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Fostering Chemistry Students' Scientific Literacy for Responsible Citizenship through Socio-Scientific Inquiry-Based Learning (SSIBL)

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Abstract: Fostering secondary education students' responsible citizenship and preparing them to be critically engaged with global socio-environmental challenges are of crucial importance toward achieving sustainability. This paper contributes to the effort to understand how to support students' scientific literacy for responsible citizenship by reporting on a study evaluating the impact of a learning intervention on biofuels, structured upon Socio-Scientific Inquiry-Based Learning (SSIBL) pedagogy. The participants were 93 students in secondary chemistry education; these students were assigned to the SSIBL group (n = 46) or to the control group (n = 47), which participated in Business-As-Usual (BAU) instruction. Quantitative data were collected with the Global Scientific Literacy Questionnaire (GSLQ) before and after the learning intervention for evaluating students' perceptions of science as a human endeavor (i.e., nature of science), as well as their personal responsibility and willingness to take action for maintaining a sustainable environment (i.e., values and attitudes). Qualitative data were also collected through video recordings of the SSIBL implementation to examine how the SSIBL instruction was enacted. The findings indicated that, after the implementation, students in the SSIBL condition outperformed their counterparts in the control condition. These findings provide empirical documentation supporting the use of the SSIBL learning intervention to foster students' scientific literacy for responsible citizenship. The video recordings also shed light on how the SSIBL instruction phases (i.e., Ask, Find out, Act) contributed to the development of students' responsible citizenship, as a pre-requisite for achieving sustainability.

Keywords: chemistry education; responsible citizenship; scientific literacy; Socio-Scientific Inquiry-Based Learning (SSIBL); sustainability

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1. Introduction

The world is facing severe global challenges, such as climate change, the depletion of natural resources, and food insecurity [1,2]. These challenges indicate that science educators should prepare their students to enact more responsible forms of citizenship, as well as to think and act in scientifically responsible ways to achieve a more sustainable future [3]. Students should be empowered to successfully fulfil their roles as "responsible citizens", in order to be able to make evidence-based decisions grounded on scientific ideas, as well as to take socio-political actions to resolve issues for the larger good of the global society [4,5].

To achieve these goals, we posit that students should develop an integrated form of scientific literacy, which expands beyond the mere understanding of science, into encompassing "science as a tool" for addressing global socio-environmental challenges [6,7]. Students should develop a form of "global scientific literacy" entailing (a) an integrated understanding of the core ideas of science, realizing that science is a human endeavor (i.e., nature of science), as well as (b) values, morals, and worldviews that can lead people to make appropriate choices and decisions to ensure a sustainable planet (i.e., values and attitudes) [8].

Both aspects are well related to the PISA and NGSS frameworks. For instance, the nature of science as a human endeavor is discussed among the practices and core ideas of the NGSS framework, as particular emphasis is placed on the fact that scientists rely on human qualities and are guided by habits of mind, as well as the fact that science is affected by society and technological advancements and vice versa [9]. Likewise, the PISA scientific literacy domain refers, among others, to an individual's "[. . .] understanding of the characteristic features of science as a form of human knowledge and enquiry; their awareness of how science and technology shape our material, intellectual and cultural environments; and their willingness to engage with science-related issues, and with the ideas of science, as a reflective citizen" [10] (p. 7). In addition, according to the PISA framework, students' values and attitudes, in terms of responsibility toward science-related issues, which have local and global consequences, should be an important outcome of science education. In particular, students are expected to show a sense of personal responsibility for maintaining a sustainable environment, to demonstrate awareness of the environmental consequences of individual actions, as well as to demonstrate willingness to take action to maintain natural resources [10].

Reforming science education to respond to these calls for responsible citizens has become a main focus of policy, research, and education. As a response to these calls, there has been a shift toward the use of socio-scientific issues (SSIs) in science teaching with regard to serious problems which involve moral, ethical, and financial aspects and lack clear-cut solutions [11]. The global science education landscape has sought to integrate SSIs into science education as a means toward responsible citizenship [12]. This is not surprising given that an ever-increasing research corpus has provided evidence that SSIs can improve students' scientific understanding and argumentation skills and can empower them to deal with complexity and take part in debates, while also supporting them to make informed decisions and better understand the nature of science [13,14]. SSIs, in many cases, may also be linked to sustainability education, especially when they focus on technologies and human practices affecting the environment [15]. Moreover, sustainability issues are comparable to the nature of SSIs, given that they are also "open-ended, difficult to solve, and have personal and global implications" [16] (p. 182).

Despite the effort to reform science education via the lens of SSIs, research on how to infuse SSIs into mainstream science education, in relation to sustainability issues, is still limited [15,17]. SSI instruction is usually narrowed down to the presentation of socio-scientific challenges, with no attempt to promote students' civic engagement, participation, or action, while there is also a lack of research in pedagogies associated with responsible citizenship [18,19]. In this context, we present a study which evaluates a learning intervention, structured upon Socio-Scientific Inquiry-Based Learning (SSIBL) pedagogy, as a novel pedagogy which highlights the importance of presenting the societal aspects of science to students while also inviting them to take action. This paper examines the following questions. (1) What was the impact of the SSIBL instruction compared to the Business-As-Usual (BAU) 8th grade chemistry instruction on scientific literacy for responsible citizenship in terms of (a) students' perceptions of science as a human endeavor (i.e., nature of science) and in terms of (b) students' sense of personal responsibility and willingness to take action for maintaining a sustainable environment (i.e., values and attitudes)? (2) How the SSIBL instruction contributed to the enhancement of students' scientific literacy for responsible citizenship? This study contributes to the need of implementing and providing empirical substantiation to pedagogies which may foster students' responsible citizenship as a pre-requisite of achieving sustainability.

2. Theoretical Framework

2.1. Scientific Literacy for Responsible Citizenship through SSIs

Scientific literacy has become one of the most overused terms in the literature, as it has been deployed over the decades to point out what the ultimate goal of science education should be. As other researchers have previously stated "Discussions of the aims of science education often begin with 'scientific literacy'" [20] (p. 910). However, the actual meaning of the term and what it really entails has been subjected to various interpretations over the years, thus lacking a universal consensus [7,20,21].

Regarding taxonomies, the most influential taxonomy classifies the purposes of science education in two visions (Vision I and Vision II) [22]. Vision I reflects the idea that the primary goal of science education is about helping the learners to develop accurate scientific knowledge and scientific skills and to obtain well-informed epistemological ideas about the nature of science for future career use within the sciences [6,20,22,23]. On the other hand, Vision II reflects the idea of using science to support learners to make informed decisions about societal issues related to their everyday lives, thus emphasizing the "social dimension" of science [6,24,25]. Vision II shifts away from prioritizing decontextualized scientific concepts and highlights the importance of situating science in meaningful contexts which involve personal decision-making [20]. The tension between Vision I and Vision II is, therefore, obvious, with Vision I focusing on the preparation of future scientists and Vision II capturing the idea of "science for all" [26].

