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Inquiry-based science education: Tools for supporting the design of schoolteacher professional development programs

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Abstract

For many teacher educators, designing programs to assist pre- and in-service teachers in implementing *inq*uiry-based science education (IBSE) in school classrooms is a complex and challenging task. However, applicable teacher *pro*fessional *dev*elopment (TPD) frameworks are rare. Thus, the goal of the presented educational design research was to yield a TPD framework, called the ProDevInq framework, and a set of underlying design principles (DPs). These TPD design tools are based on seven components from the science TPD literature. The components include a learning theory, goal, learning strategy, and instructional design model. We generated the DPs based on a systematic review of the relevant literature. After screening the principles based on hallmarks from the literature on what makes science TPD effective, we could synthesize the ProDevInq framework. The resulting TPD design tools have theory-, practice-, and research-related implications in supporting the implementation of IBSE worldwide.

Keywords: design principles, inquiry-based science education, teacher professional development, ProDevInq framework, school education

INTRODUCTION

In the presented research, we put forth tools for supporting pre- and in-service science teacher educators and researchers. The tools are usable when designing programs to foster the implementation of inquiry-based science education (IBSE) in school classrooms. The tools include a science teacher professional development (TPD) program blueprint, underlying design principles (DPs), and the associated educational design research (EDR) process. In what follows, we provide helpful background information and explain the research focus.

Background Information

There are several interpretations of the term IBSE in the science education literature (Capps et al., 2012; Furtak et al., 2012; National Research Council, 2007). In one of the interpretations, IBSE is considered to provide opportunities for developing students' understanding of science, including the process that natural scientists undergo to generate and validate scientific knowledge (Hodson, 2014; National Research Council, 1996; Zambak et al., 2017). With a focus on the process, Crawford (2014) defines IBSE, as a process that

> "involves engaging students in using critical thinking skills, which includes asking questions, designing and carrying out investigations, interpreting data as evidence, creating arguments, building models, and communicating findings, in the pursuit of deepening understanding by using logic and evidence about the natural world" (p. 515).

As Strat et al. (2023) also explained, these definitions refer to providing learning experiences that actively engage learners in enhancing their understanding of science subject matter, the nature of science, and core scientific practices. Although the term 'scientific

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Contribution to the literature

- The first contribution is the utilization of EDR to yield a science TPD framework and its underlying DPs.
- The presented TPD design tools address several calls, gaps, and needs found in the literature, relating to the design of pre- and in-service science TPD programs on IBSE.
- Although context-generic, the tools are well informed and focus on the adoption, customization, and creation of IBSE activities and materials.

practices' has recently been used as a synonym of IBSE (Gericke et al., 2023; Rönnebeck et al., 2016; Strat et al., 2023), we have chosen to use the term IBSE in this research.

The IBSE strategy has been regarded as essential and widely incorporated in school curricula at all levels and in science teacher education curricula worldwide (Lederman et al., 2021; Lehesvuori et al., 2011; Nugent et al., 2012; Rundgren, 2018; Sjøberg, 2019; Strat et al., 2023; Wang, 2020; Yager & Akcay, 2010; Yoon et al., 2012). Anderson (2002) describes the term inquiry-based learning as when pre-service teachers participate in an inquiry-based experience as learners, and inquiry-based teaching is when they implement inquiry-based experiences and reflect on their experiences as teachers.

Many pre- and in-service science teachers are enthusiastic about implementing IBSE in their classrooms (Havu-Nuutinen et al., 2019; Kang et al., 2013; Silm et al., 2017). However, it has been well noted that IBSE is a complex and daunting endeavor for many such teachers, that demands considerable teacher education (Baroudi & Helder, 2021; Constantinou et al., 2018; Havu-Nuutinen et al., 2019; Ireland et al., 2014; Lowell, 2023; Pérez & Furman, 2016). This is not surprising, considering that under this teaching strategy, the role of a teacher includes a "motivator, diagnostician, guide, innovator, experimenter, researcher, modeler, mentor, collaborator, and learner" (Crawford, 2014, p. 526). A range of capabilities are considered to be required to successfully implement IBSE in school classrooms. The capabilities consist of sound subject matter knowledge, an understanding of scientific inquiry and the inherent practices, knowledge of the nature of science, and substantial practical experience in the design, development, and implementation of inquiry-based learning experiences (Crawford & Capps, 2018; Van Joolingen & Zacharia, 2009). Common challenges inherent in IBSE include insufficient teacher experience, knowledge, skills, and strategies (Diaconu et al., 2012; Havu-Nuutinen et al., 2019; Nicol, 2021; Ødegaard et al., 2014).

Research Focus

Pre- and in-service teacher educators are essential in providing opportunities for learning about and implementing IBSE (Arsal, 2017; Berry & Van Driel, 2013; Strat et al., 2023). However, doubts have been expressed about preparing these educators, from various backgrounds, for their task (Berry & Van Driel, 2013). The task has been described as complex and challenging (García-Carmona & Acevedo-Díaz, 2017; Luft et al., 2019; Riga et al., 2017; Sancar et al., 2021). Specifically, Crawford (2007) noted that assisting teachers in understanding how to enact IBSE in their classrooms is a significant challenge in the science teacher education sector. Thus, it is not surprising that there have been calls for means, processes, methods, and models for providing high-quality, scaffolded, and coherent support, in addition to learning opportunities that allow pre- and in-service science teacher education outcomes to be achieved in implementing IBSE (El-Deghaidy et al., 2015a; Ireland et al., 2014; Kazempour & Amirshokoohi, 2014; Strat et al., 2023; Tsaliki et al., 2024). These calls reflect a gap in knowledge on the design of successful science TPD programs.

To contribute to addressing the gap reflected in these calls, we opted for the presented design research to put forth DPs on which basis we synthesized a TPD framework. Generally, a framework has been described as a structure, plan, or system that incorporates implementation guidance and practices to realize a defined goal (Sabatier, 2007; Tomhave, 2005; Verbrugge, 2016). With reference to TPD, Stolk et al. (2012) describe a framework as the blueprint of a TPD program and, as such, a predictor of the PD process that is expected to take place.

We mostly find TPD frameworks that are not specifically for science teachers, in the education literature (Loucks-Horsley et al., 2003; Saderholm et al., 2017; Sancar et al., 2021; Sasere & Makhasane, 2023; Srikoom, 2021). Also included are frameworks for use in non-school contexts, such as with science educators in higher education (Al-Naabi et al., 2021; Chookaew et al., 2017; Cormas et al., 2021; Hungerford-Kresser & Amaro-Jimenez, 2020). TPD frameworks and the underlying DPs for supporting the designing of TPD programs in the implementation of specific teaching strategies in school science classrooms are rare. One of the rare examples is the TPD framework by Stolk et al. (2012) for supporting school chemistry teachers to implement context-based curriculum units. In the context of IBSE, a similar tool, and its underlying DPs are lacking.

In light of the discussion in the preceding text, the specific purpose of the presented EDR was to yield a *pro*fessional *dev*elopment framework for supporting the implementation of *inq*uiry-based science education in school classrooms and a set of underlying DPs. While we have called the framework the ProDevInq framework, the presented research was guided by the following two research questions (RQs):

RQ1. What DPs inform the ProDevInq framework?

RQ2. What form can the ProDevInq framework take?

The response to these questions is significant globally, in the context of pre- and in-service teacher education in IBSE. For example, DPs are a valuable theoretical contribution as they provide informed guidelines to people worldwide when addressing a similar challenge (Herrington & Reeves, 2011; McKenney & Reeves, 2012; Nieveen & Folmer, 2013). Also, researchers have noted that the success of PD programs for science teachers, like for other teachers, largely depends on how the program is structured (Guskey, 2014; Luft & Hewson, 2014). The ProDevInq framework and its underlying DPs can serve as tools for guiding the structuring of the process in teacher learning opportunities, that focus on implementing IBSE in any school classroom. These tools may be helpful not only in in-service but also in pre-service teacher education contexts. The joint participation of pre- and in-service teachers in learning programs has been recommended and practiced (Havu-Nuutinen et al., 2019; McDonnough & Matkins, 2010). The EDR process we utilized to yield these TPD design tools is a significant tool in the field of science TPD research.

CONCEPTUAL FRAMEWORK

To lead to the desired science TPD design tools, we started by compiling a suitable design process. Within the process, we conceptualized the overall form of the TPD design tools.

Design Process Incorporating Tool Conceptualization

Science TPD is an educational design endeavor that involves iterations of design and implementation activities (Brown et al., 2020; Hewson, 2007b; Kaya & Kaya, 2024; Loucks-Horsley et al., 2010; Thomas & Drew, 2022). While evaluation is involved in each of these activities, the presented research is in the context of the design activity and is a piece of EDR.

