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Alternative Concepts in the Teaching of Photosynthesis: A Literature Review 2000-2021

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Abstract

The acquisition of abstract concepts in science education is a major challenge as acquisition of accurate scientific knowledge depends on a complexity of processes, including teachers' capability to adopt a generative co-inquiry stance. In a previous article in *Higher Education of Social Science* we proposed a 'good enough' practice approach to this 'problem': an iterative pedagogical cycle of 3Rs: Recognition, Reduction and Removal within an understanding that affordances for conceptual conflict are often necessary and can increase the probability of reduction and possible removal of alternative concepts (*details with Editor*). We advance processes of deep meaning making and (re)construction that support affordances for productive pedagogies beyond deficit discourses of didactic failure or seeking some form of elusive perfection. In this article, we continue this reasoning to conduct a literature review of alternative concepts, often referred to as misconceptions in the teaching of photosynthesis inclusive of primary education, secondary (high school) education and higher education within the timeline 2000 to 2021. Photosynthesis was chosen as it is a prevalent biology topic that students and teachers often find conceptually challenging. Findings indicate approaching the problem of acquisition of accurate scientific knowledge in the teaching of photosynthesis requires a multiplicity of pedagogical strategies and a rich variety of professional supports. A productive engagement with alternative concepts is already underway in the literature, seeking a co-inquiry stance within an understanding of the crucial role of teacher upskilling in subject matter knowledge in science education (Bevins & Price, 2016; Greca, 2016; Karakaya, Yilmaz & Aka, 2021; Windschitl, 2002). It is a hypothesis worthy of further consideration and research.

Key words: Science education; Teaching photosynthesis; Literature review; Alternative concepts; Misconceptions; Productive pedagogy; Professional supports; Good Enough practice

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1. INTRODUCTION

It is well recognised in the literature that the problem of teaching photosynthesis for the acquisition of accurate scientific knowledge is crucially important in the biology curriculum, in the nature of science and across all sectors, in primary education, secondary (high school) education and higher education (Karakaya, Yilmaz & Aka, 2021). This is a problem that cannot be approached in a simplistic way, and while pedagogical and professional approaches have moved beyond classical methods to advocate an active learner-centred constructivist model the problem has not abated and continues to trouble the literature in science education (Bevins & Price, 2016; Greca, 2016; Karakaya, Yilmaz & Aka, 2021; Métioui, Matoussi & Trudel, 2018).

Recent literature argues that new expansive models of science education are needed, new paradigms of science education that offer transformative pedagogies suited to a diversity of inquirers in the ontological and epistemic complexity that is contemporary science education (Windschitl, 2002, Windschitl, Thompson & Braaten, 2008). This debate is found in Bevins & Price's (2016) call for a reconceptualization of inquiry, Jin et al.'s (2016) promotion of an inquiry stance in science classrooms, Messig & Groβ's (2018) advocacy for productively working with student's current conceptions through (re)construction and Greca (2016) advocating for a new hybrid space for the integration of theory and practice in teacher education. The debate is found in complexity science literature in relation to conceptualising teacher professional learning (Opfer & Peddar, 2007). Understanding what is happening in classrooms, eschews linear rational efforts at causation and argues for understanding the endless variables in play in the macro-micro sub-levels of education and the necessity to bring into play both the universalist and the particularist, to learn from (universalist) patterns and, simultaneously to consider situated contexts (particularist).

In a previous article in *Higher Education of Social Science* we proposed a 'good enough' practice approach to alternative concepts, an iterative pedagogical cycle of 3Rs: Recognition, Reduction and Removal within an understanding that affordances for conceptual conflict are often necessary and can increase the probability of reduction and possible removal of alternative concepts (*details with Editor*). We advance meaning making and processes of conceptual conflict that support productive pedagogies beyond deficit discourses of didactic failure seeking some form of elusive perfection. An argument that mirrors much of the history of the discovery of the complex processes involved in photosynthesis itself, mired as this journey was by misconceptions while facilitating risk-taking approaches of trial and error (Métioui, Matoussi & Trudel, 2018). We continue this reasoning for a literature review of alternative concepts in the teaching of photosynthesis, in primary, secondary and higher education from 2000 to 2021.