Despite this tension, over the last decades, research has resulted in an ever-increasing corpus of evidence supporting the effectiveness of Socio-Scientific Issues (SSIs) in promoting scientific literacy across both visions [27]. Even though Visions I and II are described as the opposite ends of a continuum, "SSI instruction has been linked with improvements in outcomes associated with both visions" [23] (p. 275). For instance, several studies have reported that SSIs may support students' learning of basic scientific concepts and principles, higher-order thinking skills (i.e., argumentation, critical thinking, evidence-based reasoning, and decision making), and an epistemological understanding (i.e., nature of science) [28–34].

However, if science education is also about nurturing democracy and empowering citizens to make responsible decisions related to global socio-environmental challenges, then Vision I and II of scientific literacy seem to be inadequate [6]. For instance, scientific literacy has been related to the European sense of Bildung, given that both constructs emphasize the need to empower students for socio-political participation and action-taking in a complex world [35]. This type of socio-cultural and politicized science education has been related with a form of "critical scientific literacy" [36]. More specifically, this type of science education has been discussed as a vehicle for the empowerment of responsible citizenry, which is all about questioning authority, the trustworthiness of evidence, and the power structures in society, while also taking action based on one's values to achieve more inclusive and sustainable socio-environmental patterns. Following this argument, it **seems** that there is a need for a more humanistic perspective on science literacy that emphasizes students' social action for dealing with issues of social injustice and inequity, aiming at the creation of a more sustainable society for the common good [37].

In this context, Vision III of scientific literacy, which focuses more on responsible citizenship and sustainability has been proposed [26]. Vision III of scientific literacy is about the development of "students' critical thinking so that they can discuss and consider the ethics, values, and risks involved in societal issues that have a basis in science. It also involves learning how to use that knowledge to make decisions and take action, both personally and collectively, that will lead to a more just world for all—a justice-oriented scientific literacy" [6] (p. 240). Therefore, Vision III of scientific literacy gives emphasis on the socio-political dimensions of science education seeking to achieve socio-ecojustice [26]. For this reason, Vision III is also closely related to recent educational paradigms such as Responsible Research and Innovation [RRI] and Education for Sustainability (EfS) [38,39].

Vision III of scientific literacy is also related to recent discussions regarding the formation of student sustainable development and citizenship competences. On one hand, the formation of sustainable development competences is deemed to be of great importance for empowering young students to successfully deal with global socio-environmental challenges as well as for facilitating the societal transformation toward sustainability [40–42]. On the other hand, citizenship competence has also gained much traction at the European level given that this competence defines the ability "to act as responsible citizens and to fully participate in civic and social life, based on understanding of social, economic, legal and political concepts and structures, as well as global developments and sustainability" [43] (p. 10). Overall, both perspectives underline the significance of Vision III of scientific literacy.

2.2. SSIBL Pedagogy as an Approach for Responsible Citizenship

An emerging assumption is that SSIs could also play a vital role when teaching Vision III of scientific literacy (i.e., focus on responsible citizenship). This assumption was strengthened in the context of the Responsible Research and Innovation (RRI) movement, as there have been various attempts to link SSI instruction with RRI [30,44]. It has been argued that the European movement of Responsible Research and Innovation (RRI) shares common grounds with SSIs, as both of them highlight the societal aspects of science and, in many cases, invite students to take action [18,45]. The main idea underpinning this assumption is that by "including socioscientific issues in science learning and teaching we could move science classes towards unwrapping and engaging discussions about the intersections of science and society, promote scientific practices, and potentially invite students to act responsibly and participate actively" [3] (p. 3).

It has also been proposed that there are different foci in SSIs using continuums from "cold" (i.e., for teaching stabilized scientific concepts and epistemic values in the context of monodisciplinary issues) to "hot" (i.e., for introducing multidisciplinary controversial issues situated in work and society asking students to make decisions and take actions as responsible citizens) [46]. In the midway, between the "cold" and "hot" extremes, SSIs serve as a vehicle for students to develop their understanding of how science works (i.e., nature of science). More precisely, it has been argued that "at the 'cold end', an integration of SSIs into a teaching programme is used to motivate students learning science, or even to convince them of the merits of the techno-sciences. At the 'hot end' of the continuum, the teaching focus goes beyond the purpose of developing science conceptual and procedural knowledge to the nurturing of activist commitments amongst learners" [46] (p. 99). Grounded on this continuum, researchers have supported that if SSI-instruction is situated in the "hot" end of this continuum, then this could contribute to the development of scientific literacy, as reflected in Vision III (i.e., scientific literacy for responsible citizenship) [26].

However, considering that RRI is a relatively recent movement in science education in conjunction with the emerging nature of Vision III for scientific literacy, it is not surprising that the educational pendulum is still leaning toward SSI instruction for enhancing students' scientific literacy in Visions I and II. More simply, the SSI instruction so far was limited mostly to the presentation of social dilemmas, with no attempt to engage students with any forms of civic action [19]. Therefore, studies on how teachers can empower their students' responsible citizenship through SSIs are still in a nascent stage [18,47]. Implementing aspects of democratic citizenship education to foster critical and responsible participation in science education is still challenging for various reasons [48]. Several studies have shown that teachers manifest a relatively limited understanding of what responsible citizenship is and what citizenship education entails; they find challenging the deployment of complex SSIs in their teaching, while there is also a lack of instructional strategies supporting the meaningful integration of RRI into the practice of science education [49–53].

In this study, we focus on the Socio-Scientific Inquiry-Based Learning (SSIBL) pedagogical approach, which aims to foster responsible citizenship in K-12 science education [11,54–56]. The SSIBL pedagogical approach was formulated during the PARRISE EU project ("Promoting Attainment of Responsible Research and Innovation in Science Education") to support pre- and in-service science teachers training as well as to bring to the fore the best teaching practices and educational resources related to RRI (see https://www.parrise.eu/, accessed on 12 January 2023). SSIBL pedagogy is underpinned by the framework of critical realism and conforms broadly to a pluralistic inquiry-based learning approach, seeking to find solutions to complex and multi-dimensional problems related to scientific and technological advancements [1]. In this way, SSIBL pedagogy seeks to bring attention to the core essence of RRI by emphasizing (a) that humans have an important responsibility in the process and outcomes of scientific and technological developments as well as (b) that products of research in science and technology have to meet standards of sustainability, social desirability, and ethical acceptability [57–59].

To empower students' responsible citizenship, SSIBL pedagogy frames the integration of RRI in science education through the synergy of three constituents (Figure 1): RRI as (a) a problem-based investigation of a socio-scientific issue, (b) stimulated by inquiry-based pedagogy, and (c) requiring students to adopt responsible citizenship, which includes personal engagement and civic actions [60].