After coming to the forefront, design research is increasingly utilized in education (Anderson & Shattuck, 2012). EDR, and specifically development studies, have been noted as suitable for designing and developing interventions to address complex educational problems (McKenney & Reeves, 2012, 2021; Plomp, 2013; Tinoca et al., 2022). The intervention can be educational approaches, processes, programs, frameworks, and other products. In the process of designing an intervention, knowledge about the characteristics of the intervention is increased.

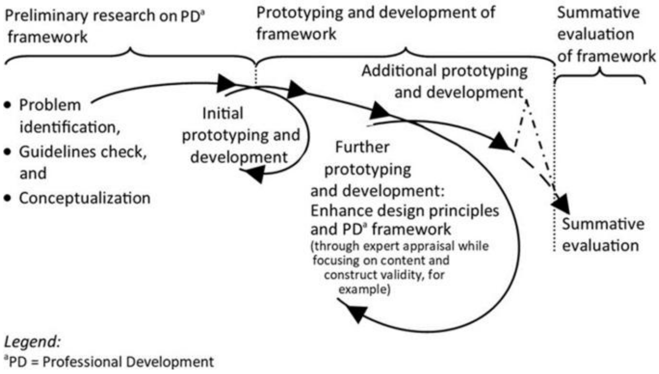

Figure 1. Process for designing and developing a TPD framework (Source: Authors' own elaboration)

Based on the literature on EDR in general and of EDR in pre- and in-service science teacher education specifically (Brown et al., 2020; Dunn et al., 2019; Nieveen & Folmer, 2013; Plomp, 2013; Scott et al., 2020; Sungur-Gul & Tasar, 2023), we compiled a process for synthesizing and developing a PD framework (**Figure 1**). As seen at the top of **Figure 1**, each of the primary phases in the process encompasses one or more secondary phases.

The presented research belongs to the "Preliminary research on PD framework" phase in **Figure 1**. Included in the research is the "Initial prototyping and development" secondary phase.

Elaborating the Preliminary Research on PD Framework Phase

Problem identification and guidelines check

The problem identification aspect in the presented research is defined before. In relation to the guidelines check component, we considered several TPD framework studies (e.g., Lo, 2021; Stolk et al., 2012; Van Rens et al., 2010). The studies either did not focus on or yield DPs that support the design of opportunities for implementing IBSE in school classrooms. As a result, and in what follows, we began by conceptualizing the desired DPs and the associated TPD framework.

Conceptualization of design principles

There are different interpretations of the term DPs in the literature (Bakker, 2019; Edelson, 2002; Van Rens et al., 2010). In one of the interpretations, DPs are considered to consist of characteristics recommended for an educational intervention and implementation procedures (Euler, 2017; van den Akker, 2010). Supporting theoretical and empirical arguments are also included. Thus, it has been noted that DPs can be used 'to help others select and apply the most appropriate substantive and procedural knowledge for specific design and development tasks in their settings' (McKenney et al., 2006, p. 73). However, in the presented research, an implementation procedure and empirical supporting arguments were left out of the DPs. We left these aspects out, as the presented research is literature-based. Also, these aspects are best added by users of the desired TPD design tools, in specific pre- and in-service science TPD contexts.

Conceptualizing ProDevInq framework

It has been noted that the components that interact in a science TPD process are context, content, teaching, and learning (Luft & Hewson, 2014). Several components of the interaction are found in the literature on science TPD frameworks regarding content, teaching, and learning. The components include goals, learning theory, strategy, phases, instructional functions, motivation, and an instructional design model (Chookaew et al., 2017; Prins et al., 2016; Stolk et al., 2012). These components can be seen in various combinations in many science TPD programs and models (Li et al., 2021; Luft & Hewson, 2014; Pedaste et al., 2015; Saderholm et al., 2017; Van der Valk & De Jong, 2009). Beginning with context, each of the components is briefly described below.

Context: Science TPD contexts can range from teachers' work environment to national policies (Luft & Hewson, 2014; Schwab, 1978). A key aspect of the context is the coherence of TPD experiences with teacher beliefs, state, district, and national policies (Capps et al., 2012; Drewes et al., 2018; Van Driel et al., 2012). However, given its literature-based nature, the context component in science TPD could not be meaningfully considered in the presented research. The result is that the TPD tools yielded are context-generic.

Goal: It has been noted that a science TPD program requires an explicit goal (Hewson, 2007b; Loucks-Horsley et al., 2010). The goals of most science TPD opportunities have focused on the improvement of teacher cognition and classroom practices (Loucks-Horsley et al., 2010; Luft & Hewson, 2014; Van Driel et al., 2012). In this regard, particular attention has been given to IBSE (Crippen et al., 2010).

Learning theory: A teacher-learning theory outlines how the learning process takes place (Reigeluth, 2013; Stolk et al., 2011). Theories that are contemporary and have been used in science TPD contexts include the cognitive, socio-cultural, and participatory learning theory (El-Deghaidy et al, 2015b; Ostermeier et al., 2010; Scott et al., 2007). It has been noted that a teacher-learning theory needs to be combined with a learning strategy to design effective science TPD programs (Stolk et al., 2009a).

Learning strategy: A learning strategy operationalizes an underlying learning theory (Stolk et al., 2009b; Welch et al., 2005). Specifically, a learning strategy is a sequence in which a learning program's goals, phases, and activities can be achieved (Hewson, 2007a; McKenney et al., 2006; Reigeluth, 1999).

Learning phases: TPD programs for science and other teachers consist of distinct phases (Deketelaere & Kelchtermans, 2006; Prins et al., 2016; Stolk et al., 2009b). Despite often having specific goals, activities, and outcomes, the phases combine to yield the overall PD process. Also, the phases inform each other and depend on the associated learning theory (Saderholm et al., 2017; Stolk et al., 2009b).

Instructional functions: Instructional functions are considered general operations or measures that help transition between the phases and activities of a (planned) learning program, thereby making for more transparency (Mettes et al., 1981; Terlouw, 2001). Instructional functions used in science TPD, and other learning contexts include providing advance organizers and learning goals, connecting to prior knowledge, providing guidance during initial practice work, providing feedback, and summarizing (Bulte et al., 2006; Havu-Nuutinen et al., 2019; Kenyon et al., 2011).

Teacher motivation: Teacher motivation is explicitly incorporated in some science TPD programs (Calleja, 2018; Stolk et al., 2012; Trna et al., 2012). Motivation plays a crucial role in determining if a teacher will opt to participate in PD, the degree of participation, and the likelihood of enacting new practices in the classroom (Karabenick & Conley, 2011; Osman & Warner, 2020).

Instructional design model: An inquiry-based instructional model is helpful as a bridge when transitioning to more inquiry-based science teaching (Rushton et al., 2011). Such a model also assists teachers in structuring and enhancing teaching as they design their inquiry-based science lessons (Svendsen, 2015; Zwiep & Benken, 2013).

Based on the discussion in the preceding paragraphs, we envisaged a ProDevInq framework and a set of underlying DPs that are based on seven interconnected components. The components are a goal, learning theory, strategy, phases, instructional functions, teacher motivation, and an instructional design model. To turn the above-provided concept of the TPD design tools into the actual tools, it was necessary to elaborate further on the EDR research process in **Figure 1**.

Elaborating Initial Prototyping and Development Phase

Components of the phase

In development research, this phase can consist of systematic analysis and the generation of DPs, in addition to the synthesis and formative evaluation of the intervention under development (McKenney & Reeves, 2019; Plomp, 2013; Reeves, 2006). Also included is the revision of the DPs and the intervention, as needed. While reflection is involved in each design activity, the intervention in the presented research is the ProDevInq framework. In this literature-based research, the

Table 1. Description of hallmarks of effective science TPD drawn from the literature

