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Capturing Pedagogical Design Capacity of STEM Teacher Candidates: Education for Sustainable Development through Socioscientific Issues

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Abstract: Even though the urge to transform educational practices towards sustainability has been widely recognized, teachers struggle with implementing socioscientific issues (SSI) such as climate change and loss of biodiversity into their lessons. While the research on SSI grows, the literature remains limited in terms of (i) the use of SSI in facilitating education for sustainable development (ESD), and (ii) teachers' professional learning of SSI-based instruction as a means towards ESD. In this empirical study, we aimed at characterizing five STEM pre-service teachers' pedagogical design capacity (PDC) by focusing on what resources they use and how they interact with these resources to design SSI-based instruction to teach about the sustainable development goals (SDGs). For this qualitative study, the data were collected through field notes, reflection reports, and semi-structured interviews. Our results reveal that pre-service teachers referred to *teacher resources* the most, followed by *collaborative resources*, and *instructional resources* during their design. Even though their use of resources shows strong connections between SSI and their pedagogical content knowledge, preservice teachers' consideration regarding assessment remains inadequate. Furthermore, our study shows that professional development sessions have the potential to foster pre-service teachers' use of PDC resources to address ESD.

Keywords: education for sustainable development (ESD); sustainable development goals (SDGs); pedagogical design capacity (PDC); socioscientific issues (SSI)

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1. Introduction

Education for sustainable development (ESD) puts emphasis on the importance of education for responding to urgent environmental challenges, such as the enhanced greenhouse effect and the sixth mass biodiversity extinction, which are caused by collective human behavior [1,2]. ESD acknowledges the transformation needed for individuals and societies to shift human behavior towards sustainability, so that the earth's ecosystems can heal before humans cause their own extinction [1]. In this regard, the United Nations set a universal agenda, namely the 2030 Agenda, to achieve this transformation in partnership with governments [3]. They introduced 17 sustainable development goals (SDGs), which balance economic, social, and environmental dimensions of sustainable development. The SDGs provide a framework for a shared vision for countries and organizations to create a world that is more equitable and prosperous. The overarching goal of the SDGs is to stimulate action for a better future that is built on the principles of sustainability, social justice, and human rights.

ESD can be seen as a roadmap for transforming our world towards a more sustainable future by contributing to the achievement of the SDGs, particularly SDG-4, quality education. SDG-4 aims to ensure that everyone has access to high-quality education, in order to become responsible global citizens and contribute to sustainable development. Education is not only a goal in itself, but also a means of achieving all SDGs. In this context, ESD plays a critical role as far as achieving the SDG-4 by providing teachers and learners with a foundation for addressing complex and multifaceted sustainability problems facing the world today. However, to effectively fulfil the mission of ESD as far as achieving the SDGs, which we accept as educational reform, teachers need to first build their own capacities in terms of knowledge, skills, values, and attitudes [4]. Otherwise, as Brown [4] indicates, teachers struggle to bridge the gap between curriculum reforms and their daily practice. Therefore, by building their capacities, teachers can become competent, regardless of their discipline, to implement instruction on sustainability issues such as climate change and loss of biodiversity to deal with the SDGs.

Issues that are complex, real-world problems which are based on science and have scientific, social, and ethical implications are defined as *socioscientific issues* (SSI) [5,6]. Previous research has shown that integrating SSI in STEM education fosters students' higher-order skills by providing a context for exploring these real-world problems [7]. Engaging with these issues requires students to analyze and evaluate scientific information, consider ethical and social values, and make evidence-based decisions [7]. Therefore, integration of SSI in teaching about the SDGs has the potential for effective ESD. One way to strengthen teachers' competences in teaching about the SDGs through SSI is to develop their pedagogical design capacity (PDC) for ESD. PDC is defined as the ability to plan and implement instructional strategies, select appropriate learning resources and technologies, and evaluate the effectiveness of teaching practices [4,8]. According to the PDC framework developed by Brown [4], teaching is a design activity where a teacher interacts with their available resources to craft instructional episodes. Although there are a huge number of initiatives for supporting teachers in teaching about the SDGs, most of these focus on identifying teacher competences and developing frameworks for ESD [9–13]. Enhancing teachers' PDC enables them to develop these competences so they can implement effective classroom instruction that promotes the learning of SDGs through SSI.

In order to support teachers in effectively addressing the SDGs in their lessons by incorporating SSI, it is important to understand what resources they use and how they use these resources to design their lessons. This understanding can help educational institutions and designers of professional development activities to identify areas where both pre- and in-service teachers may need additional support to become competent in providing ESD. By gaining a better understanding of how teachers interact with their resources to design SSI lessons to teach about the SDGs, educational institutions can develop targeted interventions in teacher education programs to enhance the PDC of pre-service teachers (PSTs) for ESD. Therefore, through this study, we introduce a case where PSTs used SSI in teaching about the SDGs in secondary school STEM subjects in the Dutch context. More specifically, this qualitative research study focuses on identifying what resources PSTs use to design SSI lessons to teach about the SDGs in secondary school STEM subjects, and how the use of resources affects their design.

Previous research on PDC has suggested that the successful implementation of educational reforms depends heavily on how teachers use their available resources to enact lessons that follow the reform-oriented goals [14]. In other words, the more effectively teachers can use their available resources to design lessons aimed at teaching about the SDGs through SSI, the better their significant potential to fulfil the mission of ESD. Hence, understanding the dynamics occurring in teachers' interactions with resources is crucial to achieve the urgent transformation of educational institutions towards sustainability. This knowledge can help educators at teacher education institutions and professional development designers identify gaps in the use of resources and develop interventions to support teachers' PDC for ESD. For this purpose, in the present study qualitative data were collected through field notes, reflection reports and semi-structured interviews.

In this paper, the theoretical background provides a solid foundation for understanding the context of the study. Subsequently, the aim and the research questions are formulated to guide the investigation and address specific objectives. The Section 2 details the qualitative research design, participants, data collection, and data analysis. The Section 3 presents the empirical findings derived from the analysis of the data. Finally, obtained results are presented followed by a comprehensive discussion.

1.1. Education for Sustainable Development and Sustainable Development Goals

Education for sustainable development (ESD) aims to empower everyone to make evidence-based decisions regarding social, political, and environmental issues [15]. It has received much attention in recent years thanks to the emphasis on including sustainability principles in education systems. ESD has been promoted since 1992 by UNESCO with a great focus on transforming education systems towards sustainable development, which requires a reorientation of teaching and learning. Throughout the history of ESD, the United Nations has provided insight and guidance for all stakeholders worldwide to fulfil the role education plays in building the capacity for sustainable development. In this regard, the Global Action Programme on ESD was developed to scale up concrete actions for teachers to become ESD-competent [16]. This program identified five priority action areas, one of which was building the capacities of educators and trainers, since educators are recognized as "*the most important levers to foster educational change and to facilitate learning for sustainable development*" [17] (p. 35).

One of these attempts to fulfil UNESCO's mission led to the identification of 17 Sustainable Development Goals (SDGs), introduced via Agenda 2030 as an urgent call to action for all countries to heal and secure our planet [3]. Education is explicitly formulated as one of these goals (Goal 4), and it is considered a means for achieving all the other SDGs [9,18]. In this regard, teachers are considered to be key agents in transforming educational systems towards sustainability [18,19].

> "*Educators are powerful change agents who can deliver the educational response needed to achieve the SDGs. Their knowledge and competencies are essential for restructuring educational processes and educational institutions towards sustainability. Teacher education must meet this challenge by reorienting itself towards ESD*" [18] (p. 51).

Several researchers from teacher education institutions have responded to this challenge to transform their institutions towards ESD by focusing on identifying key ESD competences for teachers [9–13]. For example, Widodo et al. [13] validated an ESD framework for STEM teachers, which focuses on pedagogical content knowledge, inquiry, professional practice, evaluation and assessment, professional development, and attitude. Such a framework can be used as a tool to support PSTs in their teacher training. However, education stakeholders themselves lack consensus on what competences are essential for empowering PSTs to implement ESD [20]. Additionally, some of the competence frameworks have been criticized as abstract, complex, and unmanageable [21]. Therefore, the literature on how to support PSTs effectively during their teacher training program to become competent in providing ESD is deficient [22]. In other words, little is known about how PSTs can acquire the necessary knowledge and skills for successful implementation of ESD. It has been shown that teachers who are exposed to sustainability education as part of their teacher training are more likely to implement ESD compared to others [23]. Therefore, it is important to provide PSTs with opportunities to discover ESD during their teacher preparation [24]. Several studies have shown that teachers mentioned the lack of training as a barrier to their actual implementation of ESD [25,26]. Therefore, ESD content should be integrated in PSTs' training programs to build capacities for teachers to become ESD-competent. Looking back to 2005, UNESCO listed 10 recommendations to guide higher education institutions in engaging PSTs in addressing sustainability [27] (pp. 41–42). These recommendations can be seen in Table 1. Unfortunately, in 2023, this advice is still valid as guidance for educational institutions, because there is a universal need for building capacity for teachers who can implement ESD [28]. A systematic literature review study on initial teacher training for ESD revealed the lack of training focusing on the development of competences needed to implement sustainability education [29]. Even though the urgency of implementing ESD is clear, teacher training programs that can equip teachers with the necessary competences have still not been established [22]. Teachers need to develop capacities for ESD to prepare scientifically literate citizens for a sustainable future [24,30–34]. Working with ESD requires teachers to develop new pedagogies that can respond to its multidisciplinary and societal nature [35]. For this reason, ESD should be integrated in PSTs' educational program [36].

Table 1. Recommendations to guide higher education institutions [27] (pp. 41–42).