Photosynthesis was selected as it is a prevalent biology topic many students find conceptually challenging (Marmaroti & Galanopoulou, 2006). Teaching photosynthesis for the acquisition of accurate subject matter knowledge, and gauging the necessary depth of that disciplinary knowledge will depend on the level at which the teaching is conducted. Whatever level, teachers need to have access to, understanding of, and sufficient knowledge of the complex processes involved in photosynthesis, scientific knowledge produced by researchers over several decades using an integrated approach across disciplines, in chemistry, biochemistry, physics and genetics (see Karakaya, Yilmaz & Aka, 2021, p.2; Mohapatra & Singh, 2015).

Studies show that students and teachers often display a weak understanding of this complex topic (Ekici, Ekici, & Aydin, 2007; Kose, 2008; Özay & Öztaş 2003). Accurate disciplinary knowledge in photosynthesis is important in that it plays a key role in understanding other aspects of living systems (Deshmukh, 2012; Mikkila-Erdmann, 2001). There are already a number of identifiable sources contributing to alternative concepts, including everyday experience and inaccurate communication with teachers, social media and textbooks (Abimbola & Baba, 1996; Angell, Ryder, & Scott, 2005; Dikmenli & Cardak, 2004; Gibson, 1996; Kose, Uşak, & Bahar, 2009; Van Steenbrugge, Valcke, & Desoete, 2012).

Many different terms have been used to describe inaccurate abstract concepts in the sciences, such as, alternative frameworks (Taber, 2000), alternative concepts (Mulford & Robinson, 2002), preconceptions and misconceptions (Brown, 1992; Chambers & Andre, 1997; Gonzalez, 1997; Griffiths, 1994; Griffiths & Preston, 1992; Michael, 2002; Schmidt, 1997).

In this paper, we define alternative concepts as 'inaccurate ideas that can predate or emerge from instruction' and view alternative concepts not as an aberration but rather as providing productive 'opportunities for cognitive and social dissonance that students encounter as they progress in their learning' (Crowther & Price, 2014, *details with Editor*). Good science teaching requires proficiency in multiple forms of knowledge, such as, disciplinary and theoretical knowledge, knowledge of pedagogy and pedagogical content knowledge, knowledge of inquiry and reflexive practices, all operationalised through non-linear pathways of translation, mediation and interpretation (*details with Editor*).

In this study, we examine the most frequently cited alternative concepts, the pedagogical approaches used and professional supports employed. We move beyond a deficit discourse of teaching young people photosynthesis and approach science education from a holistic and nuanced positioning that supports transformative possibility and the acquisition of accurate subject matter knowledge rather than a technocratic and clinical reading of pedagogies and teacher professional learning (*details with Editor*).

Science teachers' depth of conceptual understanding and engagement with subject matter knowledge is considered to have a significant influence on student's acquisition of accurate scientific knowledge (Kapyla, Heikkinen, & Asunta, 2009; Krall, Lott, & Wymer, 2009; Partosa et al., 2013). Studies show that science teachers need productive pedagogies and professional supports for an inquiry stance in order to confront alternative concepts (Allen, 2014; Burgoon, Heddle, & Duran, 2011; Lim & Lee, 2014; Yip, 1998, 2007).