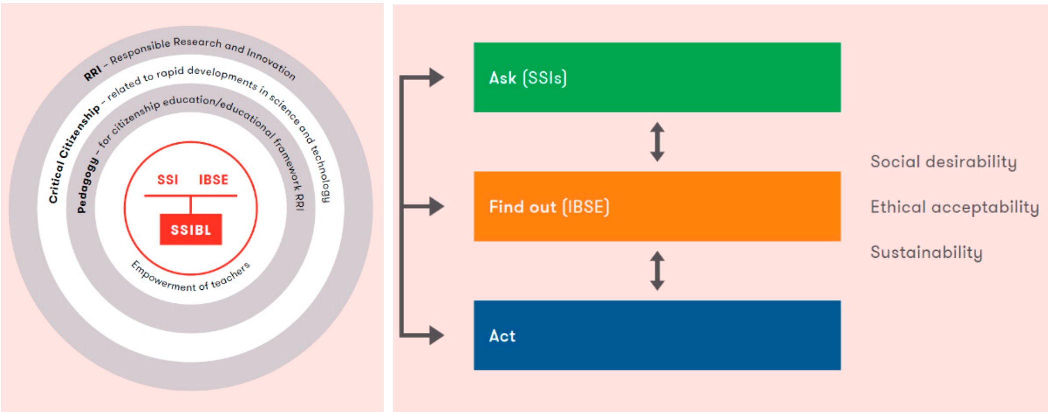

Figure 1. Socio-Scientific Inquiry-Based Learning (SSIBL) [56].

In alignment with these three constituents, SSIBL pedagogy comprises three instructional phases (Figure 2), as follows: (a) Ask—i.e., focuses on formulating authentic questions relating to a particular SSI); (b) Find out—i.e., focuses on students' inquiry-based investigations in relation to the SSI); and (c) Act—i.e., focuses on students' action-taking to contribute responsibly within their communities [11]. In this way, SSIBL pedagogy may provide an instructional sequence in support of students' scientific literacy, as captured by Vision III (i.e., focus on RRI and forms of responsible citizenship, sustainability, and socio-ecojustice) [26].

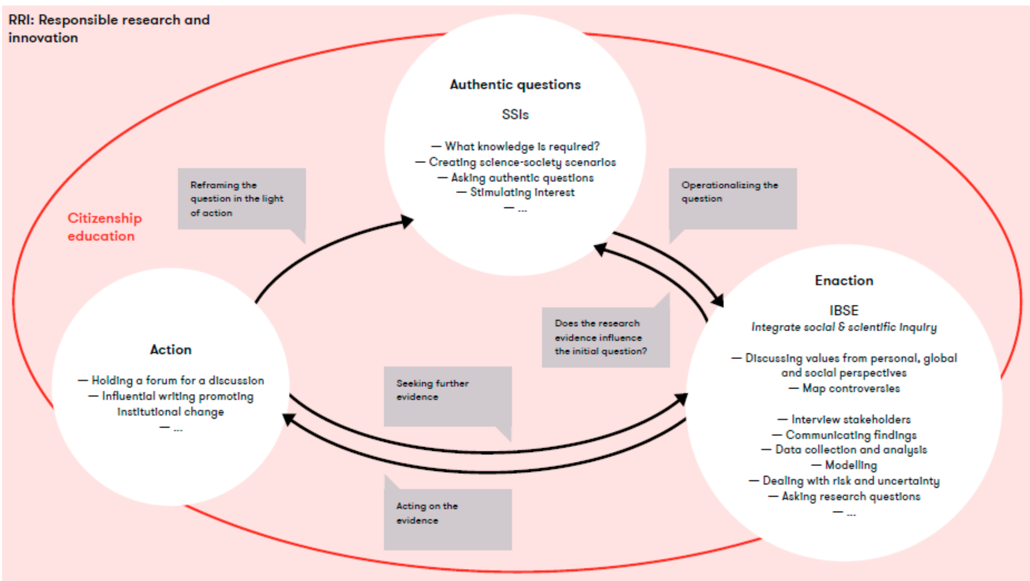

Figure 2. The SSIBL instructional phases [56].

3. Research Questions and Hypotheses

The main goal of this study was to evaluate the impact of a learning intervention, which was situated in the context of sustainability education and structured upon Socio-Scientific Inquiry-Based Learning (SSIBL) pedagogy, as a novel pedagogy which highlights the importance of presenting the societal aspects of science to students while also inviting them to take action. More specifically, we put forward two distinct research questions accompanied by two corresponding research hypotheses as follows:

RQ1. What was the impact of the SSIBL instruction compared to the Business-As-Usual (BAU) 8th grade chemistry instruction on students' scientific literacy for responsible citizenship in terms of (a) students' perceptions of science as a human endeavor, and (b) students' sense of personal responsibility and willingness to take action for maintaining a sustainable environment?

Our first research hypothesis was that students in the SSIBL condition would overcome their counterparts in the BAU condition at the end of the intervention, both in terms of understanding the nature of science (i.e., science as a human endeavor) as well as in terms of values and attitudes (i.e., sense of personal responsibility and willingness to take action) (H1). This hypothesis is grounded on two different aspects. First, the SSIBL pedagogical framework was designed with a direct aim of enhancing students' responsible citizenship, emphasizing that humans are accountable for the nature and impact of scientific and technological developments, as the essence of RRI [9,52–54]. Second, even though empirical studies reporting on the deployment of SSIBL pedagogy in authentic school classrooms are still limited, a significant corpus of studies has previously deployed SSIBL pedagogy in professional development sessions with science teachers, who have reported on the added value of SSIBL for their teaching [1,7,48,60–64].

RQ2. How the SSIBL instruction contributes to the enhancement of students' scientific literacy for responsible citizenship?

Our second research hypothesis was that SSIBL pedagogy would contribute to the enhancement of students' scientific literacy for responsible citizenship due to its multidimensional nature (H2). This hypothesis draws on the fact that the SSIBL pedagogical framework comprised three different constituents: SSIs, Inquiry-based learning, and Citizenship education [9,52–54]. These pedagogical approaches are translated in three corresponding instructional phases (Ask–Find out–Act) providing a learning trajectory for students to improve their scientific literacy for responsible citizenship.

4. Materials and Methods

4.1. Context

The present study took place in the context of the PARRISE continuous professional development program at Cyprus, which employed a participatory co-design model to enact science teachers' professional development [60,64–67]. According to this model, the participating science education teachers worked as "co-designers" of curriculum materials to introduce the notion of responsible citizenship in their biology, chemistry, and elementary education classes by using the SSIBL-based approach. To achieve this goal, the teachers collaborated in disciplinary teams (biology education, chemistry education, elementary science education) to develop SSIBL-based learning modules aiming at the meaningful integration of RRI in their classrooms.

4.2. Research Design

This study was grounded on naturalistic experimental research design, adopting the natural experiment methodology [68]. This type of research is appropriate for studies taking place in real-world settings (e.g., in authentic classrooms), where variance is likely to have been greater due to the impact of other uncontrollable variables [69,70]. The aim of this study was to compare the impact of a SSIBL-based module co-designed by a group of three chemistry teachers on their students' scientific literacy for responsible citizenship in comparison to the Business-As-Usual (BAU) 8th grade chemistry instruction and was enacted in real classroom settings. For this purpose, this study included 2 cohorts of 8th graders; each cohort was assigned to 1 of 2 conditions: Condition1: SSIBL group, Condition2: Control group. The dependent variable was scientific literacy for responsible citizenship in terms of students' understanding of the nature of science (i.e., science as a human endeavor), as well as in terms of their values and attitudes (i.e., sense of personal responsibility and willingness to take action). The independent variable was the type of instruction (i.e., SSIBL instruction, BAU instruction). However, given the naturalistic context of this study (i.e., authentic classrooms), there was a lack of control over learner and teacher characteristics.