Hallmark	Description
1. Collective participation	When teachers from the same school, department, subject, or grade, participate in a PD program together (Capps et al., 2012; Desimone, 2009; Lumpe et al., 2012).
2. Science content knowledge development	Entails that the PD program focuses on science subject matter and content learning for the science teachers (Capps et al., 2012; Nugent et al., 2012; Sjøberg, 2019; Supovitz & Turner, 2000). The teachers need to have a sound and an up-to-date understanding of the science subject matter knowledge including the nature of science.
3. Adequate total time	Research supports programs that last for a substantial amount of time, in terms of duration and hours (Lumpe et al., 2012; Nichol et al., 2018; Supovitz & Turner, 2000; Van Driel et al., 2012). The activities involved can be spread over a semester and include 20 or more hours of contact time, for example.
4. Extended support	This is support provided in programs that persist over an extended period of time (Bayar, 2014; Lumpe et al., 2012; Nichol et al., 2018). The support can be through periodic workshops or classroom visitations throughout the year, or remotely.
5. Coherency with standards	This refers to the alignment of local, state, or national reforms and policies with what is taught during PD (Desimone, 2009; Van Driel et al., 2012).
6. Providing teachers authentic inquiry experiences	This is when teachers are instrumental in defining and carrying out an inquiry activity, including, but not necessarily as if they were real scientists (Crawford & Capps, 2018; Ruebush et al., 2010; Sjøberg, 2019; Van Driel et al., 2012).
7. Development of inquiry-based lessons	This occurs when teachers learn about inquiry as a teaching strategy, and design inquiry-based lessons for use in their classrooms (Capps et al., 2012; Nugent et al., 2012).
8. Modelling inquiry-based lessons	There is the modelling of inquiry-based teaching for the teachers (Capps et al., 2012; Nugent et al., 2012). The modelling gives teachers an opportunity to experience what inquiry-based instruction might look like, usually using the same lessons the teachers would later teach their students
9. Reflecting on experiences	This is when teachers have an explicit opportunity to carry out activities that promote reflective thought as an individual activity and/or group discussion (Capps et al., 2012; Lumpe et al., 2012; Nugent et al., 2012).
10. Transference	This means that the teacher learning opportunity includes an explicit discussion about enacting the curriculum in the classroom (Bayar, 2014; Capps et al., 2012).

intervention is not implemented. As a result, instead of the intervention, the DPs undergo formative evaluation.

Formative evaluation

This activity focuses on incorporating feedback in a prototypical intervention and its DPs (Dowse & Howie, 2013; Kenyon et al., 2011; Leary et al., 2016; McKenney & Reeves, 2019). Specifically, the evaluation involves identifying omissions and weaknesses, while gathering suggestions for improvement. In the presented literature-based research, the gathering of suggestions about the framework was not involved, as the evaluation was non-empirical.

In the preliminary research phase (as in the case of the presented research), it is sufficient to focus the evaluation on content validity based on developer screening using a checklist (McKenney & Reeves, 2019; Nieveen, 2009). A product (e.g., the ProDevInq framework or its DPs) is content valid if needed, and its components are based on state-of-the-art research knowledge (Nieveen, 2009; Rochmad, 2012). We have outlined the need for the ProDevInq framework and its DPs before. Also, we noted the scarcity of applicable DPs before. To yield state-of-the-art knowledge, we will subsequently conduct a systematic analysis of the science TPD literature.

Evaluation criteria

We needed criteria to consider the content validity of the ProDevInq framework's DPs. In light of Zeggelaar et al. (2022), we noted the existence of hallmarks about what makes TPD programs effective in the literature. The hallmarks continue to inform the designing of effective pre- and in-service science teacher education programs (Capps et al., 2012; Lee et al., 2023). While some hallmarks are similar to those in the education literature for teachers in general, ten are described in **Table 1**.

Many programs designed with the hallmarks in **Table 1** have been found to positively impact the knowledge and practices of science teachers (Brand & Moore, 2011; Brown & Crippen, 2016; Crippen et al., 2010; Li et al., 2021; Nichol et al., 2018). It has been noted that to ensure that TPD increases student learning, we must begin by incorporating the hallmarks of effective teacher learning in TPD programs (Desimone, 2011). Thus, we considered the hallmarks as suitable criteria for formative evaluation of the desired DPs.

The preceding text discussed the interconnected components we envisaged for the ProDevInq framework and its underlying DPs. Also included is the form of the desired underlying DPs and a suitable EDR process.

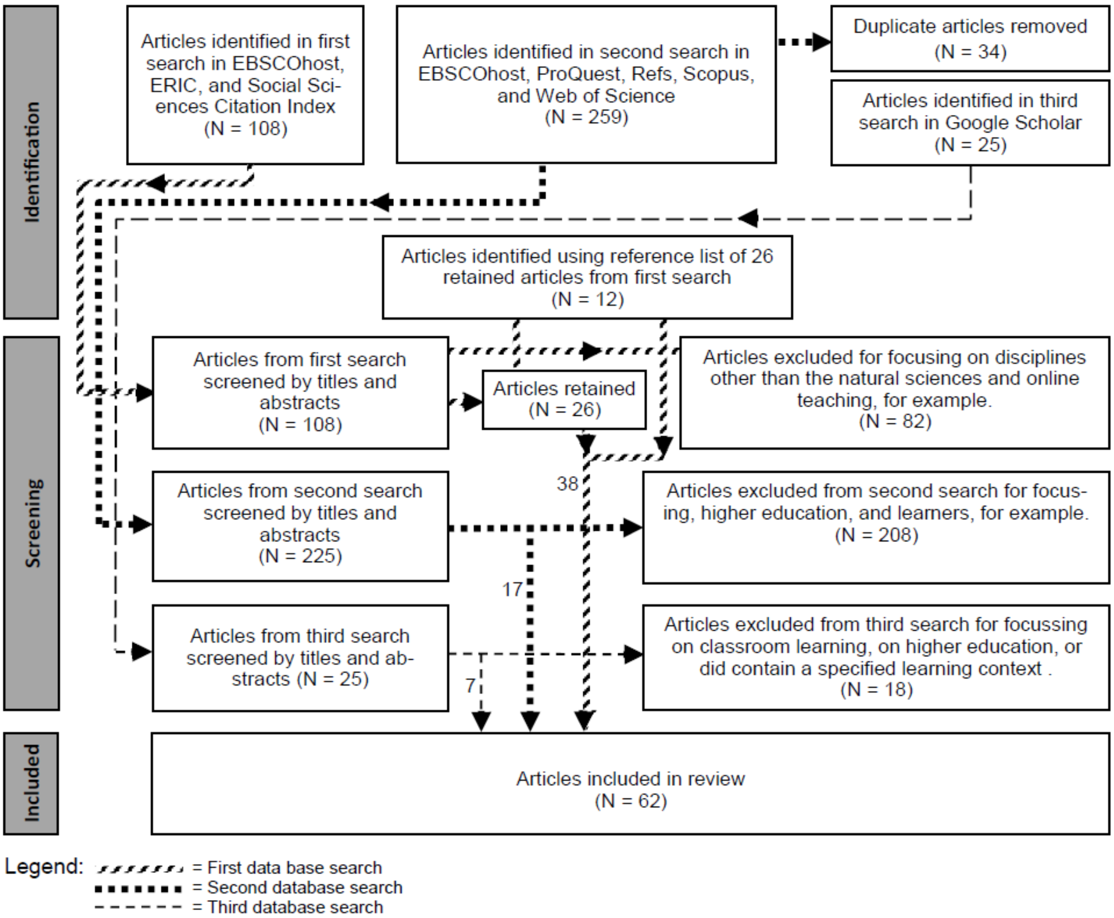

Figure 2. Summary of article identification and screening process (adapted from the PRISMA 2020 flow diagram in Page et al., 2021)

IMPLEMENTING INITIAL PROTOTYPING AND DEVELOPMENT PHASE

Systematic Analysis and Generation of Design Principles

We systematically reviewed the science TPD research literature to lead to the DPs that underlie the ProDevInq framework. The review focused on the teacher learning process in the context of IBSE. However, in a few cases when faced with limited data, we incorporated data in the context of innovative and reform-based teaching strategies, such as context-based science teaching. As Van Driel et al. (2012) noted, most science TPD opportunities are designed in terms of reform efforts.

The purpose of the literature review was to inform the generation of DPs for each of the seven components envisaged for the ProDevInq framework. Recall that the components are a goal, learning theory, strategy, phases, instructional functions, motivation, and an instructional design model. However, the review also allowed us to gain an indication of the amount of support there is for each TPD framework component in the included articles. In the literature review, we proceeded step-wise, as described next.

Searching and screening articles

This was a phased process, as seen on the left of **Figure 2**. As illustrated at the top of the figure, we carried out three database searches. It is worth noting that the searches were sequential, as the need to better inform the DPs arose. **Figure 2** outlines the identification and screening process for each search. In this regard, the use of the legend is essential.

In the first search (**Figure 2**, top left), the search terms consisted of 'professional development' in combination with the following terms: 'framework', 'designing', and 'process'. We used the OR operator between the search terms. While searching the complete text, the criteria we used to limit the search results included the source type (scholarly journals), publication type (journal articles; article or review), and publication date range. We included articles from within the ten years preceding our search and found 108 articles.

Guided by the purpose of the presented research, we screened the 108 articles regarding the disciplinary focus, educational level involved, and delivery mode in terms of in-person or online, to name a few examples. As a result, we excluded 82 articles focusing on PD in areas such as pharmacy, healthcare, and online teaching. However, as shown in the second row in the identification band in **Figure 2**, using the reference list of the 26 retained articles, we found 12 additional articles in line with our inclusion criteria. This raised the number of articles we could include from the first database search to 38.

