific insight, and the satisfaction toward the pathway. Moreover, this kind of experience enhances the public speaking and leadership abilities of undergraduate students.

The participation to live dissemination events, especially in an international context, is one of the most appreciated activities proposed by the project. **Figure 6** shows the results of a survey proposed to all the classes who took part in the RM@Schools project in the years 2016–2018. Four aspects were evaluated: the topics, the hands-on activities, the communication activities, and the participation to international events. The participation to international events, such as the Raw Material Week and the final project conference, was rated as excellent by most of the students, underlining the interest in connecting with peers from different countries. We observed that students appreciated being involved in live events also at local level. Student satisfaction is clearly expressed in the slides created by Class 2 to report their SWA experience (RM@Schools, 2019, Don't Throw Your Mobile

Phone Away, 2017) and in the video created by Class 6 at the end of the European Researchers Night (Students for Challenge at the European Researchers' Night 2019, 2019). Moreover, we observed that some of the students repeated the experience, if they had the chance. For example, Class 3 made peer education to younger students; one girl of Class 7 decided to participate in the competition "5 min of science." Students also showed a good capability to choose a different form of communication on the basis of the target to be reached. For example, movies were preferred as a tool to communicate with a remote and large public (Class 1 and 6) and to document the instructions of experiments for peers (Classes 2 and 4). They were shared on the Youtube channel of Challenge and RM@Schools, obtaining a high number of visualizations. Games were used to catch the interest of passers-by during open-access events such as the European Researchers Night and to reinforce the acquired key concepts provided to the audience by a previous seminar. Similarly, showing an experiment to the public and giving scientific information about the issues and solutions linked to it, was a successful approach to engage the public. As regards the seminars given during events, the link from a social problem to the application in real life of a research finding thoroughly improved the understanding of scientific phenomena among students and fostered a more positive storytelling.

CONCLUSION

Experiences in science classes at school can have a significant impact on engagement with science (Venville et al., 2013; Reinhold et al., 2018). Strategies to maintain or promote engagement of teenagers in science field are needed as this is the critical age students make choices, knowingly or subconsciously, of what they will pursue in their future as well as to develop informed and engaged future citizens.

The learning path present in this paper represents a replicable case-study able to promote some of the 21st century skills (Hidayatullah et al., 2021) and the image of science and technology for students aged 14–18 years with a particular attention to raising awareness on the sustainable use of some materials and new professional careers in science material sector. The experience of combining science communication and work-based experiences with science found students more engaged than in their typical science class. In fact, sustainability competences do include not only cognitive components, such as knowledge and understanding of environmental, social, and economic systems, but also social skills, values, and emotions, collectively referred to as the affective domain of learning (Faham et al., 2017). By involving student in a creation/communication work, students are asked to defend in principles and practices how they explained the reutilization of raw material to others, therefore, placing them at the center of the learning transaction of person to person or person to groups.

This case-study, contrary to the predominantly fragmented approach currently available, generates a unifying, boundary-crossing experience with positive indicators of cultural change. In fact, the creation of communication products requires the use of skills related to the ways of thinking and working. Information literacy and English language mastering are necessary for information retrieval, and due to the wide variety of the social and scientific RM-related issues, a selection of the information to deliver to the public was constantly realized. Additionally, the learning path improved the set of skills related to citizen education and personal and social responsibility, beside the career orientation of teenagers.

In addition, the advantages of experiential learning include higher student motivation and better retention of knowledge compared to traditional lectures as well as an improvement in critical thinking about the transfer of research findings to the market.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: www.rmschools.eu.

ETHICS STATEMENT

Written informed consent was obtained from the individuals for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

MC is a researcher in the field of electronics. She created the lesson "Don't Throw Away Your Mobile," the experiment on ITO substitution, and the lesson "Electronics for Electric Cars"; she directed all the described paths and analyzed the students' output. AZ and MS are researchers in the field of novel materials for batteries and photovoltaics; they gave extra seminars on the topic to the classes that twinned with Class 1 and Class 3 in the live events. AE is a researcher and she is responsible of the project website that is a repository of the dissemination products and events. AT is a researcher and the RM@Schools project coordinator. She perfected the RM@ Schools methodology and organized the pathways with the schools.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2021.690294/full#supplementary-material

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