Moreover, the lived reality of classrooms, the many solvable and unsolvable dilemmas, tensions and contradictions encountered by science teachers poses many constraints in productive corrective practices to alternative concepts in teachers and student's understandings. Many teachers, due to the constant outcome demands of a standardized curriculum, feel compelled to seek expedient approaches and not pay sufficient attention to interrogation of conceptual understandings and the enactment processes involved in engagement with students' understandings (Chen, Kirkby, & Morin, 2006). When science teachers underestimate this complexity, and the diversity of pedagogical interactions needed to support students' meaning making, then students' acquisition of accurate subject matter knowledge may become negatively impacted (Ravanis & Bagakis, 1998; Stepans & Kuehn, 1995). Studies show teachers' challenge to access productive practices, active learning strategies and appropriate professional supports outside the classroom, such as, open access to research, networks of support and school-university partnerships, and supports that include up-skilling in subject matter knowledge (Ruohotie-Lyhty & Moate, 2014; Opfer & Pedder, 2011; *details with Editor*).

In this article, we first outline the research methodology used in relation to the literature review. Second, we analyse the findings according to (a) the most frequent alterative concepts found in relation to the teaching of photosynthesis (b) the pedagogical strategies used and (c) the professional supports reported for teacher learning. Third, we discuss the findings and their implications in relation to seeking new productive approaches for the acquisition of accurate conceptual subject matter knowledge in the teaching of photosynthesis. This continues a debate already underway in relation to the complexity of science education and a co-inquiry stance that necessitates conceptual conflict and meaning-making processes with a diversity of inquirers (Bevins & Price, 2016; Greca, 2016; Jin et al., 2016; Windschitl, 2002; Windschitl, Thompson & Braaten, 2008).

2. RESEARCH METHODOLOGY

The systematic review of the literature on alternative concepts in the teaching of photosynthesis began by deciding what criteria were to be included and excluded (Petticrew & Roberts, 2008). The review included studies whose main focus was identifying and interacting with alterative concepts among all levels of science education, primary, secondary and higher education and was confined to a timeline between 2000 and 2021. The electronic databases searched were Science Direct, ERIC and ProQuest Education journals. The key words used were 'photosynthesis', 'alterative concepts', 'misconceptions', 'conceptual change', 'pre-service and qualified teachers'. The key questions driving the systematic review were seeking to elicit the most frequent alternative concepts found in teaching the topic of photosynthesis, the reported pedagogical practices and the professional structures used to interact with alternative concepts. This literature review yielded 46 peer-reviewed journal articles specific to alternative concepts in photosynthesis and science education. Table 1 lists the participants, their age range or group identity and the pedagogical strategies and professional supports employed.

Table 1
A literature review of alterative concepts in the teaching of photosynthesis, 2000-2021

Age/Group	Pedagogical strategies used to identify alternative concepts	Strategies used to address alternative concepts	Author (s)
Primary education			
7-12 yrs	Drawings, written explanations and requested identification	Not available	Barman et al. (2006)
11-13yrs	Drawings, MCQ	Models, discussion, experiments	Clegg (2011)
10-11 yrs	Concept cartoons	Interviews and discussions	Ekici, Ekici, and Aydin (2007)
10-12 yrs	Interviews	Animations and question cards	Keles and Kefeli (2010)
11 yrs	Not available	Computer based instruction to overcome	Kici (2012)
10-11 yrs	Conceptual change text	Conceptual change texts and imagery	Mikkila-Erdmann (2000)
Secondary education			
13-14 yrs	MCQ and open questions	Conceptual change approach	Akpinar (2007)
16-17 yrs	Questionnaire pre and post tests	Concept mapping and conceptual change text	Al Olaimat (2010)
13-14 yrs	MCQ	5E and conceptual change text	Balci, Cakiroglu, and Tekkaya (2006)
13-14 yrs	Close ended Questionnaire	Models	Boomer and Latham (2011)
14-15 yrs	Not available	Concept mapping	Brown (2000)
16-17 yrs	Close ended questionnaire	Computer assisted instruction	Cepni, Tas, and Kose (2006)
14-16 yrs	Open ended questionnaire	Concept connections and creating dissatisfaction	Deshmukh (2012)
16-18 yrs	Open ended questions	Cooperative learning strategies and inquiry model	Deshmukh and Deshmukh (2007)
15-16 yrs	Observations	Inquiry constructivist approach	Domingos-Grilo et al. (2012)