Number	Description
1	Require interdisciplinary coursework on sustainability for student teachers and make materials available for student teachers on local and global sustainability issues
2	Demonstrate pedagogical techniques that foster higher-order thinking skills, support decision-making, involve participatory learning, and stimulate formulation of questions
3	Emphasize to student teachers that citizenry in a sustainable community requires active participation and decision-making; challenge them to create ways to incorporate participation and decision making into their classroom procedure and curriculum
4	Discuss social equity (e.g., gender, racial, ethnic, and generational) with student teachers and identify ways in which the local community exhibits social tolerance, societal intolerance, equity, and discrimination
5	Request that student teachers analyze the mandated curriculum they will be teaching to identify topics and themes related to sustainability and those that are linked to local sustainability issues
6	Provide student teachers with opportunities to explore their own values and attitudes towards local sustainability problems and those of the surrounding region
7	Promote understanding of global sustainability in order to encourage critical thinking and decision making that influence personal lifestyle and economic choices
8	Develop specialized ESD programs for student teachers (e.g., mini courses) with certificates of completion, so that student teachers can include them in their resumes for seeking employment
9	Promote graduates with ESD specializations, who are knowledgeable in ESD and its contribution to society
10	Place graduates who have completed courses in ESD in key schools and ministerial positions to help influence and bring about change

1.2. Pedagogical Design Capacity

Teacher education aims at equipping teachers not only with necessary content knowledge, but also with relevant competences so that they can respond to students' needs. The recommendations listed in Table 1 aim to support PSTs in implementing sustainability education. To illustrate, recommendation number 5 acknowledges the fact that the mandated curriculum may not be explicit in terms of sustainability-related topics. For this reason, educational institutions are advised to encourage PSTs to analyze the curriculum to recognize the opportunities to integrate sustainability issues in their practice. Recommendation number 2 focuses on pedagogical techniques for PSTs so that they can identify appropriate methods for ESD depending on the instructional goals. All in all, UNESCO's recommendations reveal the significance of capacity-building for PSTs as a way to transform educational systems towards sustainability. Achieving such an educational reform requires teachers to have an active role in (co-)designing the curriculum through enactment [37]. Teachers are also expected to adapt their teaching methods to address immediate societal needs. It is impossible to fully prepare teachers for an unpredictable future such as the recent COVID-19 pandemic which required teachers to adopt and modify their instruction in response to changing circumstances by making use of available resources as co-designers. Thus, teachers need to build their capacities to adapt the curriculum to ensure that education remains relevant and effective in response to the challenges of tomorrow. In the face of a rapidly changing world, individuals need to be adaptable, as the world is becoming increasingly complex and unpredictable [38]. Teachers who are able to design their instruction as a response to the changing world will be better equipped to prepare their students for the future. This includes the ability to integrate new technologies, adapt to changing social and cultural contexts, and respond to emerging global issues such as climate change and the urgency for ESD. This perspective on building the capacities of teachers to embrace their role as (co-)designers for meaningful teaching was labeled pedagogical design capacity (PDC) by Brown [4,8]. In his own words, PDC is teachers' "*ability to perceive and mobilize existing resources in order to craft instructional contexts*" [4] (p. 24). He interpreted teaching as design to explain that teachers' act of instruction is the product of interaction between themselves and the resources available to them, which in turn allows teachers to make their practice meaningful in a unique way. Brown [8] focused on the gap between curriculum reforms and teachers' capacities to put these reforms into action in their daily practice. In this regard, we consider implementing ESD in STEM subjects as a reform that aims at transforming education towards sustainability. For this reason, it is important to characterize teachers' capacities and their interactions with curriculum materials as vehicles to shift educational systems towards ESD.

The concept of PDC has been accepted by many researchers as an essential competence for teachers when making instructional decisions through design to meet their students' needs [39]. According to Forbes [37], (p. 24), PDC is about "*teachers' abilities and competence to perceive and mobilize both personal teacher resources (. . .) and external curriculum resources to craft instruction and instructional contexts in light of instructional goals.*" In his PhD project, Forbes studied PSTs' development of PDC for inquiry-based elementary science teaching. He concluded that PSTs rely heavily on available materials rather than adjusting them. For this reason, PSTs should be provided with opportunities to design lessons during their training, to strengthen the development of their PDC [37]. Another study, which contributed to the notion of PDC in mathematics education, defined PDC as "*more than the degree of approximation of the affordances of curricular resources by the teacher: it is also about the quality of opportunities for mediation of mathematics that the teacher creates*" [40] (p. 89). The study revealed how teachers interact with their resources to make decisions, focusing on omissions and amendments of the components of a lesson to create opportunities for learning. Looking from this perspective, capturing PSTs' PDC during the design process of integrating ESD in STEM subjects can help teacher educators and curriculum designers to identify how to promote teacher candidates' involvement in teaching sustainability.

At this point, it is important to note that PDC is different from subject-matter knowledge or pedagogical content knowledge (PCK). Both subject-matter knowledge and PCK are considered as resources which teachers use to design their lessons. The interactions between teachers and their resources such as subject-matter knowledge or PCK are what fosters their PDC. Considering that teachers' knowledge relates to the quality of their instruction, [41,42], Brown's vision of PDC went beyond what teachers know; he also focused on teachers' capacities to use that knowledge [4,8]. He referred to this distinction as interaction *nouns* versus interaction *verbs*. Teachers' knowledge does not necessarily guarantee the efficient transfer of that knowledge to the students. Teachers' meaning- and decision-making processes in terms of enactment of what is known to them is affected by their personal beliefs. Teachers bring their personal resources to the use of the curriculum through meaning-making that results in instructional practices.

To understand teachers' role in transforming education systems towards sustainability, it is important to capture their knowledge as well as the process by which they use such knowledge for their lessons. In order to analyze this process of interactions between available resources, Brown [4,8] introduced a theoretical framework that refers to two types of resources: *curriculum resources* and *teacher resources* for PDC. This framework has enabled researchers to characterize what teachers make use of when they design lessons, while PDC itself describes how they make use of such resources for instructional outcomes. Knight-Bardsley and McNeill [43] contributed to PDC research on facilitating reform-oriented instruction by using a broader perspective on curriculum resources. As an adaptation of Brown's original conception of PDC, they referred to *instructional resources* instead of curriculum resources, which include professional development workshops and other tools together with the curriculum. This adaptation can be seen on the left-hand side of Figure 1, while the right-hand side is in line with Brown's original framework. When teachers were introduced to scientific argumentation via a series of professional development workshops as a reform-oriented instruction method, their use of the knowledge gained via these workshops resulted from their ability to recognize the necessary components in the resources provided to them [43]. Therefore, teachers need support in identifying the necessary components of workshops to be able to efficiently make use of the resources to facilitate reform-based instruction, such as argumentation in science education. Compared to Brown's original conception of PDC, the inclusion of professional development workshops together with curriculum and other tools as *instructional resources* allows us to have a better understanding of teachers' decisions when it comes to designing classroom instruction to transform education.

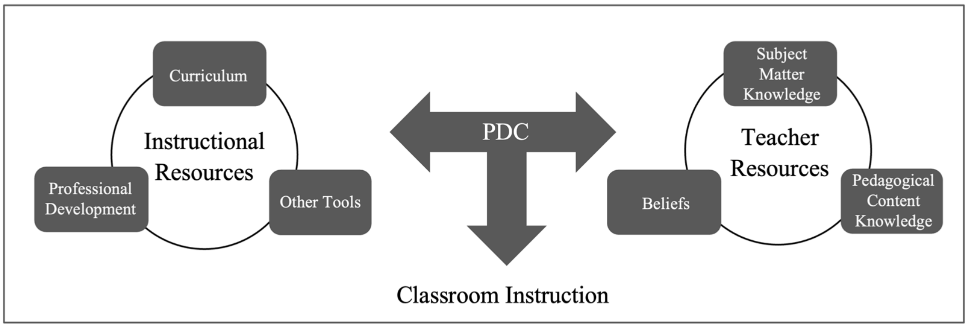

Figure 1. Framework for PDC [43] (p. 647).

Looking at how PDC research has grown in recent years, analysis of teachers' interactions with their available resources showed that when teachers were asked to work in a team to design lessons collaboratively, they based their decisions on using each other as resources [44]. According to Ellingson's [44] doctoral study, teachers did not refer to *instructional* or *teacher resources* to justify their decisions—their decisions were based on each other. The impact of collaboration on teachers' decisions regarding their design was therefore considered to warrant adding another dimension, *collaborative resources*, to the PDC framework [44]. For this reason, we adapted the PDC framework suggested by Knight-Bardsley and McNeill [43] by adding *collaborative resources*, as proposed by Ellingson [44]. This perspective allows us to capture PSTs' interactions not only with their *instructional resources* or *teacher resources*, but also with each other as *collaborative resources* when it comes to designing SSI lessons to teach about the SDGs.

Framework for PDC Based on Previous Studies

The review of the previous work on a framework for PDC allowed us to identify three resources that teachers use during their lesson design: *instructional resources*, *collaborative resources,* and *teacher resources;* see Figure 2. Below we explain these three resources in detail.

Instructional resources. Professional development workshops, curriculum, and other tools are considered to be *instructional resources* [43]. In this context, professional development workshops aim at supporting teachers in improving their instruction. Providing teachers with instructional strategies for argumentation in science lessons can be given as an example of a professional development workshop. Curriculum materials, on the other hand, consist of domain representations, procedures, and physical objects. Brown [8] identified the curriculum materials as "*vehicles for reform*" to emphasize the importance of the materials in facilitating transforming educational systems. Physical objects refer to tools, such as the materials needed for data collection in a STEM lesson. Domain representations are concepts in a subject-matter domain and their presence in models, diagrams, charts, or analogies. For example, the order of covering different topics in a unit represents domain concepts and how they relate to each other. Finally, procedures include instructions, textbooks, lesson plans, or scripts that are designed for teachers and students. In this regard, educational curriculum materials that aim to support teachers' learning to improve instruction [45] are great examples of procedures. These materials provide guidance for teachers to facilitate meaningful instruction to fulfil the vision of educational reforms [46]. Educational curriculum materials are known to have the potential to support teachers' learning of subject-matter knowledge, and their pedagogical content knowledge (PCK) to enact reform-based curricula such as project-based learning in science education [47].