At the top middle of **Figure 2** is our second database search outline. We carried out this search to increase the total number of articles included and articles focusing on TPD in IBSE. Thus, for this second database search, we adjusted the search terms to 'professional development' AND 'inquiry-based science', resulting in 259 articles in the search results. However, this number included 34 articles retained from the first database search. Removal of the duplicate articles left us with 225 unique articles to consider, as seen in the second row in the screening phase in **Figure 2**. After reviewing the abstracts, we could not include up to 208 articles. These articles focused on aspects of IBSE other than the PD process. Examples are teacher attitudes regarding IBSE and the learning effects of IBSE. The number of articles that we could retain from our second database search was only 17.

The third database search, outlined in the second box on the top right of **Figure 2**, focused on learning theories. The search was triggered by our realization that this aspect of TPD was specified in very few articles in the two preceding database searches. We conducted the third search using the search terms 'learning theory' or 'teacher learning theory'. In the search results, we focused on the first 25 journal articles in order of relevance. This number was arbitrary. However, the intent was to include only articles that more closely focused on learning theories to add to articles previously included. By reading the titles and abstracts, we found that eighteen articles focused on classroom learning and higher education or did not contain a specified learning context. As a result, we eliminated these articles and retained 7.

Considering the three described database searches, the total number of retained articles was 62, as seen at the bottom of **Figure 2**. The number of articles retained was much lower than originally in the search lists. However, this was consistent with the point by Clarke et al. (2012) that few studies have focused on the learning processes within TPD programs.

Citations belonging to the included articles are marked with an asterisk (*) in the findings section below. Also, the retained articles are cited in **Appendix A**'s first columns, with references for the articles shown in **Appendix B**.

Coding retained articles

We coded the 55 articles from the first two database searches, separate from the seven articles from the third search. This decision was informed by the uniqueness of the third search.

In coding the 55 articles, we focused on the type of research (empirical or review), study location, involvement of IBSE, and the science discipline. The coding of the articles in this regard is shown in **Table A1** in **Appendix A**. Analysis of the coding data revealed that the articles were predominantly empirical research articles, mainly focusing on IBSE. Additionally, the articles were comprehensive regarding the study location and the science disciplines involved.

We coded the seven articles included from the third database search in terms of the learning context under which the learning theory is considered (**Appendix A**, **Table A2**). As a result, we found that the articles discussed learning theories in the context of adult and continuing education (1), self-directed and lifelong learning (1), teacher learning (1), and TPD specifically (4). Overall, we saw a pattern toward a cognitive and contextual dimension in TPD and continuing education regarding learning theory.

Based on the above outcomes from coding the included articles, we considered the articles satisfactory in informing the generation of the seven desired DPs.

Data extraction and analysis

The data in the presented research consisted of state-of-the-art information helpful in generating a DP for each of the seven components we envisaged for the desired TPD design tools. Recall that the components are a goal, learning theory, strategy, phases, instructional functions, motivation, and an instructional design model. In this regard, the descriptions of these components in our conceptual framework helped identify the needed data.

The seven components served as pre-determined categories in our data analysis. In this way, we utilized the deductive approach in thematic analysis, as described in Crabtree and Miller (1999). As a result, we assigned data extracted from reading each included article in full to the corresponding pre-determined categories.

At the end of the data extraction, we counted the different pieces of data in each pre-defined category. This counted as an indication of the amount of support for the components we envisaged for the ProDevInq framework in the included articles.

To further our data analysis, we used the constant comparison method (Strauss & Corbin, 1990) of the data in each populated pre-determined category. The result was inductively generated secondary categories of data about each component of the ProDevInq framework. Finally, based on the findings and, to a limited extent, on our literature-inform reflections, we could generate DPs per component of the ProDevInq framework.

Table 2. Number of appearances of components of TPD design tools in included articles

Component	n	Examples of included articles in which component appears
1. PD goal	24	Amolins et al. (2015), Kapanadze et al. (2015), and McLaughlin and MacFadden (2014)
2. Learning strategy	16	Kapanadze et al. (2015), Tuan et al. (2017), and Zambak et al. (2017)
3. Instructional functions	16	Morrison (2014), Tuan et al. (2017), Whitworth and Chiu (2015)
4. Teacher learning theory	15	Amolins et al. (2015), El-Deghaidy et al. (2015), and Tuan et al. (2017)
5. Learning phases	14	Kapanadze et al. (2015), Pedaste et al. (2015), and Pérez and Furman (2016)
6. Teacher motivation	14	Rozenszajn and Yarden (2014), Visser et al. (2012), and Zwiep and Benken (2013)
7. Instructional design model	10	Pedaste et al. (2015), Stolk et al. (2012), and Zambak et al. (2017)

Note. n: Number of appearances

Findings of Systematic Analysis and Initial Design Principles

Firstly, we present the support for the components of the desired TPD design tools in the included articles. Next, the findings of the analysis are stated per component of the framework. In some cases, our reflections based on extra pertinent literature are embedded in the findings to better inform the generation of the DPs. As a result, we have used an asterisk (*) to indicate citations to the included articles. Under each component of the ProDevInq framework, we immediately utilized the findings and reflections to generate the initial version of the associated DP.

Support for components of TPD design tools in included articles

We found that the seven components envisaged for the desired TPD design tools were mentioned or discussed in the PD process in multiple included articles (**Table 2**).

Based on **Table 2**, the component that appeared in the most included articles is the PD goal. The component with the smallest appearances is an instructional design model. In any case, we consider appearance a form of empirical support for including the envisaged components in the TPD design tools.

Findings and design principles per component of TPD design tools

Teacher-learning theory: We found that several specific learning theories have been utilized in the TPD process described in the included articles. The theories include cognitive learning, participatory learning, and socio-cultural learning (e.g., Ebert & Crippen, 2010*; McLaughlin & MacFadden, 2014*; Tuan et al., 2017*). However, it has been noted that learning programs based on social-cultural and cognitive learning theories simultaneously enhance teacher knowledge and practice (Clarke & Hollingsworth, 2002*). Bandura's (1986) social cognitive theory combines the socio-cultural and cognitive learning perspectives (Watson, 2013*). This theory has self-efficacy and self-regulation as its key elements (Bandura, 1986).

Self-efficacy is critical in determining whether a teacher will persist in learning about IBSE (Schunk & Pajares, 2009). In self-regulated learning, learners (teachers) control their thoughts, feelings, actions, and behavior while pursuing a given task (Zimmerman, 2013). In the presented research, the task is the implementation of IBSE in the school classroom.

The findings and reflection in the preceding paragraphs provide a basis for generating the DP below, associated with the teacher learning theory. When reading this and subsequent DPs, ignore the legend first and focus on the essence of the principle.

DP#1 (Teacher-learning theory): The social cognitive learning theory is recommended for incorporation into the PD framework. The theory is a combination of learning theories, which embodies a learning process involving participation, conceptual change, self-regulated learning[1], and self-efficacy[2]. The recommended learning theory allows for the effective and simultaneous enhancement of teacher self-efficacy, knowledge, and practice.

PD goal: Based on the selected social-cognitive learning theory, the broad goal of the ProDevInq framework is to enhance teacher knowledge, self-efficacy, and practice in the context of implementing IBSE. However, in terms of elaborating on this broad goal, many of the goals we found in our review were not in alignment with this broad goal. Specifically, the goals were either focused on student learning, were too general, focused on a different strategy in science education, were not comprehensive, or did not allow for a scaffolded process of TPD in IBSE (e.g., Johnson & Marx, 2009*; Klieger & Bar-Yossef, 2011*; Sherman et al., 2008*).

Amongst the appropriate TPD goals we found was one from Ruebush et al. (2010*). The goal was to offer participating teachers an opportunity to experience

[1] Achievable stepwise through observation of a model, replication under supervision of the model, task performance somewhat independently, then enactive mastery (modification and adaptation of initial techniques)

[2] Resulting from performance accomplishment and viewing the success of similar peers (modeling/vicarious experiences), for example

authentic inquiry adaptable to classroom environments and reflect upon their current practices. Another appropriate goal was to enhance teacher competencies such as awareness of different aspects of IBSE and understanding scientific practices and content knowledge that can be incorporated into inquiry-based lesson plans and curricula (McLaughlin & MacFadden, 2014*). Experimentation, investigation, and collaboration (Kapanadze et al., 2015*) are also included. Other goals focused on preparing teachers to implement IBSE practices, principles, and curriculum units in the classroom (e.g., Amolins et al., 2015*). The last goal that we noted was to provide authentic inquiry experiences, to increase science content knowledge, while supporting teachers in planning inquiry-based learning experiences (Capps et al., 2012*).