Age/Group	Pedagogical strategies used to identify alternative concepts	Strategies used to address alternative concepts	Author (s)
Not available	Concept maps	Not available	Lin and Hu (2003)
15 yrs	Two-tier diagnostic test	Not available	Liu and Li (2013)
13 yrs	Close ended questionnaire	Not available	Marmaroti and Galanopoulou (2006)
15 yrs	Eliciting students' prior schema, images and conceptions and working with them to (re)construct them.	Productive use of conceptual conflict while approaching students' knowledge in science from a place of fruitful learning rather than a deficit place.	Messig & Groβ, 2018
11-18 yrs	A synthesis of the research affecting pupils' conceptions of photosynthesis	Using the history of the topic as a novel approach of teaching photosynthesis	Métioui, Matoussi & Trudel, 2018
13-14 yrs	Discussions	Inquiry based approach	O' Connell (2008)
14-15 yrs	Open ended questions	Not available	Ozay and Oztas (2003)
16 yrs	Not available	5E model	Ray and Beardsley 2010
11-16 yrs	Two-tier diagnostic test	Graphic explanations connecting information	Svandova (2013)
14-17 yrs	Open ended, true false and MCQ	Not available	Tekkaya and Balci (2003)
14-15 yrs	Observations	Concept cartoons and argumentation text	Webb, Williams, and Meiring (2008)
13-14 yrs	Two-tier diagnostic test and test of logical thinking	Conceptual change texts, models, discussions	Yenilmez and Tekkaya (2006)
Higher education			
Pre-service teachers	Questionnaire and mind map, interviews	Argumentative text	Ahopelto et al. (2011)
Pre-service teachers	Interviews and questionnaires	Concept cartoons	Birisci, Metin, Karakas (2010)
Pre-service teachers	Observations and interviews	Analogies	Brown and Schwartz (2008)
Pre-service teachers	MCQ questionnaire	Not available	Cakiroglu and Boone (2002)
Pre-service teachers	Interviews	Problem solving activities	Carlsson (2002)
Pre-service teachers	Use of drawings and interviews with pre-service teachers in preparation for secondary education	Making alternative concepts explicit through the use of drawings and professional conversations	Karakaya, Yilmaz & Aka, 2021
Science undergraduate	Drawings and interviews	Not available	Kose (2008)
Pre-service teachers	Use of classical teaching by an expert researcher and higher education teacher complemented with students partaking in a dramatization of the in-depth processes involved in photosynthesis	Dramatization of the various reactions, phases and cycle taking place in photosynthesis at an atomic/molecular level	Mohapatra & Singh, 2015
Science undergraduate	MCQ questionnaire, open ended responses, essays and interviews	Not available	Parker et al. (2012)
Pre-service teachers	Two-tier diagnostic test and interviews	Not available	Partosa et al. (2013)
Science undergraduate	Models, text, role play, discussions, CD-rom	Not available	Ross, Tronson, and Ritchie (2010)
Science undergraduate	Not available	Multimedia CD-rom	Russell, Netherwood, and Robinson (2004)
Pre-service teachers	Not available	Group work and experiments	Sert Cibik and Diken (2008)
Teacher education			
NA	Lesson plans and interviews	NA	Kapyla, Heikkien, and Asunta (2009)
NA	MCQ	NA	Krall, Lott, and Wymer (2009)
NA	Two-tier diagnostic test	NA	Liu and Li (2013)
NA	The design of valid measurement instruments for different dimensions of teacher's PCK in the teaching of photosynthesis	Two valid measurement tools development for examining two components of PCK: teacher's knowledge of students understanding in science and teacher's knowledge of instructional strategies and representations.	Park, S., Suh, J., & Sen, K., 2018.
NA	Two-tier diagnostic test and interviews	NA	Partosa et al. (2013)
NA	Close ended Questionnaire	NA	Yip (2007)

3. FINDINGS

Findings are considered under three headings: (a) the most frequent alternative concepts found, (b) the pedagogical strategies used and (c) the professional supports deployed.