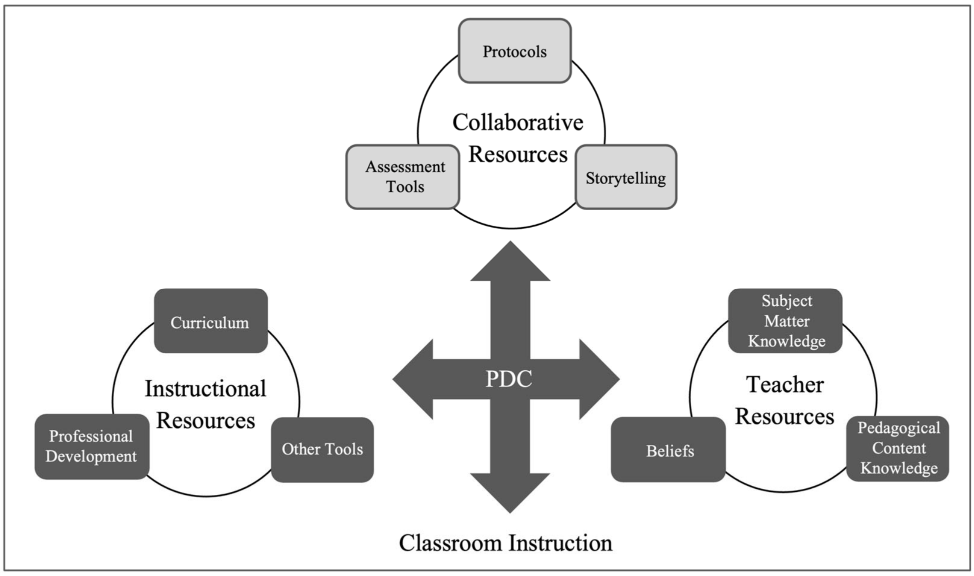

Figure 2. Framework for PDC adapted from previous studies [43,44].

Collaborative resources. *Collaborative resources* consist of protocols, evaluation of assessment tools, and storytelling. Teachers make agreements with each other regarding their lesson design when they work in collaborative teams. Such protocols help teachers to focus on student learning to design effective classroom instruction to meet students' needs. Throughout the design process, teachers evaluate assessment tools to adapt them to their students' needs and share their experiences and classroom events with each other through storytelling. Storytelling helps teachers to grow their PDC in STEM education [44].

Teacher resources. *Teacher resources* include subject-matter knowledge, beliefs, and pedagogical content knowledge (PCK). PCK includes teachers' knowledge of learning objectives, students' understanding, instructional strategies, and ways of assessment [48]. Beliefs are teachers' orientations and personal motivations towards teaching the content, rather than their ability to do so. For example, previous studies have reported that teachers' orientations towards curricular reforms are determining factors in bridging theory and practice in education [8]. In other words, educational reforms are prone to failure if they do not consider teachers' personal beliefs.

1.3. Socioscientific Issues

Socioscientific issues are societal issues that are conceptually tied to science [5,6]. SSI are controversial in nature and consist of complex problems that include ethical or moral dilemmas. These issues do not have obvious solutions, and they require scientific knowledge to be addressed from various perspectives [49]. In addition to science, they relate to ethics, economics, and politics, thanks to their interdisciplinary characteristics. Examples of SSI include climate change, genetically modified foods, alternative energy choices, and animal testing.

Since SSI arise from societal problems and are interdisciplinary, they link daily life with classroom instruction. Introducing SSI as part of a teaching strategy has been shown to improve students' environmental citizenship skills [50]. Students become passionate about environmental issues, and they show willingness to implement actions based on scientific arguments when they are exposed to SSI [51,52]. Since moral aspects of citizenship skills are usually missing in teachers' practice, SSI can provide a context to support students' moral development and other citizenship skills [53]. Therefore, SSI capture students' attention and promote the development of higher-order skills such as argumentation, evaluating scientific information, and making informed decisions [7]. For this reason, SSI-based instruction has received much attention in recent years, focusing not only on student learning, but also teacher practices. However, even though there has been some research on SSI to promote higher-order skills, Evagorou and Dillon [54] noted the absence of studies on teachers, especially their professional learning for SSI teaching [55].

ESD emphasizes the integration of key sustainability issues such as climate change and loss of biodiversity into teaching and learning, so that tomorrow's citizens will be equipped with necessary skills such as critical thinking and media literacy [56]. As we experienced during the COVID-19 pandemic, the aforementioned skills are crucial to be able to deal with societal issues that are based on science. However, when teachers are asked to integrate sustainability issues into their lessons, they struggle with identifying an appropriate method [30]. In this regard, one way to support PSTs in addressing these issues in their lessons is to provide them with SSI to use to promote environmental citizenship [50,57]. However, PSTs usually merely refer to environmental topics at the beginning of their lessons as an introduction to foster student engagement in science lessons [58]. Even though they acknowledge the controversial aspects of SSI, PSTs rarely facilitate society-related discussions of SSI to promote the development of higher-order skills [58]. For this reason, it is important to introduce SSI as an effective context for ESD in PSTs' training programs.

When students are instructed based on SSI, their scientific literacy improves, because SSI meaningfully relate scientific knowledge to everyday life [59]. The National Research Council in the U.S. introduced a framework for K–12 science education focusing on STEM to promote scientific literacy [60]. However, this framework was criticized due to its lack of attention to the use of SSI to promote responsible citizenship [34]. Additionally, SSI contribute to the development of societal aspects of scientific literacy, which have a greater focus on informed decision-making regarding ethical, moral, and economical dilemmas [61]. For this reason, SSI are recognized as a sociocultural response to STEM education to promote ESD [62]. SSI allow students to discuss their personal values with one another, which enables students to experience perspective-taking and building empathy [63]. In this regard, Simonneaux and Simonneaux [64] argued "*the notion of Sustainable Development, in itself, can be considered as an SSI*".

1.4. Aim and Research Questions

Integrating environmental issues into STEM education requires teachers to build their pedagogical capacities to address these issues in their lessons, due to the complex nature of these issues [31]. For this reason, various researchers have studied teachers' subject-matter knowledge, PCK, beliefs, and attitudes in the separate contexts of ESD and SSI [42,65–68]. However, to our knowledge, little is known about teachers' pedagogical capacity to use their subject-matter knowledge, PCK, beliefs, and attitudes to co-design the curriculum to incorporate SSI as a means towards ESD in STEM subjects. Although incorporating SSI into STEM lessons is considered an effective way to address the higher-order skills necessary for environmental citizenship, little attention has been paid to implementing SSI for ESD [69].

Teachers' PDC has been researched in several contexts such as scientific argumentation [43], inquiry-oriented science lessons [70], and digital curriculum resources in mathematics education [71]. However, it has not been examined with respect to PSTs' design of SSI lessons that focus on sustainability education. From previous studies on teachers' PDC, we understand that teachers need support with using *instructional resources* and *teacher resources* in the best ways to facilitate student learning [39,72]. From the ESD perspective, teachers' competences to implement environmental issues have been identified as one of the greatest barriers to ESD [73]. An interview case study showed that none of the

16 chemistry teachers designed lessons with ESD as the core, and they could not identify any teaching strategy for integrating ESD [30]. Several studies in this field have shown that there is a universal need for competent teachers with a holistic view who can handle the multidisciplinary complexity of sustainability topics [28,34]. Understanding how PSTs interact with their available resources and develop their PDC competence can help educational institutions, professional development designers, and curriculum designers to meet PSTs' needs to promote ESD and fulfil their role in transforming education towards sustainability [36]. For this reason, this empirical study aims at capturing preservice STEM teachers' pedagogical design capacity for incorporating SSI in their lessons to teach about the SDGs. The shortage of studies that focus on understanding STEM teachers' use of SSI to teach about the SDGs shows the significant contribution of this study for ESD. This study shows what kinds of resources teachers use when they are asked to design SSI lessons to teach about the SDGs, and how they interact with these resources in collaboration with other STEM teachers. Therefore, this study empowers teacher educators, professional development designers, and curriculum designers to embrace practices that will effectively promote PSTs' involvement in co-designing to transform educational systems towards ESD.

In conclusion, teachers experience difficulties with implementing ESD in their teaching practice. Integrating SSI and reflecting on the impacts of these issues on society is not an easy task, especially for novice teachers. It requires teachers to adapt or improvise curriculum materials based on their instructional goals by co-designing the curriculum. In this empirical study, we want to inform higher education institutions as far as providing training for PSTs to facilitate ESD. With this in mind, we focused on capturing PSTs' PDC for using SSI as a means to teach about the SDGs, with the following research questions:

(1) How can STEM pre-service teachers' pedagogical design capacity for designing SSI-based lessons to teach about the sustainable development goals be characterized?
(2) How does the use of the different types of resources impact PSTs' lesson design for teaching about the SDGs through SSI in Dutch secondary education?

By answering these questions, we can establish a relation between the different resources (*instructional resources*, *teacher resources*, and *collaborative resources*). This could help us to formulate grounded recommendations for PSTs' education and for the professional development of STEM teachers to teach about the SDGs in secondary education. To our knowledge, this is the first study that focuses on PSTs' use of resources, according to the PDC framework, for teaching about the SDGs. The findings of this study will inform both PSTs' education programs and in-service teachers' professional development programs in STEM subjects.

2. Method

2.1. Research Design

The chosen methodological approach for this study is a qualitative research design where the research was performed in a professional learning community (PLC) set-up. There are two reasons for this: working in a PLC setting fosters teachers' SSI knowledge development [42,67], and empirical evidence shows that teachers' co-learning plays a crucial role in the successful implementation of ESD [74]. Ariza et al. [50] emphasized the importance of collaboration between teachers from different disciplines, for teachers to experience SSI as learners as part of their professional development. For this reason, we aimed at providing the PSTs with an opportunity to strengthen their PDC collaboratively by setting up the PLC meetings.

The PLC meetings were facilitated by two researchers from the teacher education program at a university in the Netherlands. Previous research on facilitators' role in higher education PLCs has shown that encouraging PSTs to reflect on their decisions and providing them with relevant resources fosters their professional growth [75]. Therefore, in the PLC where PSTs worked together, there was a focus on promoting reflection and providing them with resources related to SSI and ESD. Throughout the process, the PSTs were required to submit *360-degree feedback* reports twice to promote reflection as a process of learning. In these written reports, the PSTs were asked to reflect on their research skills, communication skills, and self-management skills.