Based on these findings, we generated the second DP, as follows:

DP#2 (PD goal): The goal recommended for the PD framework is to provide science teachers with experiences in authentic inquiry. Also included is enhancing their competencies (including content knowledge, skills, confidence, and teaching practices) in the context of the adoption, customization, and design, as well as classroom implementation and revision of inquiry-based curriculum units. This would deeply engage teachers in their teaching while supporting the implementation of IBSE.

Phases of PD: Six articles described a PD process consisting of two or three linear or cyclical phases (e.g., Eylon et al., 2008*; Visser, Coenders, Terlouw, & Pieters, 2013*). However, for more guidance in the ProDevInq framework, we focussed on articles with more elaborate descriptions of the TPD process (e.g., Elster, 2009*; Rozenszajn & Yarden, 2014*). In one case, the PD phases that could be identified are initiation, planning, doing, and evaluating/reflecting (Elster, 2009*). One of the most relevant descriptions of a TPD process is in the Ark of Inquiry project (Pedaste et al., 2015*). The six phases in this PD process were motivation, orientation, stabilization, completion, and integration (Trna et al., 2012*). The second most elaborated description of the PD process is in the PROFILES project (Kapanadze et al., 2015*). The project incorporates an introduction phase and the customization and/or development of new inquiry-based lesson units. Next is implementing the units, sharing and discussing the experiences, and reflecting on the feedback and insights gained. A revision of the learning units may follow if necessary. Finally, the teachers disseminate their units, insights, and experiences.

It has been noted that PD can involve individual preparation and assessment activities, in addition to considering issues such as required learner competencies, questions arising, and the availability of materials in school, before bringing participating teachers together (Pérez & Furman, 2016*; Visser et al., 2012*). In addition, the cyclical and non-linear nature of effective teacher development is well recognized (Clarke & Hollingsworth, 2002*; Voogt et al., 2015).

The above findings allow for the generation of the third DP:

DP#3 (phases of PD): It is recommended to incorporate in the PD framework a pre-participation phase[3] in addition to one or more loops of an orientation and collaborative planning phase[4], a classroom implementation phase[5], and a post-implementation phase[6]. This combination of phases fosters guidance and aligns with the cyclical nature of learning.

PD strategy: We found strategies, such as lectures, that were either not in line with DP #1 (social cognitive learning), not specific to curriculum design and implementation, or not associated with a particular sequence for planning and implementing learning activities (Klieger & Bar-Yossef, 2011*; Tytler, 2007*). The strategies we sought needed to be in the context of TPD in IBSE, or at least in innovative curriculum design and implementation. In this regard, four exemplary strategies follow:

- Providing teachers with modeled inquiry-based lessons and opportunities to reflect on lessons and collaboratively design similar lessons that could be implemented (Zambak et al., 2017*).
- Participants customize existing and/or develop new curriculum units, implement them, share and discuss their experiences, reflect on feedback and insights, and revise the units before disseminating their outcomes (Kapanadze et al., 2015*).
- Expressing preconceptions about inquiry-based teaching, discussing existing open inquiry lesson plans/videos, experiencing and discussing authentic inquiry, and expressing associated conceptions and concerns. This is followed by the collaborative design and classroom implementation and guided group discussion of the resulting experiences (Tuan et al., 2017*).
- Engaging participants in experiences that challenge their assumptions and beliefs about

[3] e.g., for enhancing teacher interest and motivation while requesting individual teacher preparation (e.g., examining a pre-developed curriculum unit and availability of materials in school)
[4] including experiencing authentic inquiry, acquiring related knowledge, adapting/developing curriculum units
[5] for teaching adapted/developed units in the classroom
[6] involving sharing/discussing classroom experiences, reflection, revision of units if necessary, and dissemination of units and insights

science teaching (Johnson & Fargo, 2014*). Then, participants will be involved in discussions about practice, modeling effective strategies, immersing participants in these strategies, and encouraging them to reflect on changes in their assumptions and beliefs.

By designing innovative curriculum units (in the current case, inquiry-based), teachers grow in their knowledge and understanding of the innovation, acceptance, and confidence in designing such units (George & Lubben, 2002).

Based on the findings about PD strategies, we could formulate the fourth DP for synthesizing the ProDevInq framework:

DP#4 (PD strategy): Incorporating the evolving PD strategy below in the PD framework is recommended. The strategy is suitable for inquiry-based curriculum design and implementation and allows for a change in assumptions and beliefs regarding science teaching. The strategy also aligns with a cyclical PD process involving the collaborative adoption, customization, or design of inquiry-based curriculum units. Also, the step-wise strategy allows for increased success in the enhancement of teachers' knowledge, understanding, and acceptance of IBSE, in addition to their confidence in designing inquiry-based curriculum units:

- Loop I: Collaborative clarification of learning goals, detecting preconceptions and discussing IBSE; observing model authentic inquiry-based lesson and discussing; experiencing model lesson as learners; discuss unit and new conceptions and concerns linked to IBSE; implement unit in their classrooms and collaboratively reflect on their teaching experiences
- Loop II: Teachers collaboratively reflect upon and customize inquiry-based curriculum unit; implement and reflect upon; then refine unit and report progress
- Loop III: Teachers collaboratively design an inquiry-based unit, implement and observe the unit in their classrooms, collaboratively discuss and reflect on teaching experiences, refine the unit (if they see the need for this), and disseminate their materials, insights, and experiences.

Instructional design model: From the data, we found that for structuring science TPD experiences in IBSE, some designers have used the orientation, conceptualization, investigation, and conclusion model (Pedaste et al., 2015*). Also widely utilized is the engage, explore, explain, elaborate, and evaluate (5e) instructional model (Bybee et al., 2006; Sherman et al., 2008*). The model is a mediating artifact that helps teachers structure and enhance instruction (Svendsen, 2015). The 5e instructional model has been commonly used in science TPD programs (Zambak et al., 2017*).

The preceding findings about instructional design models allowed us to generate the fifth DP towards synthesizing the ProDevInq framework:

DP#5 (Instructional design model): An inquiry-based instructional model (or learning cycle) is recommended for inclusion in the PD framework. Examples are the orientation, conceptualization, investigation, and conclusion model; the predict, observe, and explain model; and the engage, explore, explain, elaborate, and evaluate model. The model would help teachers move to more inquiry-based science teaching and enhance the structure and implementation of curriculum units.

Instructional functions: The instructional functions we identified included providing learning goals and overviews of PD modules (Amolins et al., 2015)*. The former increases teacher success in the classroom (MacIsaac et al., 2001), while the discussion of both aspects helps in building teacher confidence in the next module (Visser et al., 2012*). The instructional functions also included providing guidance during group discussions, suggesting ideas, and scaffolding (e.g., Mamlok-Naaman & Eilks, 2012*; Tuan et al., 2017*). On-going scaffolding is needed during an instructional design process (Eylon et al., 2008*). Scientists and science educators have been found to provide teachers with feedback on implementing an inquiry-based science instruction plan (Morrison, 2014*). The feedback includes comments and clarification, can be from peers, following peer classroom observation (Johnson, 2007*), or provided by facilitators online following in-person sessions (Sherman et al., 2008*).

With the preceding findings on instructional functions in mind, we could formulate the sixth DP:

DP#6 (instructional functions): It is recommended that instructional functions be included in the TPD framework. This is given, for example, that designing is a complex skill and that instructional functions increase teacher confidence, self-efficacy, and success. Also, instructional functions assist when transitioning between learning activities and phases. The instructional functions that can be incorporated into the framework include:

- Providing learning goals and overviews
- Providing guidance (such as through suggesting ideas and scaffolding)
- Providing (individualized) feedback, including comments, and clarification

Teacher motivation: Teacher motivation is widely considered intrinsic or extrinsic, with the latter including tangible rewards. Examples of the rewards used in the PD processes in the included articles are recertification credit and curricular materials for use in the classroom (Penuel et al., 2007*; Sherman et al., 2008*). However, teacher motivation was more often through gathering

Table 3. Screening of the preliminary version of the DPs

Hallmarks of effective (science) teacher professional development	Incorporated in DPs		
	Adequately	Inadequately	Not at all
1. Collective participation		x	
2. Science content knowledge development			x
3. Adequate total time for PD			x
4. Extended support		x	
5. Coherency with standards		x	
6. Providing teachers with authentic inquiry experiences	x		
7. Development of inquiry-based lessons	x		
8. Modelling inquiry-based lessons	x		
9. Reflecting on experiences	x		
10. Transference (discussing of classroom curriculum enactment)	x		
Total	5	3	2

learning goals and expectations, setting goals, and experiencing success (Rozenszajn & Yarden, 2014*; Stolk et al., 2012*). More autonomous types of motivations (intrinsic and internalized extrinsic motivation) foster learning better than controlled motivation from rewards, for example (Schunk & Usher, 2012).