(a) Most frequent alternative concepts in the teaching of photosynthesis

The literature review identified four key problem areas in which students and teachers commonly hold alternative concepts: the location of photosynthesis in the plant, where plants get energy for photosynthesis, where plants get carbon for photosynthesis, and the relationship between cellular respiration and photosynthesis.

Location of Photosynthesis

The first problem was in relation to the location of photosynthesis in the plant, with a frequently held alternative conception that photosynthesis only occurs in the leaves of the plant (Boomer & Latham, 2011). Although, it is true that photosynthesis for the most part occurs in the leaves students and teachers alike needed to comprehend that photosynthesis also occurs in any chloroplast that contains chlorophyll. Labelled diagrams in textbooks were often a source for this misconception (Clegg, 2011; Marmaroti & Galanopoulou, 2006).

Where Plants gets Energy for Photosynthesis

The second problem area in relation to where the plant gets energy, how plants use and store energy. For example, misunderstandings between energy and nutrients included comments, such as: 'Plants obtain their food from the soil', 'Plants are fed in the same way as humans and animals', 'Food for the plants is anything taken in from the environment', 'The soil supplies water and food for the plant' and 'Carbon dioxide, water, fertiliser and minerals are food for the plant' (Deshmukh, 2012; Ekici, Ekici, & Aydin, 2007; Özay & Öztaş, 2003).

While there was awareness that light is necessary for photosynthesis students and teachers were often less certain of its specific role and internal pathways in this regard (Prokop & Fančovičová, 2006). Many students appeared unsure as to how plants used and stored energy (Balci, Cakiroglu, & Tekkaya, 2006; Lin & Hu, 2003), believing that sunlight provides the plant with warmth, and once used this solar energy is either lost or destroyed (Carlsson, 2002; Ekici, Ekici, & Aydin, 2007; Marmaroti & Galanopoulou, 2006). Pre-service teachers have weak knowledge of the conversion of light energy by plants into chemical energy, and the various stages and processes whereby the plant manufactures sugar and releases oxygen to the environment (Karakaya, Yilmaz & Aka, 2021). This diminishes understandings of the role of plants as primary generators of food, their importance in the production of natural products, such as cotton and timber and their role in climate change and wellbeing.

Where Plants get Carbon for Photosynthesis

The third problem was found in relation to the source of carbon. Carbon in the form of carbon dioxide from the atmosphere is taken in by plants, along with water, and used to produce carbohydrates and oxygen. Students may be given different versions of the processes involved and can often appear confused in relation to the pathways involved (Ekici, Ekici, & Aydin, 2007; O'Connell, 2008).

Relationship between Respiration and Photosynthesis

Finally, the fourth problem was found in relation to confusing photosynthesis with cellular respiration. There was some evidence of a tendency to regard cellular respiration as synonymous with breathing (Marmaroti & Galanopoulou, 2006; Mikkila-Erdmann, 2001). Alternative concepts cited in this literature included: 'Photosynthesis is the means by which plants respire', 'Photosynthesis is the respiration of plants in light', 'While photosynthesis in plants is the taking in of carbon dioxide & giving off of oxygen during the day, it is the taking in of oxygen and the giving off of carbon dioxide at night', 'Photosynthesis is the process by which the plant breathes', 'Both processes are solely the kind of gases exchange', 'Plants only respire at night' and 'Respiration is the reverse of Photosynthesis'.