Handelzalts [76] (p.7) described collaborative design in teams as "*a group of at least two teachers from the same or related subjects, working together on a regular basis, with the goal to design and enact their common curriculum*". It has been shown that the collective dimension is an important aspect of teachers' professional development and capacity- building [71]. For that reason, this study adopted collaborative design in a team as part of the teacher training program for developing PSTs' pedagogical design skills for ESD. Throughout the process, several support options were provided in order to enable STEM PSTs to collaboratively design their lessons. These support options were collaboration with guest in-service teachers from neighborhood schools, collaboration with experts in educational design research, and two researchers in STEM education as facilitators of the PLC meetings. The two researchers who facilitated the PLC meetings provided guidance and support in terms of prompting the PSTs to review the literature, collaborate with in-service teachers as their co-designers, and work with exemplary lessons. Exemplary lessons empower teachers in creating their own lessons by serving as a model [77]. Additionally, PSTs followed a professional development session where they heard a lecture about an efficient tool for designing their lessons, namely, the Curricular Spider Web [78].

2.2. Participants

This research involved five STEM PSTs working together in one team to design SSI lessons to teach about the SDGs at secondary schools in the Netherlands. The PLC group consisted of five PSTs with different STEM subject backgrounds. The PSTs were students in a STEM teacher education master program at a Dutch university. All PSTs enrolled at the university were expected to take the course 'Educational Design Research' where the PSTs were expected to combine design and research in the context of the Dutch secondary education system. Five of these PSTs voluntarily chose to focus on designing lessons to teach about the SDGs through SSI. Therefore, a purposeful sampling strategy was used. Table 2 shows the background data for the participants.

Table 2. The participants.

Participant	Subject	Gender	Age	Background
PST 1	Computers	Female	24	Current program: Dual Master's degree in Data Science, and Science Education and Communication Previous study: Bachelor's degree in Data Science
PST 2	Physics	Male	56	Current program: Master's degree in Science Education and Communication Previous study: PhD in Applied Physics
PST 3	Physics	Male	24	Current program: Dual Master's degree in Sustainable Energy Technology, and Science Education and Communication Previous study: Bachelor's degree in Mechanical Engineering
PST 4	Mathematics	Male	50	Current program: Master's degree in Science Education and Communication Previous study: Bachelor's degree in Mining and Petroleum Engineering
PST 5	Mathematics	Female	23	Current program: Dual Master's in Industrial and Applied Mathematics, and Science Education and Communication Previous study: Bachelor's degree in Mathematics

Informed consent was obtained from all individuals participating in this study in accordance with the ethical guidelines of the Ethical Review Board of the same university.

2.3. Data Collection Process and Sources

There were 6 PLC meetings organized over a period of 5 months; and each meeting lasted 2 h. Table 3 provides information regarding what happened during these meetings.

Table 3. PLC meetings.

PLC Meetings	Description
12 October 2022	PSTs discussed what SSI are, their relevance for teaching about the SDGs, and how to implement the use of SSI. Two experienced teachers (Biology and Physics) joined this meeting to share their experiences with integrating SSI as a means towards ESD.
23 November 2022	PSTs discussed their findings in the literature related to SSI. They compared SSI with other ways of teaching, discussed the framework for SSI and effectiveness of SSI at secondary schools.
7 December 2022	PSTs chose two focus points for their design: teachers' role in SSI-based instruction and students' motivation to learn about the SDGs through SSI. PSTs discussed how to design lessons based on these two focus points.
11 January 2023	PSTs focused on how to motivate their students by integrating SSI. They discussed how to capture motivation, to show the effectiveness of SSI as a way of teaching about the SDGs.
18 January 2023	PSTs focused on the documentation of their work and on creating a poster to present their work to their peers studying in the same teacher training program.
8 February 2023	PSTs reflected on the PLC meetings and gave feedback to each other.

The data collected included field notes from 6 PLC meetings, 360-degree reflection reports written by the PSTs, and transcripts of semi-structured interviews that were held individually with two PST volunteers. Therefore, this study incorporated three qualitative data sources: field notes, reflection reports, and interviews. Data collected through field notes aimed at capturing observations made during participant interactions. These field notes were recorded by the first author who joined the PLC meetings as a participant observer. Secondly, reflection reports written by the participants themselves were utilized as a valuable source to gain comprehensive insights. Finally, interviews were conducted to delve deeper into participants' experiences. These interviews lasted approximately 40 min which were audio-recorded and transcribed verbatim. By using diverse data sources, we ensured the collection of in-depth qualitative data enhancing the richness of our findings. Moreover, triangulation was done by gathering data from different data sources.

2.4. Data Analysis

The data analysis started with Boeije's [79] qualitative data analysis spiral via ATLAS.ti (version 23.2.0), qualitative data analysis software. To code the data, a deductive coding approach was initially used by deriving three categories from the PDC framework [43,44], which is given in Figure 2. These PDC categories were *instructional resources*, *collaborative resources*, and *teacher resources*. Our initial codes were the nine sub-categories of these resources shown in the same figure (e.g., for *instructional resources*: 'Curriculum', 'Professional Development', and 'Other Tools'). Throughout the coding process, new codes were created for each category via axial and selective coding [79]. Thus, a combination of deductive and inductive coding approaches was used in this study. Table 4 presents the final codebook that resulted from the different cycles of coding and discussions between the first two authors to reach interrater reliability.

Table 4. Final code book resulting from open, axial, and selective coding process.

PDC Resource Categories	Codes
Instructional Resources	Professional Development (PD) Sessions
	Curriculum
	Other Tools
	SSI *
	Literature *
	Bridging the Curriculum *
	Lack of Tools/Support *
Collaborative Resources	Protocols
	Storytelling
	Assessment Tools
	Finding Common Ground *
	Giving and Receiving Feedback *
	Consulting with Experts *
Teacher Resources	Beliefs
	Subject-matter Knowledge
	PCK—Goals and Objectives (PCK-GO)
	PCK—Instructional Strategies (PCK-IS)
	PCK—Students' Understanding (PCK-SU)
	PCK—Assessment (PCK-AS)
	Previous Experiences *

* Codes that were added throughout the axial and selective coding.

2.5. Interrater Reliability

Interrater reliability was calculated by performing a coding exercise as follows: the first author coded the data independently and developed a code book with clear definitions for each code. Secondly, a project was created via ATLAS.ti where all the codes were removed but not the quotations. This means the project contained all the data to be coded, pre-defined quotations, and the list of codes. The project was then shared with the second author where the second author coded the data independently [80]. The intercoder reliability was 81%.

3. Results

3.1. What Resources Were Used

In this study, five PSTs co-designed two SSI-based lessons to implement instruction about the SDGs in their STEM subjects. To answer our first research question (*how can STEM pre-service teachers' pedagogical design capacity for designing SSI-based lessons to teach about the sustainable development goals be characterized?*), we explored the PSTs' use of resources during their lesson design by analyzing the field notes of the PLC meetings, reflection reports, and the interviews. The result of this analysis is represented in Figure 3. The PSTs used different resources from all three resource categories. They mostly referred to *teacher resources* (f = 293), followed by *collaborative resources* (f = 178), and *instructional resources* (f = 176). Throughout the design process, PSTs' interactions with available resources resulted in a shift in their 'Beliefs'. One PST said how his role changed as a PST and how engaging the unmotivated students in the internship lessons became more important to him. This change occurred as a result of the interactions between the three PDC resources; namely, *instructional*, *collaborative*, and *teacher resources*. This shift was captured in the interview with the PST as follows:

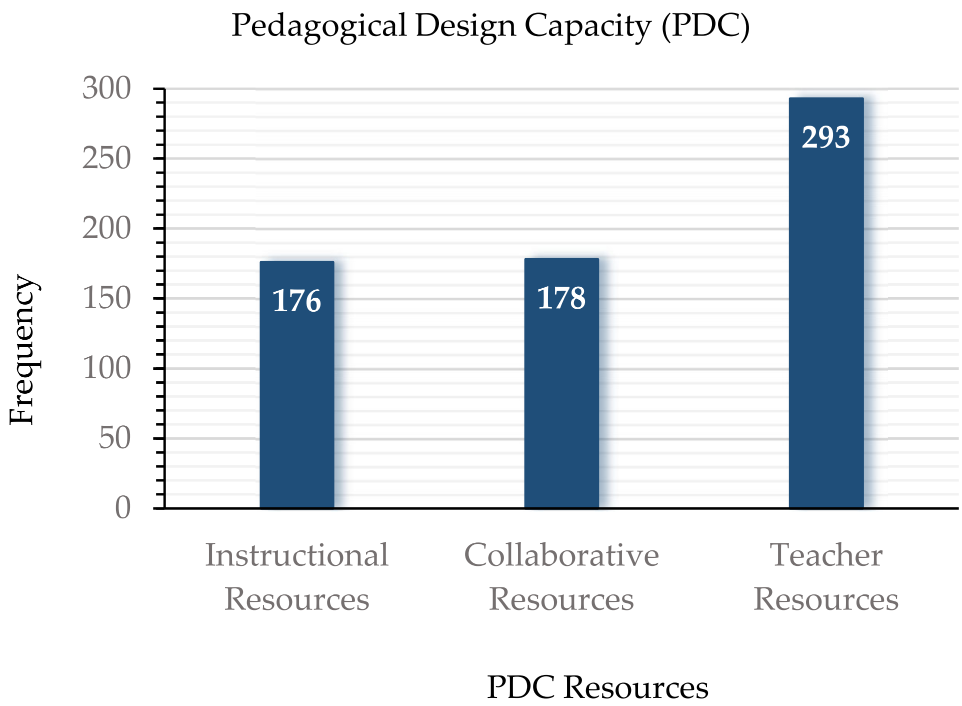

Figure 3. PSTs' use of PDC resources, by category.