Based on Bandura's (1986) social cognitive learning theory, one source of teacher motivation is finding that their efforts lead to success and observing peers succeeding (Schunk, 2012). Evidence of improved practice is an effective intrinsic incentive in teacher learning (Harrison et al., 2008*). However, teachers are autonomously motivated by providing pre-formulated learning goals, gathering their PD goals, or the joint formulation of these goals (Zwiep & Benken, 2013*). It is also autonomously motivating to allow teachers involved in PD to express their expectations (Rozenszajn & Yarden, 2014*).

These findings allowed us to formulate the seventh and last DP for the synthesis of the ProDevInq framework:

DP#7 (teacher motivation): Autonomous motivation is recommended for inclusion in the PD framework. Autonomous motivation aligns with the social cognitive learning theory, lasts longer, and fosters learning better than controlled motivation. This type of motivation can be incorporated into the framework, as follows:

- encouraging the expression of expectations
- providing goals that are pre-formulated, teacher-formulated or collaboratively-formulated
- getting teachers to observe the success of their peers (modeling/vicarious experiences)
- getting teachers to accomplish tasks and experience improvement in their practice
- enhancing self-efficacy in inquiry-based teaching

Formative Evaluation of Initial Design Principles

The evaluation focused on the content validity of the set of DPs in the preceding section (DP#1–7). As evaluation criteria, we used ten hallmarks taken from the literature on what makes science TPD effective (**Table 1**). We did not include these hallmarks of effective science TPD in the terms we searched, for articles to include in our systematic analysis of the science TPD literature. When using the hallmarks in our evaluation, we checked the extent to which each was incorporated into the DPs (**Table 3**).

Table 3 shows that the incorporation of Hallmarks 1, 4, and 5 in the initial DPs needed enhancement. Hallmark 2 and Hallmark 3 were also to be incorporated into the principles. By reflecting on these outcomes, the set of DPs, and the descriptions of the hallmarks of effective science TPD efforts (**Table 1**), we reached several decisions about improving the DPs.

Firstly, we decided to incorporate Hallmark 1 and Hallmark 2 in DP#3 (phases of PD). Also, in DP#4 (PD strategy), we incorporated Hallmark 3 and enhanced the incorporation of Hallmark 4. It was left to address the inadequate incorporation of Hallmark 5 in the DPs. We incorporated the hallmark in DP#2 (PD goal).

Based on the reflection, we revised and renumbered DP#2, #3, and #4, as seen below. The revised segments of the three DPs are shown in italics:

DP#2b (PD goal): The recommended goal for the PD framework is to provide science teachers with experiences in authentic inquiry. Also included is enhancing their competencies (including content knowledge, skills, confidence, and teaching practices) in the context of the adoption, customization, and design, as well as classroom implementation and revision of inquiry-based curriculum units. This would deeply engage teachers in their teaching while supporting the implementation of IBSE. *This goal and other core elements of the framework can be adjusted to enhance their alignment with national, state, district, and school reform, in addition to standards and policies.*

DP#3b (phases of PD): It is recommended to incorporate in the PD framework a pre-participation phase[7] in addition to one or more loops of an orientation and collaborative planning phase[8], a classroom implementation phase[9], and a post-implementation phase[10]. This combination of phases fosters guidance and aligns with the cyclical nature of learning.

DP#4b (PD strategy): It is recommended that the evolving PD strategy below be incorporated into the PD framework. *The strategy can be implemented over a semester with at least 20 hours of contact time.* The strategy is suitable for inquiry-based curriculum design and implementation and allows for a change in assumptions and beliefs regarding science teaching. The strategy also aligns with a cyclical PD process involving the collaborative adoption, customization, or design of inquiry-based curriculum units. Also, the step-wise strategy allows for increased success in the enhancement of teachers' knowledge, understanding, and acceptance of IBSE, in addition to their confidence in designing inquiry-based curriculum units:

- Loop I: Collaborative clarification of learning goals, detecting preconceptions and discussing IBSE; observing model authentic inquiry-based lesson and discussing; experiencing model lesson as learners; discuss unit and new conceptions and concerns linked to IBSE; implement unit in their classrooms and collaboratively reflect on their teaching experiences
- Loop II: Teachers collaboratively reflect upon and customize inquiry-based curriculum unit; implement and reflect upon; then refine unit and report progress
- Loop III: Teachers collaboratively design an inquiry-based unit, implement and observe the unit in their classrooms, collaboratively discuss and reflect on teaching experiences, refine the unit (if they see the need for this), and disseminate their materials, insights, and experiences

The three DPs revised as seen above (DP#2b, DP#3b, and DP#4b) and the four in the preceding section that remained unchanged (DP#1 and DP#5–7) are our final DPs. These principles answer our first research question (**RQ1**).

Synthesis of ProDevInq Framework (RQ2)

The synthesis of the framework was based on the final DPs. We applied the principles in the framework's body and the legend (**Figure 3**). The exception is DP#1 (teacher-learning theory), whose application in the framework is not localized but through other DPs (e.g., DP#2b, 4b, and 7). When reading the framework for the first time or before a reader is familiar with the structure of the framework, we advise that they initially ignore the legend. In any case, we have conveniently placed the PD goal at the beginning of the body of the framework. The goal results from DP#2b. The three colors used in the goal for the terms "**adopt**", "**customize**", or "**design**" reappear later in the framework.

The four phases of the PD process are prominent in the framework, resulting from DP#3b (phases of PD). Although not as per the design principle, the phases are colored green and numbered to assist in reading the framework. The numbering is the order in which the phases may be completed in a PD opportunity based on the ProDevInq framework. However, it is essential to note that the last three PD phases (numbered 2, 3, and 4) embody an iterative PD process with three loops. The loops reflect DP#4b (PD strategy). The text and arrows in **purple** make up **loop I**, while the text and arrows in **red** and **blue** make up **loop II** and **loop III**, respectively. **Loops I, II, and III** focus on the **adoption**, **customization**, and **designing** of inquiry-based curriculum units, respectively. Each loop must be read clockwise across the three associated PD phases. Please start **loop I** in the orientation and collaborative planning phase, and after returning to this phase, jump to **loop II**. Read this loop in the same manner and eventually read **loop III** similarly.

To decongest the framework's core, we have incorporated some DPs with the help of legend. For example, DP#2b (PD goal) is only fully incorporated thanks to the legend in the framework, as seen through the superscript (^). The remaining three DPs (DP#5–7) are incorporated within the phases and loops in the body of the framework or the legend. For example, due to DP#5, the framework contains the heart sign (♥) in the body and the legend. The heart sign, as seen in the legend, says that an inquiry-based instructional model is recommended for all curriculum units involved in the TPD opportunity. Specific examples of the models that may be considered are also recommended. Other signs (§ and ♦) are similarly used to incorporate instructional functions (DP#6) and teacher motivation (DP#7) in the framework. The remaining signs complete a DP, define an acronym, or provide reading instructions.

[7] involving *recruitment of science teachers for collective participation,* starting to provide motivation; individual teacher preparation (e.g., examining a pre-developed curriculum unit; considering required learner competencies, questions arising, and availability of materials in school)

[8] including *a whole group* experience *and discussion* of authentic inquiry; *small-group-based* acquisition of related *content and other* knowledge, adaptation/development of curriculum units

[9] for teaching adapted/developed units in the classroom

[10] involving sharing/discussing classroom experiences, reflection, revision of units if necessary, and dissemination of units and insights