4.3. Sample

The sample of this study comprised six 8th grade chemistry education classes at three Greek-speaking public middle schools in Cyprus, and each class was assigned to one of the two conditions. In each school, the same chemistry teacher taught one classroom per condition. More specifically, the participants of this study were ninety-three (n = 93) 8th grade students from six classrooms at the lower secondary education. Condition 1 (SSIBL) had 46 students (23 boys, 50%, mean age = 13.3 years), and Condition 2 (Control) had 47 students (20 boys, 43%, mean age = 13.4 years); there was no statistically significant difference in students' age between the two conditions ($Z = -0.47$, $p = 0.635$). Permission was provided by the national authorities to conduct this research, given that the students' parents and legal guardians would provide written informed consent; this consent was indeed obtained for all the students.

4.4. Learning Intervention

4.4.1. The Business-As-Usual (BAU) Unit

Students of the control condition deployed the BAU unit, which was structured around the topics of atmospheric air and air pollutants. The unit comprised a sequence of student worksheets focusing on relevant aspects, as follows: (a) definition of atmospheric air, (b) synthesis of atmospheric air, (c) defining combustion, (d) types of combustion, (e) conceptualization of air pollution, (f) air pollutants and their sources, (g) impact of air pollution on human/environment (greenhouse effect and acid rain), and (i) suggestions for pro-environmental human actions. Therefore, as structured, the BAU unit mainly aimed to foster students' conceptual understanding of the topic, thus contributing to the development of students' competences related to knowing, using, and interpreting scientific explanations of the natural world [71]. The BAU intervention lasted for five 40 min lessons, which were delivered through teacher-led lectures to facilitate the students' completion of their worksheets.

4.4.2. The SSIBL-Based Module

In the SSIBL-based learning intervention, the chemistry teachers co-designed and deployed the module "What type of fuel would you choose?", as an alternative approach to addressing the topics covered by the BAU unit while promoting their students' responsible citizenship. More simply, while the BAU unit was mostly related to students' conceptual understanding, the SSIBL unit also aimed at fostering students' competences related to generating and evaluating scientific evidence and explanations (i.e., science process skills), understanding the nature and development of scientific knowledge (i.e., epistemological understanding), and participating productively in scientific processes and discourse (i.e., participation and attitudes) [71]. To do so, this module placed students in the context of a socio-scientific controversy on selecting conventional diesel or biodiesel of the 1st or 2nd generation. The intervention was hosted on the STOCHASMOS web-based platform [72] and took the form of a collaborative-inquiry-learning activity, supplemented by whole-class discussions and hands-on tasks. Like the BAU instruction, this intervention lasted for five 40-min lessons, but it was structured upon the SSIBL instructional phases (Table 1).

Table 1. Overview of the SSIBL-based module per instructional phase.

Phases	Learning Goals	Activities	Planned Outcomes	Activity Forms
Ask (1 × 40′)	Introduction to: • The socio-scientific controversy; • Learning mission.	The students: • Shared their prior knowledge about diesel and biodiesel; • Reported an initial position in the controversy; • Reflected on the importance of the topic.	• Familiarization of the students with the SSI; • Connection of the issue with students' interests and everyday lives.	Whole-class discussions.
Find out (2 × 40′)	Inquire into the: • Scientific/technological background of the topic; • Aspects of the socio-scientific controversy.	Students studied multimedia sources about: • Air composition, quality, and pollution in relation to the combustion of energy sources. • the chemical structure of diesel/biodiesel and their industrial production; • the arguments of different stakeholders (economists, ecologists, biodiesel/ diesel producers); • how scientists can tackle the issue, focusing on the shortcomings of the different fuel types.	• Development of an evidence-based view grounded on scientific ideas; • Reflection on the role of science and technology in relation to current socio-environmental challenges.	Web-based platform (in pairs).
Act (2 × 40′)	Responsible citizenship through: • Reflecting on possible individual sustainable actions; • Undertaking a collective citizenship action.	• Designed an informative brochure on the topic to sensitize their fellow citizens; • Campaign in schools for collecting and delivering waste oil to biodiesel production companies.	• Acting as responsible citizens.	Hands-on tasks (groups of 4–5).

During the first phase ("Ask"), students were introduced to the socio-scientific controversy, which was framed within a pedagogical scenario. The scenario presented a debate on the topic among four 8th graders during the school break. As per the scenario, these students expressed diametrically opposing views in favor of or against diesel and biodiesel as well as about the significance of this issue in relation to their everyday lives. The pedagogical scenario was presented by the teacher to the plenary and was followed by a whole-class discussion. The students were asked to share their prior knowledge about diesel/biodiesel and report their initial position regarding the controversy. Students were also asked to reflect on the significance of the topic. Acknowledging the value of this issue, students were introduced by the teacher in their learning mission: To explore the socio-scientific controversy in order to shape an evidence-based stance, as well as to inform their fellow citizens (parents, siblings, other teachers, and students in their school) on the topic. This phase was concluded with the teacher demonstrating the affordances and functionality of the STOCHASMOS web-based platform.

During the second phase (Find out), the students were divided into pairs to conduct their inquiry-based investigation on the web-based platform (see Figure 3).

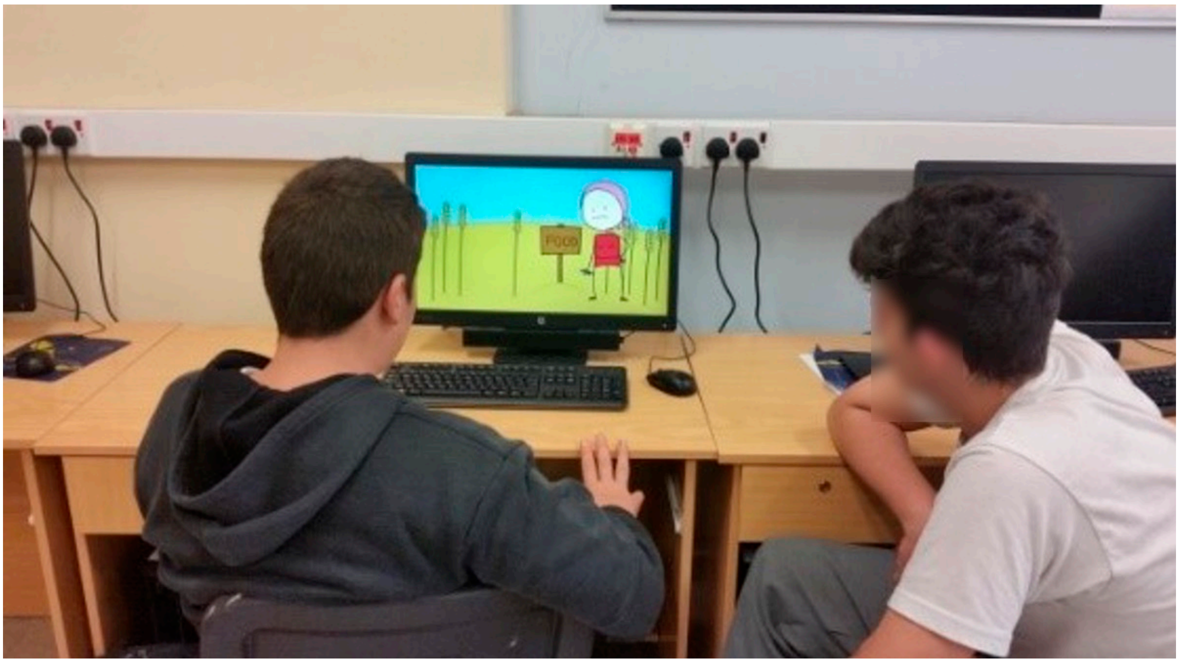

Figure 3. Students working on pairs of the web-based platform.