> "*I think the teacher role is very interesting because I am also still looking for my role as a teacher. Initially I started my internship with the idea that I am just there to tell them my expectations, I am only going to focus on the students who are interested in the subject. If they do not pay attention, then so be it. And now actually I noticed that I am shifting towards the other end. If they do not pay attention, I really want them to pay attention.*" (PST 3)

In order to answer this study's research questions, we analyzed the qualitative data from various perspectives to enhance our understanding of PSTs' use of resources to design SSI lessons to teach about the SDGs. First, we present the resources used during PSTs' collaborative lesson design according to three categories based on the PDC framework (see Figure 2), as follows: *instructional resources*, *collaborative resources*, and *teacher resources*. Second, we report on the interconnectedness between these three resource categories, which helped us to identify the nature of the relationships between the resources and how PSTs used these resources. Third, we present the code co-occurrence analysis results which enriched our understanding in terms of how often two resources were related to one another in PSTs' lesson design. Finally, we present how PSTs' use of resources changed over the PLC meetings in order to identify how interventions foster or hinder PSTs' use of resources.

3.1.1. Instructional Resources

Our analysis showed that when PSTs interacted with the *instructional resources*, they mostly used 'SSI' as a new way of teaching (f = 44), followed by 'Professional Development Sessions' (f = 37), and 'Literature' (f = 36). However, 'Curriculum' (f = 9), and 'Bridging the Curriculum' (f = 12) were taken into account least often in designing lessons to teach about the SDGs through SSI. This can be seen in Figure 4.

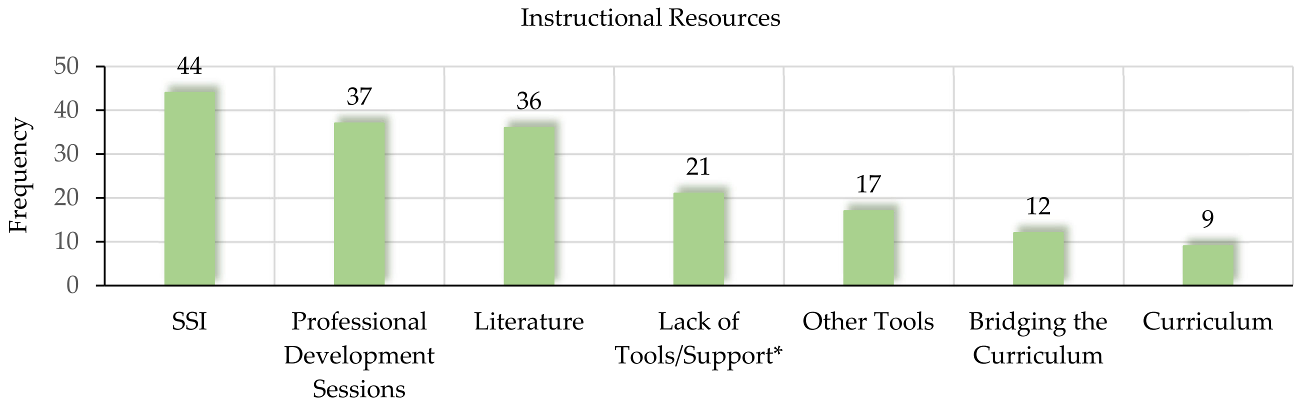

Figure 4. PSTs' reference to instructional resources. * Lack of Tools/Support represents PSTs' reference to the absence of instructional resources.

PSTs often referred to 'SSI' during the PLC meetings as an effective way to teach about the SDGs. One PST considered why SSI are appropriate to teach about the SDGs by reflecting on his understanding of sustainability. According to this PST, the SDGs bring all the pillars of sustainability together and the interdisciplinary nature of SSI empowers teachers from different disciplines to tackle instruction about the SDGs through SSI in secondary schools.

> *"If you are like me, and you think of sustainability, you think of creating energy and energy transition. But, well, the SDGs showed that it is much bigger than that and we think SSI would be very effective because you can really apply them in very much more. You can use SSI in Physics, but you can also apply it in Geography or History. This allows you to use it in a lot of different courses in secondary schools."* (PST 3)

PSTs considered SSI as being different from traditional ways of teaching. They referred to SSI-based instruction as a process that encourages students to work towards a solution, rather than focusing on finding the solution for an environmental issue. By doing so, PSTs showed acknowledgement of the complexity of sustainability issues and emphasized the importance of contributing to the solution of a problem. In this regard, they identified uncertainty as an aspect of SSI that allowed them to change their role as a teacher in their lesson design to help the students deal with this uncertainty. PSTs expressed their perception of SSI as a way to deal with multifaceted issues as follows:

> *"Students find SSI really, really hard because they find it hard that they do not have like very clear goals, they have to set it themselves and they are used to from other courses just like getting a lot of content sent to them."* (PST 1)

> *"SSI is different from just teaching the SDGs, because then you go back to the class, "these are the SDGs, and they are important!", whereas I think that if you allowed the students to tackle the SDGs using something like SSI, then they also know what it is like in practice."* (PST 3)

Here it is important to mention that PSTs' perception about using SSI to teach about the SDGs was reflected in their 'PCK—Students' Understanding'. PSTs adapted their role as a teacher in their lesson design because they decided that SSI are different from what the students are used to. According to the PSTs, SSI bring uncertainty in terms of working towards a solution. This shows that even though, in the PDC framework, *instructional resources* and *teacher resources* are presented as two distinct pools of resources, they are internally connected when it comes to designing lessons. PSTs used their 'PCK—Students' Understanding' to justify the adaptations they made to their role as a teacher because they agreed that use of SSI is a new way of teaching and learning. They justified the changes they made in terms of the teacher's role in SSI by referring to students not being accustomed to this new way of learning.

Another resource PSTs referred to during the lesson design was using 'Literature'. We coded this as an *Instructional Resource* since PSTs aimed at using the literature to understand the nature of SSI and how to implement SSI in STEM subjects to teach about the SDGs. The data analysis showed that PSTs relied on 'Literature' to define what SSI mean to them and to reach a common understanding of 'SSI' for their lesson design. Reviewing the literature initiated the group discussions for PSTs to collaboratively decide on the characteristics of SSI-based instruction to teach about the SDGs. However, they struggled with identifying relevant resources from 'Literature' and applying the theory in practice to implement instruction about the SDGs through SSI in their lesson design. It appears that PSTs need support with improving their research skills to be able to find relevant and reliable sources to reach a better understanding of SSI. They also need support with implementing theory in practice. One PST identified his struggle in this regard as follows:

> "*I have never done a literature review before. I used Google but it is difficult to filter out. When you write SSI, a lot of sources appear. The challenge is how to filter out good articles and then how to filter good information from those articles.*" (PST 4)

Another PST identified it as difficult to read the literature related to SSI due to their emphasis on social aspects of scientific problems. The PST referred to her own experiences as a student and to other members of the PLC group to justify her choices related to their design when the PSTs discussed the characteristics of using SSI to teach about the SDGs. This incident revealed that when the PST struggled with using her *instructional resources* in the SSI context, she referred to the *teacher resources* and *collaborative resources*. When it comes to applying new ways of teaching for reform-based instruction, in this case teaching about the SDGs through SSI, PSTs' use of other resources resulted from the absence of *instructional resources*. This was evident in the following quotation from one of the PSTs who justified her understanding of SSI based on her experience as a student, *teacher resources*, and others' opinion in the PLC meetings, *collaborative resources*, instead of the literature, *instructional resources*.

> "*I am not too sure how to relate it back to literature because still from literature I still feel like SSI is still fake to me and it is more like my own experience with it and how others describe it to me. Maybe it is also because I am just not that good at reading papers, especially papers that are really about these social things. I find it difficult.*" (PST 1)

3.1.2. Collaborative Resources

Our analysis revealed that the PSTs perceived each other as resources in a number of ways. This can be seen in Figure 5. PSTs referred mostly to 'Protocols' (f = 72) as one of their *collaborative resources*. This high frequency of 'Protocols' shows that PSTs interacted with each other to discuss how to design SSI lessons collaboratively. 'Protocols' also refers to PSTs' discussions regarding setting up the agenda of the PLC meetings. For example, a PST shared her opinion about how to proceed, as follows:

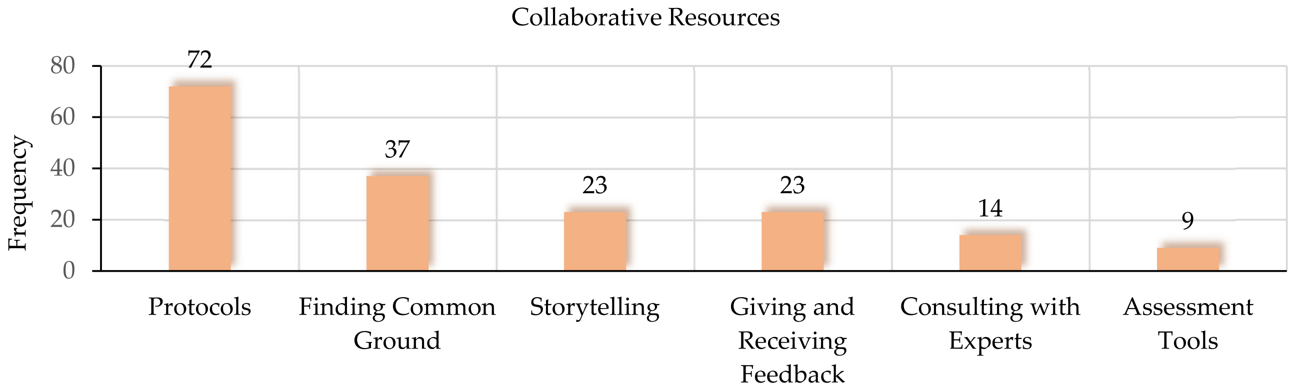

Figure 5. PSTs' use of collaborative resources.