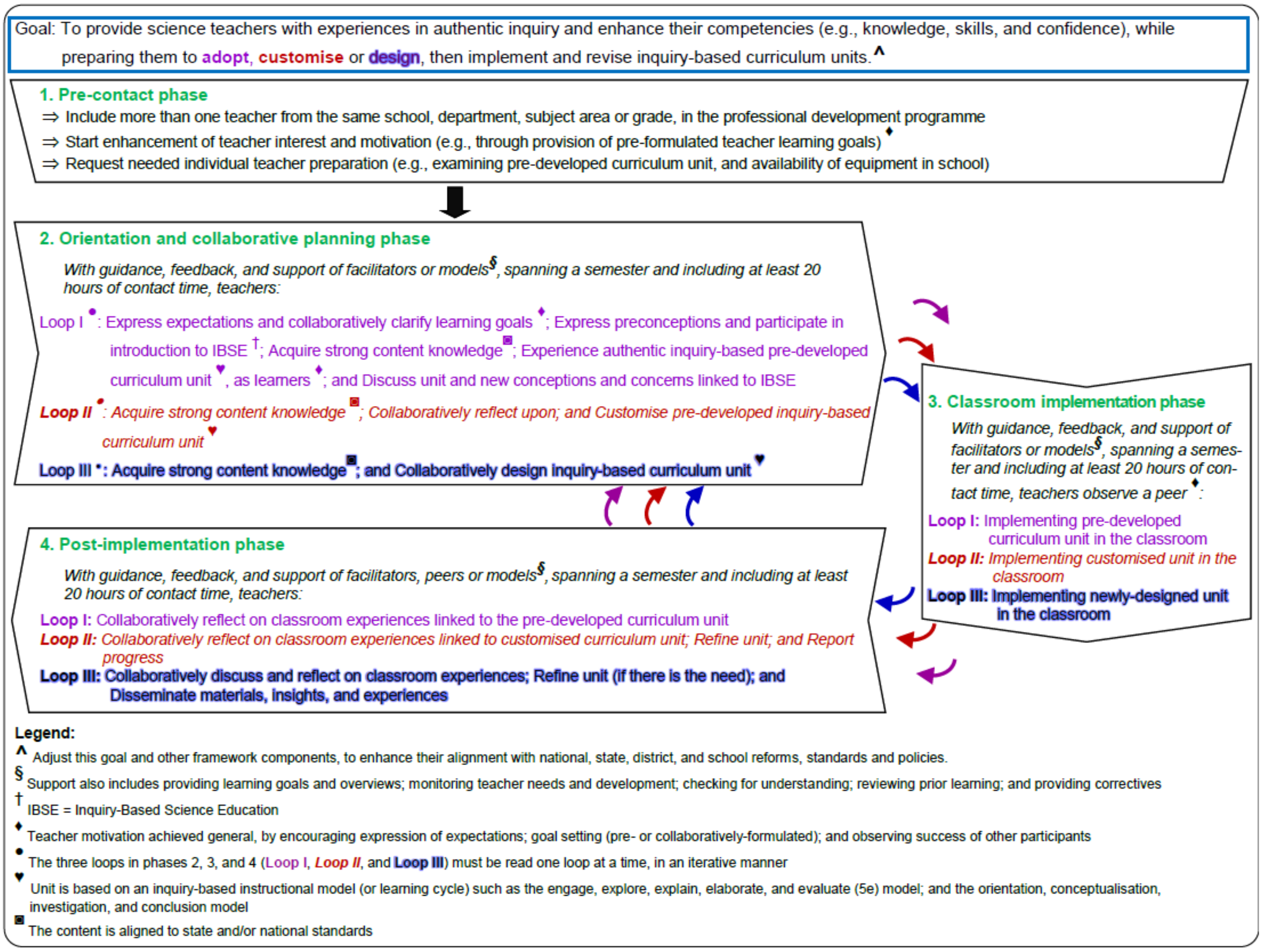

Figure 3. ProDevInq framework for supporting school science teachers in relation to inquiry-based science education (Source: Authors' own elaboration)

The framework in **Figure 3** addresses our second research question (RQ2). The synthesis of the framework marks the end of the implementation of the Initial prototyping and development phase in our design process (**Figure 1**). Seven DPs have been conceptualized, generated, revised, and implemented in synthesizing the ProDevInq framework.

DISCUSSION AND CONCLUSION

The presented EDR aimed to yield tools for supporting the implementation of IBSE in school settings. The tools are the ProDevInq framework (**Figure 3**) and the underlying DPs. The principles consist of DP#1, DP#5, DP#6, and DP#7, in addition to DP#2b, DP#3b, and DP#4b. These principles and the ProDevInq framework describe a TPD process based on seven components. The components are a goal, learning theory, strategy, phases, instructional functions, motivation, and an instructional design model. Theoretical support for these components is found in our conceptual framework and the research findings (**Table 2**).

The presented science TPD design tools and the associated EDR process are the outcomes of the presented research. These outcomes contribute to the pre- and in-service science teacher education literature on a global scale. Also, the outcomes have practice- and research-related implications on the same scale.

Research Contribution

The first contribution relates to using EDR to yield the presented TPD design tools. TPD has been noted as one of the sectors within education where EDR seems to have been embraced (McKenney & Reeves, 2019). At the same time, Zinger et al. (2017) state that EDR has focused on classroom learning leaving teacher learning behind. The presented research contributes to the implementation of EDR in science TPD. Additionally, the design process we have compiled and utilized in the presented research may be considered by researchers when designing similar TPD programs.

As a second contribution, the presented TPD design tools address several calls found in the literature. One of the calls is for ways of designing teacher education in

IBSE (Riga et al., 2017; Yoon et al., 2012). While the ProDevInq framework offers one of the ways, note has been made about the lack of a discussion about creating scaffolded science TPD opportunities (Luft et al., 2019; National Academies of Sciences, 2015). The presented TPD tools contribute to the debate and are discipline-specific. The ProDevInq framework addresses other gaps in the TPD literature. One of the gaps is in implementing the hallmarks of effective TPD to support the transformation of teaching practices (Inouye & Gunshenan, 2024; Korsager, 2022). The ProDevInq framework is a valuable contribution to fostering the development of IBSE practices in in- and pre-service science teacher education settings. It has been noted that teacher educators must provide pre-service teachers with examples of implementing IBSE in school classrooms (Lunenberg et al., 2007). The ProDevInq framework can support the implementation of adopted, customized, and teacher-designed inquiry-based curriculum units.

Thirdly, the presented TPD design tools have unique aspects. The ProDevInq framework differs from the TPD framework synthesized by Stolk et al. (2012). The difference is in the sense that the ProDevInq framework sandwiches the customization of curriculum units between the adoption and designing of these units, making for a more scaffolded and supported TPD process. The ProDevInq framework explicitly identifies instructional functions and incorporates specific examples of recommended instructional design models. In the latter regard, the ProDevInq framework is more detailed than the PD framework proposed by Akuma (2017).

Practice-Related Implications

Nieveen and Folmer (2013) provide a discussion of relevance in terms of the parties in the science TPD sector that stand to benefit from the presented design research outcomes. The parties include policymakers and teacher educators. Policymakers may utilize the presented DPs to reach informed decisions. An example is when selecting programs to support teachers to implement IBSE successfully.

The educators of the teachers can utilize the DPs and the ProDevInq framework when addressing the complex and challenging task of designing programs focusing on implementing IBSE. An example of such a program can be in relation to frameworks of teacher capabilities required for the successful implementation of IBSE in school classrooms. The capabilities have been considered to consist of subject matter knowledge, understanding of scientific practices and other aspects of scientific inquiry, knowledge of the nature of science, and substantial practical experience in the design, development, and implementation of inquiry-based learning experiences (Crawford & Capps, 2018; Van Joolingen & Zacharia, 2009). Such frameworks of the required capabilities for IBSE can be addressed using the ProDevInq framework as a TPD program design tool. Researchers have stressed the importance of program design in reaching TPD learning outcomes (Affouneh et al., 2020; Lowell, 2023).

The third practice-related implication of the presented research relates to the form of the ProDevInq framework in terms of practicality. In this regard, the PD goal is placed at the top of **Figure 3**. Also, color is used to highlight two critical components of the framework, namely, the phases and the loops. However, the ProDevInq framework is presented as a compact structure of the framework. Thus, it is essential to bear in mind the explanation and instructions provided for reading the framework in the framework itself.

Research-Related Implications

It has been noted that an EDR project usually needs several cycles before an optimal solution to a complex problem can be obtained (Nieveen & Folmer, 2013). The presented research is not an exception. In this regard, the presented research has research-based implications associated with three limitations.

One limitation is the lack of an empirical dimension in the research, as in all review studies. Also, there is a lack of a specific educational context in the research. As a result, implementation procedures and empirical arguments could not be added to the DPs. Also, although DP#2 (PD goal) recommends coherency with actual PD contexts, context could not be an integral component in the presented TPD design tools. By building on the existing tools, for example, tools that are more contextually coherent and informed by empirical data may be made available. It has been noted that TPD efforts need to be well aligned with the surrounding socio-cultural and socio-economic realities (Rundgren, 2018; Sancar et al., 2021). As an example, in this light, we plan in our further research to arrive at a version of the ProDevInq framework for supporting teachers in resource-constrained South African physical sciences classrooms in terms of inquiry-based practical work. Similar work may be done in other educational contexts.

As a further research-related implication of the presented research, recall that the formative evaluation of the DPs was limited to developer screening focusing on content validity. Considering the EDR process model in **Figure 1**, the DPs and, as a result, the ProDevInq framework may be enhanced through empirical formative evaluation. The evaluation can take place through expert appraisal focusing on content and construct validity. The practicality of the framework may also be included in the evaluation. Evaluating and enhancing the ProDevInq framework is in line with Van Driel et al. (2012) who called for an empirically-based TPD framework for IBSE, incorporating a wide range of hallmarks drawn from research on what makes TPD effective.