Finally, in the third phase (Act), the students undertook a collective action for informing and sensitizing their fellow citizens. For this, students were divided into 4 different groups of 4–5; each group was responsible for designing an informative brochure on the topic for a different target group (Group 1: Parents, Group 2: Siblings, Group 3: Teachers, Group 4: Other students). After preparing the brochure, students arranged a sequence of meetings with the aforementioned target groups for presenting the socio-scientific controversy and their relevant research while also allocating their brochures (Figure 4).

Figure 4. Students distributing flyers.

In addition, the students also organized campaigns in their schools for collecting and delivering waste oil to biodiesel production companies (Figure 5).

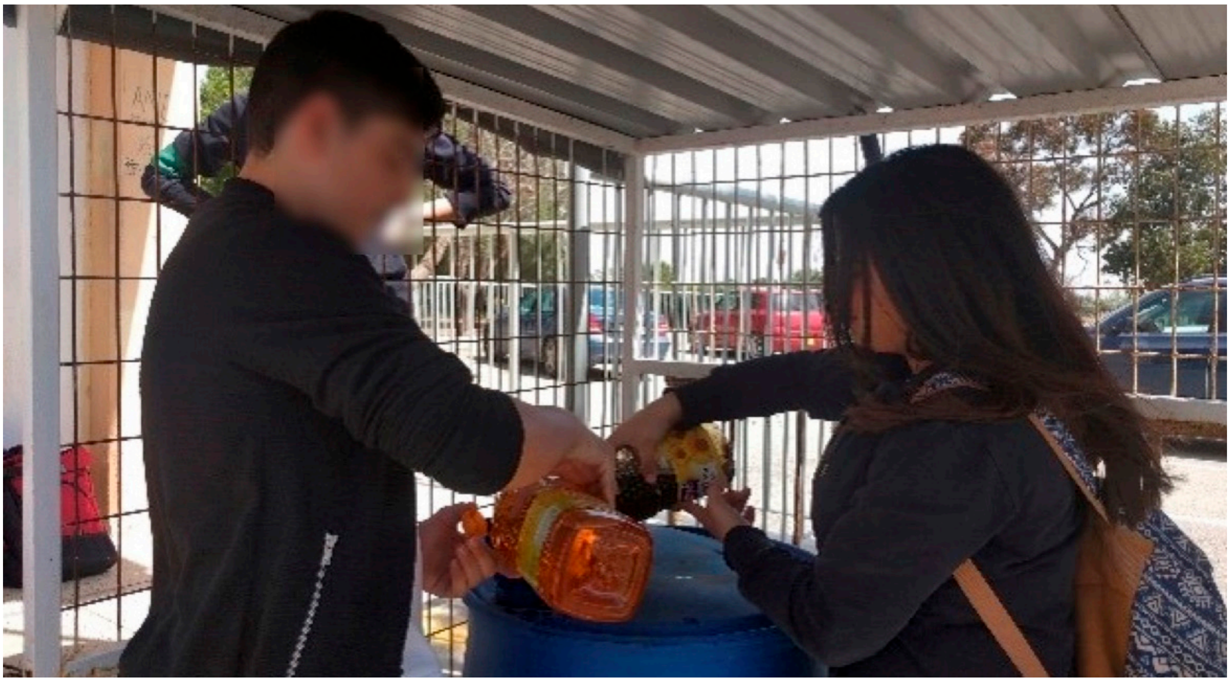

Figure 5. Students collecting waste oils.

4.5. Instruments and Techniques

The present study adopted a mixed-method approach, deploying both video and questionnaire data to allow an in-depth understanding of SSIBL pedagogy and its impact on students' scientific literacy for responsible citizenship. What follows is an overview of the instruments and techniques adopted for the collection of the data.

4.5.1. The Global Scientific Literacy Questionnaire

The students' scientific literacy for responsible citizenship was measured with the Global Scientific Literacy Questionnaire [GSLQ] before and after the BAU and the SSIBL-based learning interventions [8]. The following GSLQ scales were used: (a) the "Character and Values" scale, which comprised the "Ecological worldview/social and moral compassion" sub-scale (7 items) and the "Social Responsibility" sub-scale (2 items), and (b) the "Science as human endeavor" scale, which comprised the "Characteristics of scientific knowledge" (3 items) and the "Science & Society/Spirit of science" sub-scale (10 items). The "Character and Values" scale had a documented reliability alpha coefficient of 0.91, while the Cronbach's alpha for the "Ecological worldview/social and moral compassion" and the "Social Responsibility" subscales were 0.69 and 0.85, respectively. The "Science as human endeavor" scale had a documented reliability alpha coefficient of 0.89, while the Cronbach's alpha for the "Characteristics of scientific knowledge" and the "Science & Society/Spirit of science" subscales were 0.71 and 0.74, respectively. All items were evaluated by using Likert-type scales, ranging from 1 (low) to 5 (high). Given that the GSLQ was administered to Greek-speaking students, it was also translated into Greek. Table 2 reports the reliability alpha coefficients of the scales and sub-scales for the translated questionnaire and presents an indicative item per sub-scale.

Table 2. Scales, Sub-scales, Reliability, and Indicative Items of GSLQ.

Scales	Sub-Scales	Indicative Items
Character and Values (a = 0.81)	Ecological worldview/social and moral compassion (a = 0.81)	I am willing to take part in decision-making activities about issues that affect the world.
	Social Responsibility (a = 0.57)	My personal behaviors can influence the environment throughout the world.
Science as a human endeavor (a = 0.84)	Characteristics of scientific knowledge (a = 0.58)	Scientific ideas can change when scientists find new evidence.
	Science and Society/Spirit of science (a = 0.80)	How people make use of science and technology can help to resolve social problems.

4.5.2. Video-Recorded Observations

Video data were collected by using a camera to record the SSIBL-based implementations across the three school sites. In all cases, the camera was placed at the back corner of the classroom to reduce the intrusiveness of the video-recording taking place. A wireless microphone was placed with the classroom teacher, given that the video-recorded observations focused on how the SSIBL-based implementations were enacted by the participating chemistry teachers. An expert observer was handling the camera, listening from where the camera was positioned by using headphones. The researcher could, therefore, optimize the data collection procedure by keeping notes on critical incidents related to the SSIBL-based instruction and marking their timelines.