(b) A Multiplicity of Pedagogical Practices

Findings pinpoint a multiplicity of pedagogical strategies used by science teachers to teach for the acquisition of accurate concepts in photosynthesis. This literature showed wide range of pedagogical strategies in the diagnosis, reduction and potential elimination of alternative concepts: such as, two-tier diagnostic tests; textual approaches, such as, refutation texts using various arguments; questioning techniques, forms of observation, models, role plays, and debates; and the use of technology, such as, computer assisted instruction. Interviews and multiple-choice diagnostic tests were found to be the most frequently used pedagogical strategy and had strong support as a valid and viable approach (Dikmenli, 2010). Schönborn & Anderson (2010) showed that conventional multiple-choice tests do not adequately assess student understanding in this regard.

A useful pedagogical approach was to assess how well students explain a concept to someone else (Teichert & Stacy, 2002). Multiple-choice questions validated by asking students to provide a rationale for their answers. This provided a more reliable approach for evaluating students' understanding and identified commonly held alternative concepts (Odom & Barrow, 2006). Two-tier open-ended tests allowed teachers explore student's reasoning patterns but were often found to be time consuming (Voska & Heikkinen, 2000).

Science teachers used multiple pedagogical strategies to confront tensions and challenges in students' unearthing alterative concepts and productively engaging with a pedagogical cycle of meaning making and change (*details with Editor*). For example, the use of good analogies (Brown & Schwartz, 2009) were found to help pre-service teachers engage productively with alternative concepts (Clement & Brown, 2004). Similarly, having students generate concept maps (Brown, 2000; Lin & Hu, 2003; Al Olaimat, 2010) was shown to be successful, particularly if organised in small groupings with authentic communication and opportunities for debate (Broggy & McClelland, 2008; Cassata, Himangshu, & Iuli, 2004; Stoddart, 2006). For the teacher, concept mapping appeared as one way of identifying what students found conceptually challenging (Kern & Crippen, 2008).

Studies used a multiplicity of visual approaches and technologies, and were for the most part consistent with student-led co-inquiry, such as, digital storytelling (Fencott, 2003; Greenwood, 2011; Lim & Lee, 2014), animation and concept cartoons (Akpinar, 2007; Birisci, Metin, & Karakas, 2010; Kestler, 2014; Russell, Netherwood, & Robinson, 2004; Webb, Williams, & Meiring, 2008) and computer software (Çepni, Taş, & Köse, 2006; Kici, 2012). These co-inquiry practices were found to be effective in reducing, if not eliminating alternative concepts (Karamustafaog˘lu et al., 2003). Some studies showed that student achievement increased significantly with the use of computers, computer assisted instruction, as a valid and reliable pedagogical approach (Chang, 2001; Chou & Tsai, 2002).

Refutation text that included elements of argumentation was found to be an effective and sophisticated means of engaging with alternative concepts. Studies indicated that reading refutation text rather than traditional text was more likely to result in conceptual change (Ahopelto et al., 2011; Akpinar, 2007; Balci, Cakiroglu, & Tekkaya, 2006; Mikkila-Erdmann, 2001; Webb, Williams, & Meiring, 2008; Yenilmez & Tekkaya, 2006). Traditional texts often failed to generate the necessary dissonance to stimulate higher-order thinking and generate dissatisfaction with an alternative concept, regarded as an important dimension in the translation, mediation and interpretation processes involved in the acquisition of accurate scientific concepts (Kendeou & Van den Broek, 2008). However, refutation texts alone, while necessary were not sufficient to facilitate deep conceptual change for all students, and some students were found to gain deeper levels of comprehension through visual imagery, such as, videos, demonstrations, hands-on experiments, all found to positively increase the probability of conceptual change (Guzzetti, 2000; Tippett, 2010).

The literature showed that discussions and debates (Balci, Cakiroglu, & Tekkaya, 2006; Yenilmez & Tekkaya, 2006) played a pivotal and vital role in interacting with alternative concepts, engaging students in knowledge acquisition using meaning-making opportunities (Ekici, Ekici, & Aydin, 2007). Co-inquiry approaches to pedagogical practices, between teachers and students and between students, linking concepts (Boomer & Latham, 2011; Domingos-Grilo et al., 2012; O'Connell, 2008; Sharma & Muzaffar, 2012) and creating models (Ray & Beardsley, 2008) proved useful in the acquisition of scientific knowledge.