Consideration may also be given to the fact that in the generation of the presented DPs, we sometimes had to fall back on the literature on TPD in innovative or reform-based teaching strategies in general. Empirical evaluation of the ProDevInq framework by educators who are experts in IBSE, may yield data to strengthen the DPs and the framework in terms of their focus on IBSE, specifically.

Conclusion

The presented design research has yielded the ProDevInq framework, its seven underlying DPs, and the associated EDR process. The framework and underlying DPs are based on seven components from the science TPD research literature. The components are a goal, learning theory, strategy, phases, instructional functions, motivation, and an instructional design model. The framework and DPs are context-generic, content-specific, and discipline-specific. They are aligned with the hallmarks of what makes science TPD programs effective, taken from the literature. The framework, DPs, and EDR process we utilized are one response to the need for high-quality, scaffolded, and coherent ways to provide TPD opportunities in IBSE. The tools and process contribute to the global pre- and in-service science TPD research literature. They can be considered for guidance by decision-makers, in addition to pre- and in-service science teacher educators and researchers, when addressing the complex and challenging task of designing effective science TPD opportunities in implementing IBSE.

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APPENDIX A: CODING SHEET FOR ARTICLES INCLUDED IN THE LITERATURE REVIEW

Table A1. Articles in first and second database searches

Article[a]	Coding criteria			
	Type of article	IIBSE	Study location	Area of science involved
1. Alozie and Mitchell (2014)	E	Y	iv	o*
2. Amolins et al. (2015)	E	Y	iv	●, ○, ■, □
3. Capps et al. (2012)	R	N/A	iv	N/A*
4. Cormas and Barufaldi (2011)	R	N/A	iv	o*
5. Delclaux and Saltiel (2013)	E	Y	iii	○*
6. Ebert and Crippen (2010)	E	Y	iv	■
7. Eilks and Markic (2011)	E	N	iii	□
8. El-Deghaidy et al. (2015b)	E	Y	i	○*
9. Elster (2009)	E	N*	iii	■
10. Ergazaki and Zogza (2013)	E	Y	iii	■
11. Eylon et al. (2008)	E	N	ii	◊
12. Filippi and Agarwal (2017)	E	Y	iv	o*
13. Gillies and Nichols (2014)	E	Y	v	o*
14. Harrison et al. (2008)	E	Y	iii	◊, o*
15. Haug (2014)	E	Y	iii	o*
16. Higgins and Spitulnik (2008)	R	N/A	iv	N/A*
17. Johnson (2007)	E	Y	iv	○*
18. Johnson and Fargo (2014)	E	Y	iv	○*
19. Johnson and Marx (2009)	E	Y	iv	○*
20. Kapanadze et al. (2015)	E	Y	ii	■, □, ◊
21. Kazempour and Amirshokoohi (2014)	E	Y	iv	■, □, ◊, ○
22. Klieger and Bar-Yossef (2011)	E	N	iv	○*
23. Klieger et al. (2010)	E	N	ii	○*
24. Lieberman and Mace (2008)	R	N/A	iv	○*
25. Nam et al.(2013)	E	Y	ii	○*
26. Mamlok-Naaman and Eilks (2012)	E	N	ii	□
27. Marra et al. (2011)	R	N	iv	○*
28. McLaughlin and MacFadden (2014)	E	Y	iv	■, □, ○
29. Morrison (2014)	E	Y	iv	○*
30. Ostermeier et al. (2010)	E	Y	iii	■, □, ◊
31. Paik et al. (2011)	E	N*	iv	○*
32. Penuel et al. (2007)	E	Y	iv	○*
33. Penuel and Gallagher (2009)	E	Y	iv	○*
34. Pérez and Furman (2016)	E	Y	iv	○
35. Rozenszajn and Yarden (2014)	E	N	ii	■
36. Ruebush et al. (2010)	R	Y	iv	○*
37. Rundgren (2018)	R	Y	iii	N/A*
38. Rushton et al. (2011)	E	Y	iv	□
39. Schneider and Plasman (2013)	E	N/A	iv	N/A*
40. Sherman et al. (2008)	E	N	iv	○*
41. Singer et al. (2011)	E	Y	iv	○*
42. Stolk et al. (2009a)	R	N/A	iii	□
43. Stolk et al. (2009b)	R	N*	iii	□
44. Stolk et al. (2011)	E	N*	iii	□
45. Stolk et al. (2012)	E	Y	iii	□
46. Tuan et al. (2017)	E	Y	ii	○*
47. Trna et al. (2012)	R	Y	iii	○*
48. Tytler (2007)	E	N	v	○*
49. van Uum et al. (2016)	E	Y	iii	○*
50. Visser et al. (2012)	E	N	iii	○*
51. Visser et al. (2013)	E	N	iii	■, □, ◊
52. Whitworth and Chiu (2015)	R	N/A	iv	N/A*
53. Yerushalmi and Eylon (2013)	E	N*	ii	N/A*
54. Zambak et al. (2017)	E	Y	iv	○*
55. Zwiep and Benken (2013)	E	Y	iv	○*

Note. [a]See references for details; IIBSE: Involvement of inquiry-based science education?; N/A: Not applicable as the article does not contain a professional development process; N/A*: Not applicable as the article does not have a specific disciplinary focus; E: Empirical research article; R: Review article; Y: Yes; N: No; N*: Another reform-based strategy than inquiry (e.g., problem-based teaching and learning); i: Africa; ii: Asia; iii: Europe; iv: North America; v: Oceania; vi: South America; ■: Biology; □: Chemistry; ◊: Physics; ●: Physical sciences; ○: Other sciences (e.g., environmental sciences, life sciences, natural sciences, forensics, and biotechnology); ○*: Unspecified science areas

Table A2. Articles in third database search

Article[a]	Coding criteria	
	Learning context	Learning theory involved [e]
56. Clarke and Hollingsworth (2002)	Teacher profession development	LT3
57. Kelly (2006)	Teacher professional development	LT1, LT3
58. Korthagen (2010)	Teacher profession development	LT1, LT2
59. Pella (2011)	Teacher professional development	LT2, LT3
60. Schumacher et al. (2013)	Self-directed and lifelong learning	LT3
61. Taylor (2007)	Adult and continuing education	LT4
62. Watson (2013)	Teacher learning	LT2

Note. [a]See references for details; LT1 = Traditional cognitive theory; LT2 = Social learning theory; LT3 = Situated learning (Situated cognition); LT4 = Transformative learning

APPENDIX B: ARTICLES INCLUDED IN THE REVIEW

Table B1. Articles included in the review

Alozie, N., & Mitchell, C. (2014). Getting students talking: Supporting classroom discussion practices in inquiry-based science in real-time teaching. *American Biology Teacher, 76*(8), 501-506.

Amolins, M. W., Ezrailson, C. M., Pearce, D. A., Elliott, A. J., & Vitiello, P. F. (2015). Evaluating the effectiveness of a laboratory-based professional development program for science educators. *Advances in Physiology Education, 39*(4), 341-351. https://doi.org/10.1152/advan.00088.2015

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Clarke, D., & Hollingsworth, H. (2002). Elaborating a model of teacher professional growth. *Teaching and Teacher Education, 18*(8), 947-967. https://doi.org/10.1016/S0742-051X(02)00053-7

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Eylon, B. S., Berger, H., & Bagno, E. (2008). An evidence-based continuous professional development programme on knowledge integration in physics: A study of teachers' collective discourse. *International Journal of Science Education, 30*(5), 619-641. https://doi.org/10.1080/09500690701854857

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Gillies, R. M., & Nichols, K. (2014). How to support primary teachers' implementation of inquiry: Teachers' reflections on teaching cooperative inquiry-based science. *Research in Science Education*. https://doi.org/10.1007/s11165-014-9418-x

Harrison, C., Hofstein, A., Eylon, B.-S., & Simon, S. (2008). Evidence-based professional development of science teachers in two countries. *International Journal of Science Education, 30*(5), 577-591. https://doi.org/10.1080/09500690701854832

Haug, B. S. (2014). Inquiry-based science: Turning teachable moments into learnable moments. *Journal of Science Teacher Education, 25*, 79-96. https://doi.org/10.1007/s10972-013-9375-7

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Table B1 (Continued). Articles included in the review

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Nam, J., Seung, E., & Go, M. (2013). The effect of a collaborative mentoring program on beginning science teachers' inquiry-based teaching practice. *International Journal of Science Education, 35*(5), 815-836. https://doi.org/10.1080/09500693.2011.584329
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