> *"Now we can define some tasks, but we are not there yet. Maybe we should do like action points to go through, that we can work at. Now I think we should focus on Spider Web and make some definitions. That will make it more concrete for sure."* (PST 1)

'Finding Common Ground' (*f* = 37) was another collaborative resource that PSTs often used in this category. PSTs discussed how they perceived SSI as a means towards sustainability education with each other and with in-service teachers who were invited to PLC meetings. They compared SSI with different teaching methods such as inquiry-based and project-based learning. These discussions were represented in our analysis as 'Finding Common Ground' because PSTs compared SSI with other ways of teaching to reach a consensus regarding their understanding of SSI. Moreover, PSTs discussed two different approaches to implementing instruction about the SDGs through SSI. They considered introducing a socioscientific issue together with its associated SDGs to the students. This would require the PSTs to decide which SDGs are relevant to the socioscientific issue they wanted to introduce. However, they decided to ask the students to consider the introduced socioscientific issue from different perspectives to link it with the SDGs. According to the PSTs, this allows students to see the connections between SSI and the SDGs from their own perspective and prevents the teacher from restricting students from associating the socioscientific issue with different SDGs. Here, it is important to emphasize that PSTs used their *teacher resources* in these discussions, specifically their 'PCK—Instructional Strategies'. However, the fact that PSTs used their knowledge of instructional strategies to have a discussion with each other to find common ground shows how *collaborative resources* and *teacher resources* are internally connected with each other.

Of the *collaborative resources*, 'Assessment Tools' (*f* = 9) was the resource least often mentioned by the PSTs. This means that the PSTs' collaboration least often involved discussing how to evaluate students' understanding and skill development in their lesson design to teach about the SDGs through SSI. Even though PSTs attempted to discuss how to evaluate the success of their lesson design, PSTs' considerations of 'Assessment Tools' were superficial and no conclusions with respect to assessment were reached. For example, one PST questioned what they want the students to learn from the SSI way of teaching. Another PST suggested designing *something* to measure whether they meet the learning goals without naming it as an assessment tool.

3.1.3. Teacher Resources

Our analysis regarding PSTs' use of *teacher resources* showed that PCK played a crucial role in teachers' lesson design to teach about the SDGs through SSI. While 'PCK—Instructional Strategies' (*f* = 90), 'PCK—Goals and Objectives' (*f* = 69), and 'Beliefs' (*f* = 65) stood out in terms of PSTs' use of *teacher resources*, 'PCK—Assessment' (*f* = 3) was mentioned least often by the PSTs. This can be seen in Figure 6.

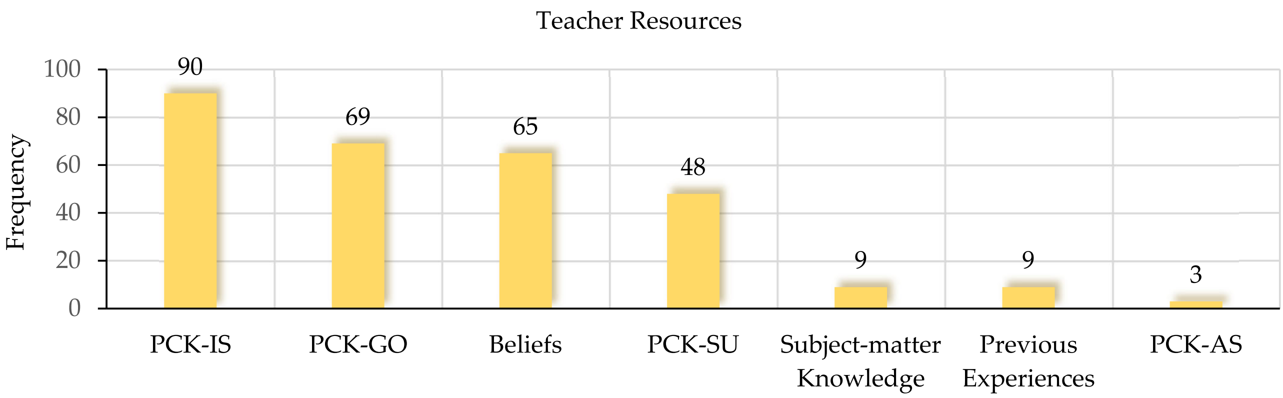

Figure 6. PSTs' use of teacher resources.

PSTs considered SSI-based instruction as a new way of teaching and learning. How they perceived SSI had an impact on PSTs' use of their 'PCK—Instructional Strategies' as part of their *teacher resources*. The PSTs identified two characteristics of their lesson design as key elements of teaching through SSI: teachers' role and students' motivation. They wanted to focus on and alter the teacher's role in their lesson design because PSTs perceived the use of SSI as a different way of teaching for themselves, referring to 'PCK—Instructional Strategies', and a new way of learning for the students, referring to 'PCK—Students' Understanding'. The PSTs decided that teachers' involvement and level of guidance provided to the students should be adjusted based on the students' previous experiences with autonomy. Additionally, apart from PSTs' understanding of SSI, the professional development session where PSTs were introduced to the Curricular Spider Web influenced their focus on the teacher's role.

In order to engage students in the SSI lesson, PSTs considered internal and external motivations for students. The discussions about how to motivate the students showed that PSTs used their 'PCK—Students' Understanding' to adapt their instruction with regard to their role as a teacher and the students' motivation. In addition, they referred to their 'Previous Experiences' when they were students at secondary school as part of their *teacher resources*. PSTs compared how their own teachers at secondary school changed the role they played in students' projects depending on how autonomous students became throughout their studies. One PST shared his experience regarding his teacher's role as follows:

> "*It is a fine line because of course you can not give in to students' demands entirely. You can train them in doing so. For example, I took Research and Design (a secondary school subject in the Dutch education system) for six years and at the start we were not really spoon-fed, but it was close to it. In the end we were like, in my sixth year of secondary school, running a project by ourselves. (. . .) We defined our own assignment, and our teacher was more watching on the sidelines. In the first years, the teacher would find the company and the assignment.*" (PST 3)

3.2. How the Resources Were Used

Our second research question was 'How does the use of the different types of resources impact PSTs' lesson design for teaching about the SDGs through SSI in Dutch secondary education?'. In this section, we go beyond describing what resources PSTs used in their lesson design and we look at how PSTs interacted with their resources during the process of designing an SSI-based lesson to teach about the SDGs.

3.2.1. Interconnectedness between the PDC Resources

Figure 7 presents the relationships between the PDC resources used when five PSTs designed two SSI-based lessons to teach about the SDGs. For example, the code 'Storytelling' was often used where 'PCK—Instructional Strategies' was also used. By looking at the quotations which link these two codes, we could conclude the nature of the relationship between the two: 'PCK—Instructional Strategies' is communicated via 'Storytelling'. Therefore, the nature of the relationships between the resources was determined by looking at the quotations which link them.

In this overview in Figure 7, we can see that 'PCK—Instructional Strategies' was related to several resources, together with 'PCK—Students' Understanding', and 'PCK—Goals and Objectives'. However, even though 'PCK—Assessment' is as important as the other components of PCK, it is isolated in the overview regarding its connection with other resources. According to Figure 7, 'PCK—Goals and Objectives' and 'PCK—Students' Understanding' influence 'PCK—Instructional Strategies', unlike 'PCK—Assessment'.

In Figure 7, we can see that the relationships between 'SSI', 'Beliefs', and 'Subject-matter Knowledge' form a triangular shape in the bottom-left corner of the figure, with 'Bridging the Curriculum' in the center. When we look at the nature of the identified relationships (arrows) between these resources, we can see that integration of 'SSI' as a new way of teaching to facilitate ESD requires the PSTs to use their 'Subject-matter Knowledge', which is needed for 'Bridging the Curriculum' and this urge results from their 'Beliefs'.

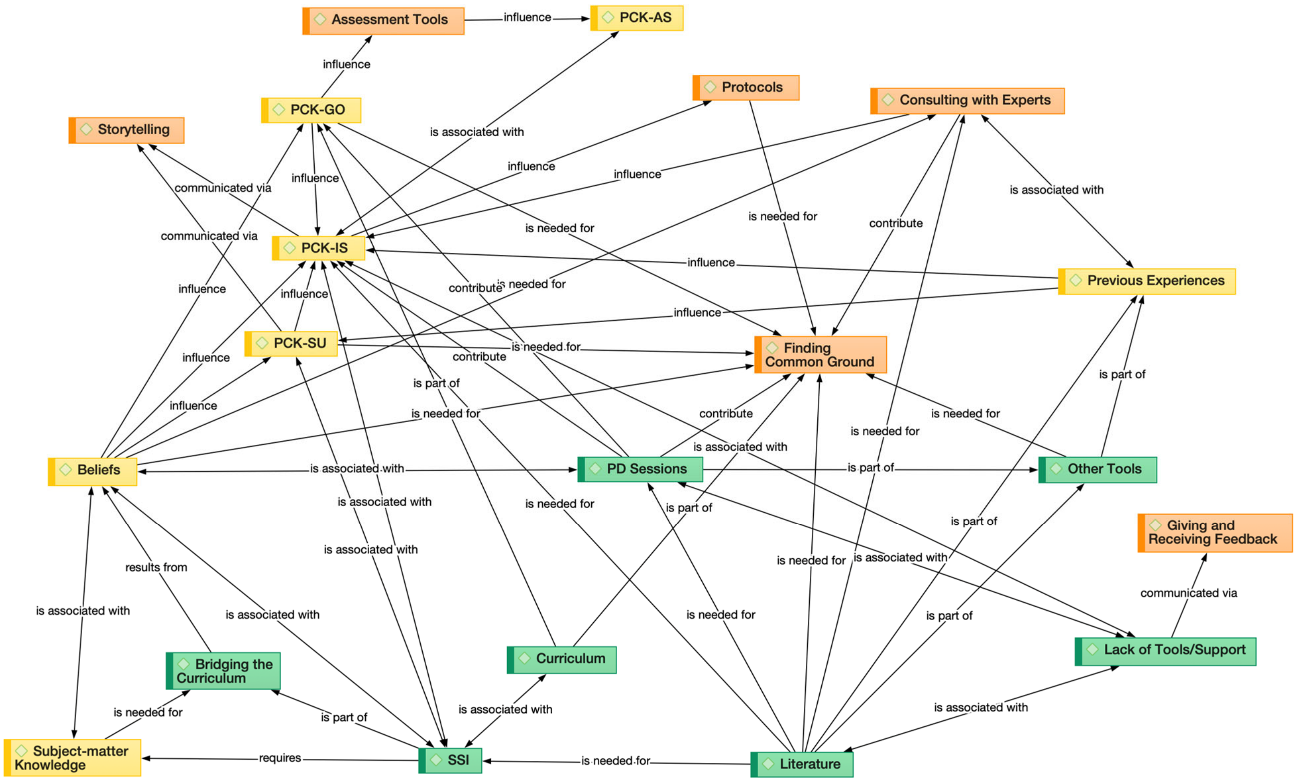

Figure 7. Network analysis of relationships between the resources (instructional resources are green, collaborative resources are orange, and teacher resources are yellow).