(c) Professional Supports for Science Teachers

The literature reviewed briefly examined professional supports and structures used to confront the contradictions encountered in real world practice settings and to support teachers' ongoing science education and development in the areas of disciplinary knowledge and pedagogical strategies. In many exemplars, teachers were provided with new meaning-making opportunities with a diversity of co-inquirers, an important dimension of teachers' intellectual engagement with alternative concepts (Ameyaw & Sapong, 2011; Driver, Newton & Osborne, 2000; Keys & Bryan, 2001; *details with Editor*).

Science teachers' professional learning appeared as an important dimension in building a specialist knowledge base for teaching (Burgoon, Heddle, & Duran, 2011). However, the focus was not always based on expansive views of teacher professional learning, from pre-service teacher education to in-career teacher development (Luft, Roehrig, & Patterson, 2003). The literature showed that teachers who identified students' prior schema and concepts were in a better position to support students in the necessary meaning-making interactions required for deep conceptual change and development (Driver et al., 2014).

A vast literature on teachers' specialist knowledge base, called PCK (Pedagogical Content Knowledge), as distinct from the knowledge of scientists has been underway since the work of Shulman in the late 1980s and has undergone several refinements including at a recent international summit in 2015 (Park, Suh & Sen, 2018). While research to date has been mainly exploratory there is nowadays a strong policy imperative to not only measure all dimensions of the PCK pentagon but to demonstrate causality between the assessment and impact of teacher's PCK and student achievement. Park, Suh & Sen (2018) conducted a mixed methods study, using a teacher survey, observations and interviews to arrive at an instrument for two key components for this 'indispensable PCK' in relation (a) knowledge of students' understanding in science and (b) knowledge of the instructional strategies and representations of this knowledge in teaching. Work presented as a critical cornerstone in the design of effective teacher education programs for improving quality and furthering learning.

4. DISCUSSION

In this literature review, we examined alternative concepts in the teaching of photosynthesis, in a timeline between 2000 and 2021, across different sectors, primary, secondary and higher education. Findings indicated the 'problem' of alternative concepts is a complex 'problem' involving teachers' adopting a co-inquiry stance with students for eliciting meaning-making processes and supported by a diversity of co-inquirers. Productive engagement with alternative concepts appears as a necessary and important dimension in students' acquisition of accurate scientific knowledge (Brown & Schwartz, 2008; Carlsson, 2002; Johnstone, 2000). The review showed that science teachers need to encounter conceptual conflict, an 'intellectual perturbation' (Windschitl, 2002, p.140) with a diversity of actors as a necessary if not sufficient approach for acquisition of accurate concepts in the teaching of science and photosynthesis (Asay & Orgill, 2010; Larkin, 2012).

Alternative concepts were mostly found as four problem areas when teaching photosynthesis (Ahopelto et al., 2011; Svandova, 2013). These were concerned with: 1) the location of photosynthesis in the plant, 2) the sources of energy in photosynthesis and 3) the sources of carbon in photosynthesis, and 4) the relationship between cellular respiration and photosynthesis (Boomer & Latham, 2011; Clegg, 2011; Ekici, Ekici, & Aydin, 2007). In several studies, science teachers developed pedagogical strategies to interrogate alternative concepts and to assure improved capability in productive engagements with students (Domingos-Grilo et al., 2012; Johnston, 2005).