4.6. Procedures

This study was enacted with the co-design of the SSIBL-based module "What type of fuel would you choose?" by three of the chemistry teachers who participated in the PARRISE continuous professional development program in Cyprus (completed during the first half of the school year, i.e., autumn semester). At the end of the co-design process, the chemistry teachers also developed a handbook of implementation, including detailed lesson plans and guidelines regarding the implementation of their SSIBL-based module. This handbook served as the intervention protocol, ensuring that the teachers would follow the same procedures during the implementation of the SSIBL-based module. Likewise, the official teacher's guidebook, which was provided by the Ministry of Education, served as the intervention protocol for the teachers during the BAU instruction.

One week prior the intervention, the three chemistry teachers collected the signed consent forms from the parents and legal guardians of their students. Immediately afterward, they administered the GSLQ questionnaire to students in both conditions within a fifteen-minute slot, serving as a pre-assessment of students' scientific literacy, in a paper-and-pencil format. This format added an extra step to the data analysis (i.e., data tabulation). However, it was more familiar to both teachers and their students, given that all school tests and assessments were also taking place in a paper-and-pencil format. What followed was the BAU and SSIBL interventions, which lasted for five 40 min lessons across two weeks. Both interventions took place during the spring semester, in parallel, within and across the three schools participating in this study. Video data were also collected to capture the SSIBL-based implementations by an expert observer, who attended the SSIBL interventions at the three school sites. By the end of the intervention, the chemistry teachers administered the GSLQ questionnaire in the same format, as a post-assessment of students' scientific literacy, in both conditions.

4.7. Data Analysis

4.7.1. Quantitative Data

The quantitative analysis started with initial checks by using the Kolmogorov–Smirnov test of normality for the assessment of the distributional properties of the GSLQ data. Given that in most cases, the distributions differed significantly from the norm, and considering the small sample size per condition, non-parametric tests were used to analyze the data, with the significance level set at 0.05. A Wilcoxon signed-rank test was used to evaluate the impact of the learning intervention per condition by using the GSLQ data. In addition, the z-score associated with the Wilcoxon signed-rank test was converted into the effect size r. The normalized learning gains in students' scientific literacy were calculated in both conditions (Post-Test scores–Pre-Test scores)/(100%-Pre-Test scores). A Mann–Whitney U test was also deployed to investigate statistically significant differences between the SSIBL and the BAU students' learning gains in terms of their scientific literacy, per condition. All the statistical analyses were conducted by using the IBM SPSS Statistics package v.25.

4.7.2. Qualitative Data

The qualitative data collected with the video-recordings of the SSIBL instructional interventions were analyzed with the "Critical Incident Technique" [73]. The technique is used to analyze and interpret observed human behavior—in our case, teacher–student interactions—to understand how SSIBL pedagogy was enacted by the chemistry teachers to foster their students' scientific literacy for responsible citizenship. For this purpose, we adopted a whole-to-part inductive approach of six stages reflecting the iterative nature of the analysis. Firstly, the whole event (video-taped instructional interventions) was reviewed, and then, after a second review of the qualitative corpus of data timelines were created, the video-taped material was segmented into parts (i.e., episodes). At a third stage, episodes of interest, named "critical incidents", were detected; in our case, these episodes pertained to the implementation of the SSIBL instructional phases (i.e., Ask, Find out, Act) by the chemistry teachers, seeking to foster their students' responsible citizenship. The identification of these episodes was facilitated, given that during the video-recording, notes were also kept by the observer regarding potential incidents of interest along with their timestamps. At a fourth stage, all episodes of interest were transcribed, and then recursive passes took place until the episodes were narrowed as possible without losing their meaning. In the last stage, the coded episodes were reviewed once again to concretize and finalize the qualitative analysis.

5. Results

5.1. Quantitative Findings

The quantitative analysis indicated that, after the implementation, students in the SSIBL condition outperformed their counterparts in the control condition in terms of their scientific literacy for responsible citizenship. What follows, is an overview of the main outcomes that emerged from the statistical analysis.

A Wilcoxon signed-rank test examined whether the differences in students' scientific literacy reached significance by the end of the SSIBL learning intervention (Table 3). The results showed significant improvement in the dimension of *Character and Values*, in terms of *Ecological worldview/Social and Moral compassion* ($Z = -2.31$, $p < 0.05$). Therefore, it seems that the SSIBL unit had a positive impact on students' sense of personal responsibility and willingness to take action for maintaining a sustainable environment (i.e., values and attitudes). The results also showed a significant improvement in the dimension *of Science as a human endeavor*, in terms of the *Characteristics of scientific knowledge* ($Z = -2.19$, $p < 0.05$). This indicates that the SSIBL unit also had a positive effect on students' perceptions of science as a human endeavor (i.e., nature of science). Moreover, it should also be noted that even though not statistically significant, there was also an improvement in terms of *Social accountability* and *Spirit of science/Science and Society*.

Table 3. Pre-Test–Post-Test comparison of students' scientific literacy in the SSIBL condition.

	PRE-Test		POST-Test		SE	CI (95%)	Z	r
	Mean	**SD**	**Mean**	**SD**				
Character and Values	3.88	0.47	4.01	0.52	0.05	[−0.25, −0.04]	−2.31 *	0.34
Ecological worldview/Social and Moral compassion	3.98	0.47	4.13	0.55	0.06	[−0.27, −0.02]	−2.46 *	0.36
Social accountability	3.45	1.03	3.60	0.75	0.12	[−0.27, −0.02]	−1.10	0.16
Science as Human Endeavor	3.82	0.60	3.90	0.45	0.06	[−0.22, 0.03]	−0.86	0.13
Characteristics of scientific knowledge	3.74	0.71	3.91	0.61	0.08	[−0.33, −0.02]	−2.19 *	0.32
Spirit of science/Science and Society	3.83	0.62	3.90	0.46	0.07	[−0.22, 0.07]	−0.55	0.08

Note. * $p < 0.05$.

Likewise, a Wilcoxon signed-rank test examined whether the differences in students' scientific literacy reached significance by the end of the BAU learning intervention (Table 4). However, in this case, the results showed a significant decrease in the dimension of *Character and Values*, in terms of *Ecological worldview/Social and Moral compassion* (Z = −2.04, $p < 0.05$). In addition, the results showed a significant decrease in the dimension *of Science as a human endeavor*, in terms of *Spirit of science/Science and Society* (Z = −3.69, $p < 0.001$). Lastly, it should also be noted that even though not statistically significant, there was also a slight decrease in terms of *Characteristics of scientific knowledge*. Overall, these findings imply that the BAU unit had a detrimental effect on students' values and attitudes, as well as on students' epistemological understanding.

Table 4. Pre-Test–Post-Test comparison of students' scientific literacy in the BAU condition.