The visual representation of the relations shown in Figure 7 reveals the importance of consensus for PSTs to work together, because many other resources are needed for 'Finding Common Ground', such as 'Professional Development Sessions', 'Curriculum', and forms of PCK. Additionally, we see that 'Consulting with Experts' influenced PSTs' PCK, and this was needed for PSTs to reach an agreement regarding their design. When we look at 'Protocols', we see that they were needed for 'Finding Common Ground', and they were influenced by PSTs' PCK.

Figure 5 showed that PSTs referred to 'Storytelling' as part of their *collaborative resources*. Figure 7 illustrates that the only connection between 'Storytelling' and other resources is with the PCK resources. In other words, PSTs used 'Storytelling' to communicate their PCK with each other by sharing their previous teaching experiences as intern teachers, as well as lesson observations and previous learning experiences as students.

Even though Figure 7 represents the nature of the relationships between the resources, it does not show how often the PSTs made connections between the concepts of the two codes (e.g., how many times two codes were linked with each other within the same quotation). For this reason, we used the code co-occurrence analysis via ATLAS.ti and created a force-directed graph to represent our analysis. The graph does not only visualize the connections between the resources but also the frequency of the co-occurrences. While the force-directed graph based PSTs' use of PDC resources can be seen in Figure 8, the table which shows the frequency of the co-occurrences can be seen in Appendix A, Table A1.

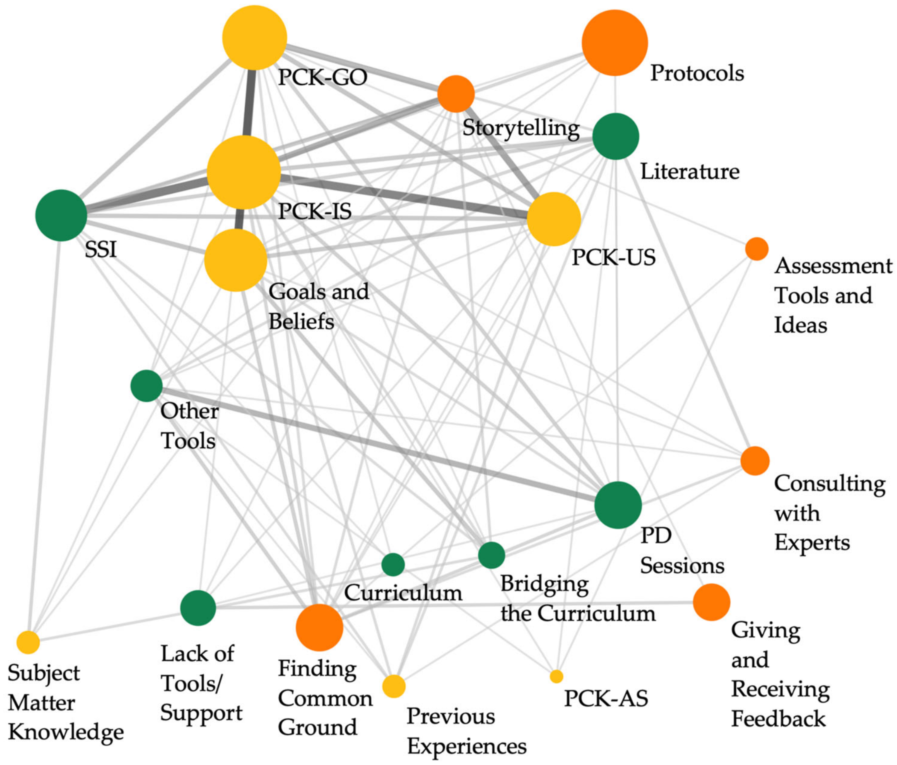

Figure 8. Force-directed graph showing results of co-occurrence analysis (instructional resources are green, collaborative resources are orange, and teacher resources are yellow, where size of the circle represents how often the source was referred to, and the thickness of the lines represents the frequency of the co-occurrence).

Figure 8 illustrates the PDC resources as interconnected circles. The size of a circle is directly proportional to PSTs' use of the resource associated with this circle. Moreover, the connection between the resources is illustrated by lines connecting them, where the thickness of these lines is directly proportional to the frequency of co-occurrence of the two resources. We interpret the high frequency of co-occurrence of the two resources as the strength of the connection between the two. For example, the frequency of co-occurrence between 'PCK—Assessment' and 'Literature' is represented by a thin line in Figure 8. In contrast, the thickness of the line connecting 'Storytelling' and 'PCK—Students' Understanding' is represented by a thick line. We interpret this as the relationship between 'Storytelling' and 'PCK—Students' Understanding' is stronger than the relationship between 'PCK—Assessment' and 'Literature'. This is because PSTs made lesser connections between 'PCK—Assessment' and 'Literature' compared to 'Storytelling' and 'PCK of Students' Understanding'.

Figure 8 shows that three PCK-related resources, 'PCK—Instructional Strategies', 'PCK—Goals and Objectives', and 'PCK—Students' Understanding' played an important role in PSTs' lesson design, unlike 'PCK—Assessment'. The other three PCK-related resources are strongly related, while 'PCK—Assessment' does not have as many connections. In addition, 'SSI' is strongly connected with 'PCK—Instructional Strategies'. This strong relationship between 'SSI' and a PCK-related resource was not revealed in Figure 7, which shows the importance of the visualization shown in Figure 8. Moreover, 'Storytelling' is strongly connected with the three PCK-related resources, which reveals the importance of *collaborative resources* for the PSTs to communicate their *teacher resources*. In other words, 'Storytelling' played an important role for the PSTs in expressing their PCK to each other. This result was also supported in Figure 7, where the only connections with 'Storytelling' are to the three PCK-related resources.

3.2.2. How PLC Meeting Agendas Foster or Hinder the Use of Resources

In this section, we report on how PSTs' use of resources changed over the six PLC meetings, which is illustrated in Figure 9. This analysis focuses on only the data collected via field notes of the PLC meetings and it allows us to see the impact of the meeting agendas on PSTs' use of resources.

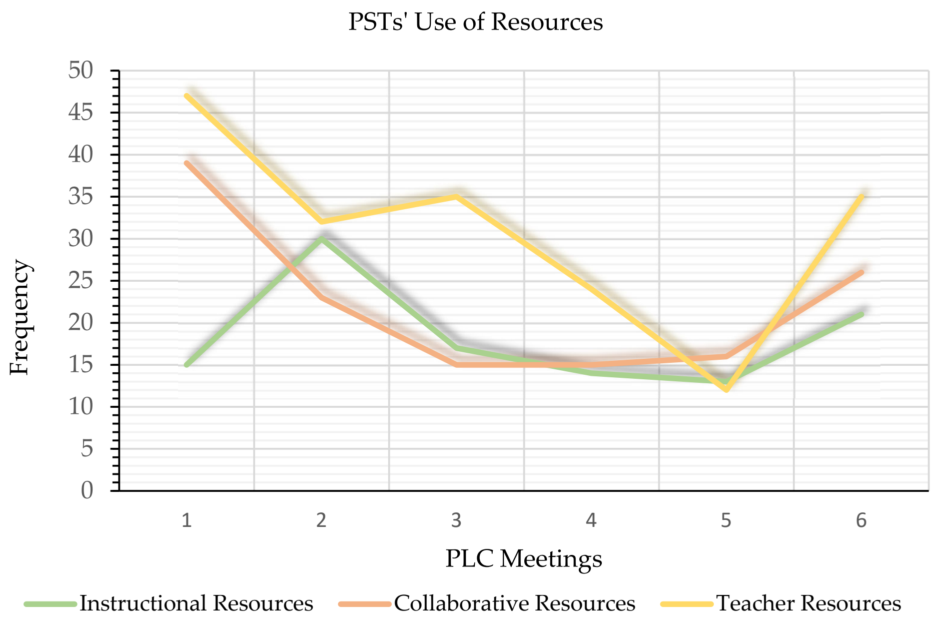

Figure 9. PSTs' use of resources during the PLC meetings over time.

We see that PSTs' use of *teacher resources* was the highest during all PLC meetings except meeting 5, where *collaborative resources* were referred to the most. Another remarkable result is how the use of *instructional resources* changed over the first three PLC meetings. Analysis of the field notes revealed that PSTs referred to *instructional resources* very often during the second PLC meeting.

4. Discussion

Prior work has shown that building capacities for teachers to successfully implement reform-based education is crucial to transform educational institutions [70]. In our study, we consider the implementation of ESD at secondary schools as reform-based education where building capacities for PSTs to successfully implement ESD plays a significant role in transforming secondary schools towards sustainability. However, previous studies have not considered interactions between teachers' available resources that result in their implementation of ESD through SSI. Data obtained in previous studies which focused on teachers' PDC indicated that *teacher resources* play an important role in teachers' successful implementation of teaching methods in an attempt to meet reform-oriented goals such as argumentation and inquiry in science education [43,70]. Teachers need support with recognizing the necessary components of curriculum materials and teaching strategies, because they rely on their existing PCK and personal beliefs in their design [43]. Another study on teachers' PDC showed that PSTs' lesson design is teacher-specific and steered by their knowledge and beliefs as well as their cultural and social background [70].