Studies of teachers' practices reported a variety of pedagogical strategies, such as: direct observation, interviews, testing and questioning techniques, multiple written and textual approaches, such as, concept mapping and drawings (Akpinar, 2007; Brown & Schwartz, 2009; Kapyla, Heikkinen, & Asunta, 2009; Parker et al., 2012; Partosa et al., 2013), open-ended questions (Deshmukh, 2012; Parker et al., 2012), prediction-observation-explanation (Domingos-Grilo et al., 2012), multiple choice questioning (Balci, Cakiroglu, & Tekkaya, 2006; Cakiroglu & Boone, 2002; Krall, Lott, & Wymer, 2009), two-tier diagnostic tests (Lim & Lee, 2014; Svandova, 2013), concept mapping (Ahopelto et al., 2011), drawings (Kose, 2008), role play and models (Ross, Tronson, & Ritchie, 2010), questionnaires (Boomer & Latham, 2011), conceptual change texts (Mikkila-Erdmann, 2001) and concept cartoons (Ekici, Ekici, & Aydin, 2007). Science lessons which elicited debate and argumentation induced conceptual change through guided processes of dissonance, interaction and meaning-making (Erduran, Simon, & Osborne, 2004; Pine, Messer, & John, 2001; Valanides, 2000).

While the literature review showed pedagogical practices generated processes for deep conceptual change, none of these strategies, on their own, was sufficient to eliminate all alternative concepts. This finding is consistent with our 'good enough' practice approach as an iterative pedagogical cycle of 3Rs: Recognition, Reduction and Reduction (*details with Editor*). The literature review briefly examined science teacher professional learning (Abell, 2008; Luera, Moyer, & Everett, 2005; Sullivan-Watts et al., 2013). Science teachers needed new capability, structures, accurate knowledge and supports to select and justify appropriate co-inquiry strategies (Zhao, 2011). By listening to student's responses, teachers determined if students' understanding were "deep" or "superficial" (Gooding & Metz, 2011; McCarthy & Anderson, 2000; Özmen, 2004). This required appropriate professional supports (Domingos-Grilo et al., 2012; Driver et al., 2014; Lessing & de Witt, 2007). The literature showed teachers accessing networks and productive school-university partnerships to interrogate, challenge and change practices (Feiman-Nemser, 2003; *details with Editor*).

5. CONCLUSION

The literature reviewed in this study, from 2000 to 2021, emphasised the importance of science teachers' role in providing meaning-making opportunities for students to engage in the necessary productive dissonance in the mediation, interpretation and translation involved in acquiring accurate scientific knowledge in science education (Ravanis & Bagakis, 1998). This presents challenges in contemporary classroom settings (Vescio, Ross, & Adams, 2008; Windschitl, 2002) and in teacher education (Karakaya, Yilmaz & Aka, 2021). It suggests that science teachers adopt a number of professional supports in order to teach science for deep conceptual understanding (Johnston, 2005; Sullivan-Watts et al., 2013). However, the up-skilling of biology teachers for the acquisition of accurate subject matter knowledge throughout the full professional lifespan is rarely if ever considered in this literature.

A debate about the need for newer models of co-inquiry with a diversity of co-inquirers has already started in the science education literature (Bevins & Price, 2016; Greca, 2016; Jin et al., 2016). Based on findings from the literature reviewed in this study, the science teacher is required to engage in a co-inquiry practice that realises productive pedagogical engagement with a diversity of co-inquirers, such as, students, peers and teacher educators and with a number of networks for professional support (Boomer & Latham, 2011; Opfer & Pedder, 2011; Ruohotie-Lyhty & Moate, 2014).

The acquisition of accurate scientific knowledge in the teaching of science, and in the teaching of photosynthesis, continues in the literature as an arena of concern in science education. The review clearly shows the complexity of the problem and the necessary affordances for conceptual conflict, intellectual perturbation and (re) construction in the teaching of conceptually challenging topics across all sectors and topics in science education (Asay & Orgill, 2010; Messig & Groβ, 2018; Windschitl, 2002). Our hypothesis of science teaching as a 'good enough' practice cycle of 3Rs (Recognition, Reduction, and Removal) with productive pedagogy approaches and professional knowledge based supports has implications for science teacher learning and is worthy of further research and consideration.

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