	PRE-Test		POST-Test		SE	CI (95%)	Z	r
	Mean	**SD**	**Mean**	**SD**				
Character and Values	4.01	0.50	3.92	0.57	0.06	[−0.03, 0.20]	−1.11	0.16
Ecological worldview/Social and Moral compassion	4.14	0.56	4.04	0.80	0.05	[0.00, 0.21]	−2.04 *	0.30
Social accountability	3.53	0.80	3.52	0.87	0.12	[−0.23, −0.25]	−0.22	0.03
Science as Human Endeavor	4.01	0.43	3.83	0.45	0.05	[0.26, 0.27]	−2.89 **	0.42
Characteristics of scientific knowledge	3.89	0.68	3.83	0.52	0.11	[−0.14, 0.29]	−0.70	0.10
Spirit of science/Science and Society	4.04	0.44	3.84	0.48	0.05	[0.10, 0.29]	−3.69 ***	0.54

Note. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Finally, a Mann–Whitney U test for the comparison of students' learning gains between the two conditions indicated that the SSIBL group outperformed the control group in terms of *Ecological worldview/Social and Moral compassion* (Z = −2.89, $p < 0.01$), as well as in terms of the *Spirit of science/Science and Society* (Z = −2.22, $p < 0.05$).

5.2. Qualitative Findings

The qualitative analysis shed light on how the SSIBL instructional phases (i.e., Ask, Find out, Act) evolved, fostering students' scientific literacy for responsible citizenship. These findings provided useful insights on how the three instructional phases were built on each other, supporting the development of students' responsible citizenship, as a prerequisite for achieving sustainability.

During the first instructional phase ("Ask"), the students focused on the driving question guiding their inquiry (i.e., "What type of fuel would you choose?") and reflected on the value and relevance of the topic to their everyday life. For example,

> ***Teacher:*** *Is this a question you would like to investigate? You don't have cars, so why bother?*

Student 1: *I disagree. We should learn more about the topic, to advise our parents.*

Student 2: *I believe that biofuels are related to our future.*

Student 3: *Diesel and fuels in general are related to the atmospheric air and the pollution of the planet. We are dealing with this problem, and we must contribute to improve this situation. We are also affected. It's not only about the car drivers.*

Next, during the second instructional phase ("Find out"), the students engaged with the inquiry process to conceptualize the scientific background of the topic (i.e., the chemical structure of diesel/biodiesel, their industrial production, and their impact on air quality), and to map the arguments shared by different stakeholders (i.e., economists, ecologists, biodiesel/diesel producers). For example,

Student 1: *But there are too many opinions. Some are in favor of the biodiesel, and some are against.*

Teacher: *Exactly! But this is your mission.*

Student 1: *They say that biodiesel of 2nd generation is the best because it is produced from the waste oils.*

Teacher: *But who is in favor of this position?*

Student 2: *The researcher!*

Teacher: *But what about the consumer?*

Student 1: *It's not in his best interest (due to its higher cost).*

During the same phase, the students also identified the complexity of the socio-scientific issue, while their teachers supported them to realize their role as responsible citizens in the context of such controversies. For example,

Teacher: *Ok, as you see there is no clear answer. And why is that? Because you need to form your own opinion considering all the perspectives.*

Student 2: *It's not possible for everyone to agree.*

Teacher: *If everyone agreed . . .*

Student 1: *. . . there would be no need for us to make this investigation.*

Teacher: *And this is the case with too many issues. All active citizens are confronted with these dilemmas. But if you don't study thoroughly a topic, you cannot make a firm decision.*

During the third instructional phase ("Act"), the students reached an evidence-based decision in favor of the biodiesel of the second generation.

Teacher: *So, what have you decided after your investigation?*

Student 1: *We have selected the biodiesel of 2nd generation because the biodiesel of 1st generation is produced from crops which are also used for food. And there are many people that are starving, and don't have money and many people are left without food. On the other hand, the biodiesel of the 2nd generation derives from vegetable oils and waste cooking oils.*

Student 2: *In addition, the prices of the 2nd generation biodiesel are relatively higher, but stable. It is also a renewable source of energy, and it is good for the environment.*

In addition, during this phase, the students considered actions which could be undertaken to achieve more sustainable patterns as consumers. They started a campaign for collecting and delivering waste oil to biodiesel production companies, and they distributed informative flyers in their local community to increase environmental awareness on this topic.

Teacher: *Ok, very nice. But I think that you were also discussing some additional points in favor of the biodiesel of the 2nd generation in the previous lesson.*

Student 3: *Yes . . . We also said that by purchasing and using biodiesel of 2nd generation we also help the scientists, because this is something pioneer. And by supporting the scientists we will help them to invent something even more optimal, something more useful . . . I mean something which will be even more friendly for the environment and for us, our health.*

6. Discussion

As we are living amidst a global socio-environmental crisis, the science education landscape has reverberated with the call to reform curricula so to as to prepare students to achieve sustainability. Well-known educational agendas around the globe, such as the *Science as a Human Endeavour' strand of the 2021 proposed Australian curriculum* or the *PISA 2024 Strategic Vision and Direction for Science* have provided much emphasis on promoting aspects such as scientific literacy, responsible research, and innovation and students' citizenship [15]. Despite the fact, this ambition develops more slowly than might be expected due to the lack of appropriate pedagogical approaches; as a result, only a few teachers have experience in addressing these aspects in their classroom practice.

Responding to this challenge, in this study, we have introduced Socio-Scientific Inquiry-Based Learning (SSIBL) as a novel pedagogical approach, which comprises an amalgam of three pedagogies: Socio-Scientific Issues (SSIs), Inquiry Learning, and Citizenship Education [11,54,55]. More specifically, we have evaluated the impact of a chemistry education module on biofuels, structured upon SSIBL pedagogy, on eighth graders' scientific literacy for responsible citizenship, in comparison to Business-As-Usual (BAU) instruction. This module was co-designed by a group of three in-service chemistry education teachers, considering that the "chemistry curricula have explicit content specific requirements related to sustainability, providing opportunities to link SSIBL to the regular 'core curriculum'" [62] (p. 49).

This empirical exploration has resulted in two main findings. First, the SSIBL-based module had a statistically significant contribution to students' scientific literacy, as a pre-requisite of responsible citizenship. The students who experienced SSIBL pedagogy outperformed their counterparts who experienced the BAU instruction, in terms of their perceptions of science as a human endeavor (i.e., nature of science), as well as in terms of their sense of personal responsibility and willingness to take action for maintaining a sustainable environment (i.e., values and attitudes). On the other hand, we identified a statistically significant decrease in these aspects for the control group students. We next discuss these findings in more detail.

By focusing on the SSIBL condition, according to the quantitative analysis, we found a statistically significant increase in students' scientific literacy in the dimension of *ecological worldview/social and moral compassion* as well as in the dimension *of characteristics of scientific knowledge*. In addition, we found that students in the SSIBL condition outperformed their counterparts in the dimensions of *Ecological worldview/social and moral compassion*, *Spirit of Science/Science and Society*, and *Characteristics of scientific knowledge*. Therefore, our findings provide empirical substantiation on the value of SSIBL pedagogy as a vehicle for students to achieve scientific literacy for responsible citizenship. More specifically, the deployed SSIBL unit was designed with the explicit aim of supporting students' understanding that humans are responsible for any scientific and technological developments. To achieve this goal, the SSIBL activities were structured so as to allow students to elaborate on the notion of RRI, focusing on biofuels of the first and second generation, as well as on conventional diesel, as products of research in science and technology, which ought to be aligned with the aspects of sustainability, social desirability, and ethical acceptability [57–59].