In our study, we asked five PSTs to design SSI-based instruction to implement instruction about the SDGs in their STEM subjects. Our participants reasoned that the use of SSI is a useful way of teaching to facilitate ESD, thanks to its contribution to scientific literacy and development of higher-order skills [50,57]. The interdisciplinary nature of SSI makes them a useful approach for STEM teachers when they design lessons in collaborative teams. PSTs' frequent use of SSI as one of their *instructional resources* strongly confirms our reasoning for introducing SSI to PSTs as a means towards ESD.

In order to characterize PSTs' pedagogical design capacity to design their lesson in STEM subjects, we used the framework shown in Figure 2, which emerged from the combination of two PDC frameworks found in the literature [43,44]. As shown in Figure 2, we looked at *instructional resources*, *collaborative resources*, and *teacher resources*. Combining the two frameworks allowed us to see how much attention teachers paid to SSI as a new way of teaching and learning to facilitate the integration of instruction about the SDGs in STEM subjects. One of the previous studies revealed that STEM teachers' decisions regarding their design relied on more than just *instructional resources* and *teacher resources*; the teachers also referred to each other as resources [44]. In our study, PSTs worked collaboratively in a PLC setting, which allowed us to capture their interactions and the extent to which they relied on each other as resources. It is evident that our PSTs' use of *collaborative resources* was well-aligned with Ellingson's [44] findings. Adding *collaborative resources* to our conceptual framework for PDC allowed us to see how important it is for PSTs to find common ground with each other and discuss their shared values in order to collaboratively design SSI lessons to teach about the SDGs.

To answer our research questions, we analyzed the data from two perspectives. First, we identified what resources the PSTs referred to the most by analyzing the field notes, reflection reports, and interviews. Figure 3 shows PSTs' use of the different types of resources during their design. This analysis showed that including the *collaborative resources* in our framework was a valuable addition, because the PSTs referred to *collaborative resources* almost as much as they did to *instructional resources*. This means that it was important for the PSTs to make agreements with each other regarding expectations, task divisions and roles in the PLC meetings. This was represented in our analysis as 'Protocols'. Therefore, our study provides a framework for future studies to use to characterize PSTs' collaborative design process in terms of PDC. Moreover, it appeared during our data analysis that PSTs spent time discussing finding shared values throughout the design process. Therefore, PSTs' emphasis on 'Finding Common Ground' has potential to improve the quality of PLC meetings in further research. Additionally, since PSTs communicated their PCK through 'Storytelling', teacher educators could put more emphasis on providing PSTs with opportunities to share their experiences when they are asked to design lessons.

Our analysis, which is summarized in Figure 6, showed that throughout the whole process, PSTs' use of *teacher resources* was almost always higher than their use of other types of resources. However, even though 'PCK—Assessment' is a *teacher resource*, it was the resource PSTs referred to least often. In other words, considering all the available resources, PSTs used their 'PCK—Assessment' the least. This result is consistent with previous research suggesting that there is a lack of assessment [54] and of assessment methods [42] in SSI-based instruction. In this regard, our results corroborate the existing evidence which suggests building the capacities of PSTs to consider assessment in their design. As an addition to the recommendations shown in Table 1, our results show that teacher education programs should emphasize the importance of assessment when it comes to ESD and sustainability-related competences [35]. One way to empower PSTs in terms of assessment could be an intervention focusing on formative and summative evaluation of students' understanding of the SDGs. For this reason, future work could focus on how to foster PSTs' use of 'PCK—Assessment' to assess their students' learning about the SDGs through SSI. Considering that assessing higher-order skills addressed in SSI-based instruction is not an easy task, teacher educators could support PSTs in building their capacities for assessment of ESD.

Second, we analyzed the field notes of PLC meetings to see how PSTs' use of resources had changed throughout the design process, over 5 months. As can be seen in Figure 9, this analysis showed that PSTs' use of *instructional resources* was highest during the second PLC meeting. The reason PSTs used their *instructional resources* the most during the second PLC meeting could be a professional development session PSTs attended before this meeting. In this professional development session PSTs were introduced to the Curricular Spider Web as a tool to design lessons. This intervention could be the reason why PSTs referred to *instructional resources* the most during the second meeting, because those data represent the immediate effect of this PD session on PSTs' use of *instructional resources* to enhance their design. During the second PLC meeting PSTs also decided to focus on the teacher's role, which is one of the components represented in the Curricular Spider Web. Moreover, the PSTs found their area of focus during this meeting, which might be why the use of *instructional resources* was never again as high as during the second meeting. This finding is promising and should be explored further, because interventions such as this have potential to foster teachers' PDC to design lessons which incorporate SSI to teach about the SDGs. In our case, this intervention fostered PSTs' PDC in terms of *instructional resources* and initiated the discussions between the PSTs to find a focal area for their design. Such an intervention has potential to increase PSTs effective use of resources. Therefore, future work could focus on exploring the types of interventions to foster PSTs' use of resources throughout their lesson design process.

Another remarkable result shown in Figure 9 was the overall decrease in the use of PDC resources in the fifth meeting. In that meeting, the PSTs focused on documenting their work to create a poster presentation to share their progress with other PSTs in the same department of the university. This was a required component of the course, which hindered PSTs' focus on designing their lesson and their use of PDC resources. In other words, the drop in the use of PDC resources during the fifth PLC meeting could have been due to the obligatory task the PSTs had to complete. Therefore, teacher educators and professional development designers should consider how the meeting agendas of PLC meetings can hinder teachers' use of resources when it comes to lesson design.

5. Limitations

This study was limited to five PSTs who voluntarily chose to design SSI-based lessons to teach about the SDGs as part of their master's program studies at a Dutch university. Furthermore, PSTs were not provided with example lesson materials or school textbooks which cover the SDG topics due to a lack of resources.

6. Conclusions

We hypothesized that PSTs need to build their capacities in terms of knowledge, skills, values, and attitudes to become competent in facilitating ESD and addressing sustainability issues. In this study, PSTs enhanced their PDC by interacting with their *instructional resources*, *collaborative resources*, and *teacher resources*. Our results show that PSTs found SSI to be an effective way to teach about the SDGs. However, they need support with understanding and applying new ways of teaching when it comes to reform-based instruction; in our case, addressing the SDGs in STEM subjects through SSI. Our study demonstrated that PSTs did not consider assessment as part of their lesson design. Therefore, they need support with evaluating students' understanding and creating assessments when it comes to incorporating sustainability issues in STEM subjects. Our study shows that looking at *collaborative resources* as a PDC resource is crucial. 'Storytelling' plays an important role for PSTs to express their beliefs and share their personal experiences with one another. Encouraging PSTs in storytelling in collaborative design teams can strengthen their overall PDC. Lastly, the SDGs provide PSTs with a framework which shows the wide relevance of sustainability as including economic, social, and environmental dimensions. Therefore, incorporating SSI and SDGs as means towards ESD offers promising pathways for building the capacities of STEM PSTs to address sustainability issues at Dutch secondary schools. Future studies may focus on how to foster PSTs' use of resources in order to design assessment tools to evaluate SSI lessons. Since sustainability issues are interdisciplinary, we advise future studies to focus on teachers' use of *collaborative resources* where teachers from different subject-matter backgrounds design SSI-based instruction to address ESD.

Our research pointed out that SSI are accepted as an effective way to teach about the SDGs at secondary schools. Thus, incorporating SSI for ESD can be considered by secondary school teachers in designing their lessons. We conclude that the use of SSI will better support teachers to teach about the SDGs in secondary schools.

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Appendix A

Table A1. Code co-occurrence analysis between the three types of PDC resources *.

	Assessment Tools	Consulting with Experts	Finding Common Ground	Giving and Receiving Feedback	Protocols	Storytelling	Bridging the Curriculum	Curriculum	Lack of Tools/Support	Literature	Other Tools	PD Sessions	SSI	Beliefs	PCK-AS	PCK-GO	PCK-IS	PCK-SU	Previous Experiences	Subject-matter Knowledge
Assessment Tools	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Consulting with Experts	0	0	2	0	0	0	0	0	0	3	1	0	0	1	0	0	1	0	1	0
Finding Common Ground	1	2	0	0	1	2	0	0	0	1	4	3	0	4	0	2	3	1	0	0
Giving and Receiving Feedback	0	0	0	0	0	1	0	0	3	0	0	0	0	0	0	0	0	0	0	0
Protocols	0	0	1	0	0	0	0	0	0	0	1	1	1	1	0	0	3	0	0	0
Storytelling	0	0	2	1	0	0	2	0	1	0	0	1	5	0	0	10	10	12	0	1
Bridging the Curriculum	0	0	0	0	0	2	0	0	0	0	0	0	2	5	0	1	2	0	0	2
Curriculum	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
Lack of Tools/Support	0	0	0	3	0	1	0	0	0	1	0	1	0	0	0	0	1	0	0	0
Literature	0	3	1	0	0	0	0	0	1	0	2	1	4	3	1	2	5	0	2	0
Other Tools	0	1	4	0	1	0	0	0	0	2	0	9	0	0	1	1	0	1	1	0
PD Sessions	0	0	3	0	1	1	0	0	1	1	9	0	0	2	0	4	4	0	0	0
SSI	0	0	0	0	1	5	2	1	0	4	0	0	0	6	0	6	19	5	2	3
Beliefs	0	1	4	0	1	0	5	0	0	3	0	2	6	0	0	16	17	5	0	1
PCK-AS	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0
PCK-GO	1	0	2	0	0	10	1	1	0	2	1	4	6	16	0	0	19	6	0	0
PCK-IS	0	1	3	0	3	10	2	0	1	5	0	4	19	17	1	19	0	18	2	1
PCK-SU	0	0	1	0	0	12	0	0	0	0	1	0	5	5	0	6	18	0	2	0
Previous Experiences	0	1	0	0	0	0	0	0	0	2	1	0	2	0	0	0	2	2	0	0
Subject-matter Knowledge	0	0	0	0	0	1	2	0	0	0	0	0	3	1	0	0	1	0	0	0

* Instructional resources are green, collaborative resources are orange, and teacher resources are yellow, where the color intensity of blue shows the level of co-occurrence.

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