Of course, it should be acknowledged that other studies have also presented and evaluated chemistry education modules about biofuel production, as a Socio-Scientific Issue (SSI). The earliest studies, though, presented instructional approaches supporting the development of Vision II scientific literacy; namely, they proposed that this SSI could provide a meaningful context to situate scientific concepts, allowing students to make informed decisions on this issue as a topic related to their everyday life [74–76]. On the other hand, more recent studies have presented and discussed the SSI of biofuel production in relation to Vision III of scientific literacy; namely, they emphasized that this SSI is aligned with education for sustainable development and can be deployed to encourage students' societal participation to achieve socio-ecojustice [77]. However, they did not present a specific instructional approach which can support the accomplishment of this goal. Instead, in this study, we have demonstrated how SSIBL pedagogy can be deployed beyond the mere presentation of the biofuel production as a socio-scientific dilemma, seeking to promote students' agency and action taking. Indeed, our qualitative findings have shed light on how the SSIBL instructional phases (Ask, Find out, Act) gradually contributed to the development of students' responsible citizenship.

On the other hand, we identified a statistically significant decrease in the scientific literacy of the students who participated in the BAU instruction. More specifically, according to the quantitative analysis, we found a statistically significant decrease in students' scientific literacy in the sub-scale of *ecological worldview/social and moral compassion*, as well as in the sub-scale of *Spirit of Science/Science and Society.* A plausible explanation for this finding is that the "traditional" instructional approach was aligned with the notion of Vision I scientific literacy; namely, it focused merely on the development of students' scientific knowledge, as well as on students' understanding of canonical laws and theories [22,24]. As such, not only did the BAU instruction not contribute to the enhancement of students' scientific literacy for responsible citizenship, but it also had a detrimental effect on it.

Collectively, our findings support that SSIBL pedagogy holds promise for fostering students' scientific literacy for responsible citizenship. Our study provides empirical evidence that SSIBL pedagogy may be deployed in support of students' scientific literacy, as captured by the scientific literacy of Vision III (i.e., focus on of RRI, sustainability, socio-ecojustice) [26]. In its essence, SSIBL pedagogy may provide a potential venue for fostering students' agency and civic engagement, taking into account the lack of SSI instructional approaches that are associated with students' responsible citizenship [18,19]. SSIBL pedagogy and its instructional phases (Ask, Find out, Act) may also provide a structured pedagogical approach for teachers, who often find it challenging to guide their students' learning in SSI and responsible citizenship toward the achievement of environmental sustainability [16,47,49,50,52].

7. Conclusions

Fostering secondary education students' responsible citizenship, as described in Vision III of scientific literacy, is a goal of paramount importance toward achieving sustainability. While SSIBL pedagogy has been argued to hold promise toward this direction, researchers have pointed out the need for more empirical evidence regarding the effectiveness of SSIBL, especially in the context of sustainability education [16].

Responding to this call, our study provides empirical documentation for the contribution of SSIBL pedagogy to the development of secondary students' responsible citizenship. More specifically, our findings indicate that students in the SSIBL condition outperformed their counterparts in the control condition in terms of their perceptions of science as a human endeavor as well as in terms of their values and attitudes. The video recordings also shed light on how the SSIBL instruction phases (i.e., Ask, Find out, Act) contributed to the development of students' responsible citizenship as a pre-requisite for achieving sustainability. Overall, it seems that SSIBL intervention empowered the students to act as responsible citizens who were involved in reflective and moral judgements, made evidence-based decisions, and enacted the motto "act locally, think globally". In addition, the SSIBL intervention prepared the students to become "agents of change rather than just passive observers of world events", while also responding to the calls of the EU commission to deploy socio-scientific pedagogical approaches in order to form characters that are ready to act in scientifically responsible ways [57,78].

8. Limitations and Recommendations for Future Research

Even though the findings of this study may help flesh out a more comprehensive picture of how SSIBL pedagogy can be integrated into science classrooms and how it relates to the development of students' responsible citizenship, some limitations of this work are also important to note. To begin with, various factors limit the potential to generalize our conclusions. First, our study adopted a naturalistic experimental design to collect data in authentic settings (i.e., real classroom contexts), where variance is likely to have been greater due to the impact of other uncontrollable variables. Future studies, investigating the effectiveness of the SSIBL-based instruction could take place in less naturalistic settings (e.g., research labs), taking the form of randomized controlled trials (RCTs), allowing also for the control of various confounding variables (e.g., contextual, teacher- and learner-related variables). In addition, the sample of this study was relatively small and drawn from a population of convenience (i.e., six classrooms of three chemistry teachers participating at the PARRISE professional development programme at three different school sites). Future studies could replicate this research with a larger sample of classrooms (clusters), ideally drawn from randomly-selected schools (e.g., clustered sampling) to increase external validity, particularly population validity. Along the same lines, the fact that both the SSIBL-based and the BAU interventions were enacted by three teachers who had previously participated in the co-design of the SSIBL-based module could be also perceived as a limitation. Future studies should investigate the effectiveness of SSIBL pedagogy with additional teachers who have not participated in the co-design process to explore the transferability of the findings.

On a different note, our study focused on the evaluation of students' "scientific literacy for responsible citizenship" rather than on responsible citizenship per se. Even though scientific literacy has been defined and operationalized as a pre-requisite of responsible citizenship, future studies can also address directly the impact of SSIBL pedagogy on students' perceived and enacted citizenship. Qualitative data were also collected only from the SSIBL condition to find out how the SSIBL contributed to students' scientific literacy for responsible citizenship. Even though collecting and analyzing qualitative data from the BAU instruction group was outside the scope of this research, future studies may address this limitation. Furthermore, future studies could also adopt additional measurements beyond the GSLQ to further investigate students' scientific literacy for responsible citizenship, such as individual interviews or focus groups with the students; these data sources could contribute to the data triangulation, while also providing more in-depth insights to the impact of SSIBL pedagogy.

Last but not least, it should be noted that while SSIBL pedagogy comprises three instructional phases (Ask, Find out, Act), this study evaluated the impact of SSIBL pedagogy holistically. Future studies could focus on evaluating separately the impact of each of the SSIBL instructional phases. Moreover, this study investigated the impact of SSIBL pedagogy on students' scientific literacy for responsible citizenship in terms of (a) students' perceptions of science as a human endeavor (i.e., nature of science), as well as in terms of (b) students' sense of personal responsibility and willingness to take action for maintaining a sustainable environment (i.e., values and attitudes). Future studies could also evaluate the impact of SSIBL pedagogy on different types of scientific literacy competencies and skills (e.g., argumentation skills, decision-making skills, critical thinking, evidence-based reasoning). Finally, it should be acknowledged that SSIBL is not the only pedagogy in support of students' citizenship; other pedagogies such as the pedagogical approach of Education for Environmental Citizenship have also emerged [79,80]. Future studies could, therefore, comparatively investigate the contribution of each pedagogy to students' citizenship as a pre-requisite for sustainability.

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