Handbook of Research on Science Education

Volume III

Edited by NORMAN G. LEDERMAN,
DANA L. ZEIDLER, and JUDITH S. LEDERMAN

ROUTLEDGE

HANDBOOK OF RESEARCH ON SCIENCE EDUCATION

Volume III

Volume III of this landmark synthesis of research offers a comprehensive, state-of-the-art survey highlighting new and emerging research perspectives in science education.

Building on the foundations set in Volumes I and II, Volume III provides a globally minded, up-to-the-minute survey of the science education research community and represents the diversity of the field. Each chapter has been updated with new research and new content, and Volume III has been further developed to include new and expanded coverage on astronomy and space education, epistemic practices related to socioscientific issues, design-based research, interdisciplinary and STEM education, inclusive science education, and the global impact of nature of science and scientific inquiry literacy.

As with the previous volumes, Volume III is organized around six themes: theory and methods of science education research; science learning; diversity and equity; science teaching; curriculum and assessment; and science teacher education. Each chapter presents an integrative review of the research on the topic it addresses, pulling together the existing research, working to understand historical trends and patterns in that body of scholarship, describing how the issue is conceptualized within the literature, how methods and theories have shaped the outcomes of the research, and where the strengths, weaknesses, and gaps are in the literature.

Providing guidance to science education faculty, scholars, and graduate students, and pointing toward future directions of the field, *Handbook of Research on Science Education Research, Volume III* offers an essential resource to all members of the science education community.

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CONTENTS

PREFACE

The third volume of this handbook builds on the seminal work of its predecessors. Volume I, published in 2007, was edited by Sandra K. Abel and Norman G. Lederman. This original volume provided the field with the first comprehensive synthesis of empirical and theoretical research represented by international scholars. The publication of Volume II, edited by Norman G. Lederman and Sandra K. Abell in 2014, carried this scholarship forward with attention to the coherent synthesis of newer research that informed theory, policy, and practice, as well as attention to emerging fields of research. Now, in 2023, we find ourselves building on the shoulders of our colleagues. In Volume III, edited by Norman G. Lederman, Dana L. Zeidler, and Judith S. Lederman, our aim is to build on past research, getting seminal works down to a science, and infuse it with the most insightful current research, raising it up to a state-of-the art collection of the most relevant themes and research to science education. We have confidence that the work in this volume will enrich our current understandings of theory, policy, and practice, as well as stimulate the growth of new directions of fruitful research that will inform our field and as it continues to evolve with the zeitgeist and tenor of the times.

This venture has not been without its unforeseen challenges on so many levels. The loss of a loving husband, colleague, and close friend made the development and production of this volume, to say the least, a difficult journey. We hereby dedicate this volume to Dr. Norman G. Lederman, who would have been quite disappointed in us had we not brought this work to its natural fruition! In a metaphorical, Aristotelian way, we can think of Norm as an unmoved mover – coalescing so many scholars around the globe to contribute their time and energy to something he deemed critical to the field. To partake in this venture, with the collective goal of promoting human flourishing through the exercise of virtues of character and the quest for scientific literacy, is Norm's legacy. Volume III is dedicated to you, Norm!

Of course, much of the development of this book took place as all of us confronted the ravishing global effects of COVID-19, and the many variants that followed. Many of the section editors and authors were faced with life-altering decisions about family, friends, professional colleagues, and rethinking how to effectively educate in the absence of the sociocultural contexts we had taken for granted. There may be topics that the reader would wish were included but could not be because of the personal hardships confronting all of us. However, it may count as a minor marvel that so many international scholars persevered to contribute to this volume, highlighting contemporary and emerging research perspectives. It may have taken a bit longer to bring this current project to conclusion than originally anticipated. We are grateful for the understanding and dedicated efforts of all who contributed to this collective endeavor, and we are confident that Volume III represents a compendium of the best global research lines impacting science education research.

The research in this volume is presented in six sections representing major themes in current research. They are as follows:

Section I. *Theory and Methods of Science Education Research*
Section Editor: William Boone, Miami University

Section II. *Science Learning*
Section Editor: Richard A. Duschl, Southern Methodist University

Section III. *Diversity and Equity in Science Learning*
Section Editors: Cory A. Buxton, Oregon State University, and Okhee Lee, New York University

Section IV. *Science Teaching*
Section Editors: Jan van Driel, University of Melbourne, and Charlene Czerniak, University of Toledo

Section V. *Curriculum and Assessment in Science*
Section Editors: Bronwen Cowen, The University of Waikato, Hamilton, and Anders Jonsson, Kristianstad University

Section VI. *Science Teacher Education*
Section Editor: Saouma Boujaoude, American University of Beirut

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19

TEACHING BIOLOGY

What Research Says

Hernán Cofré, Claudia Vergara, David Santibáñez, Paola Núñez, and William McComas

Introduction

Biology education, a field of study that focuses attention and research on effective instruction in the life sciences, is also known as the didactics of biology in parts of Europe (McComas et al., 2018; Reiss & Kampourakis, 2018) and South America (Cofré et al., 2021). Global climate change, biological evolution denial, maintenance of human health issues, the need of sustainable agriculture, sex education, and the emergence of and reaction to infectious diseases are some vital themes that require people around the globe to achieve high levels of practical biological literacy. As the COVID-19 pandemic has shown, many politicians, journalists, students, and members of the public alike fail to understand basic biological concepts and likewise misunderstand how science itself functions, which in turn has led them on many occasions to make poor decisions about their own health and the well-being of the population at large (Dillon & Avraamidou, 2020). So, while we feel it unnecessary to make the case that biology is a vital discipline of science, we are compelled to ask if the huge number of studies conducted in the field of biology education have done or might potentially do something to improve teaching and public communication of vital and interesting content with the field of biology effectively targeting misconceptions of life science content while contributing to enhanced learning outcomes of students (McComas et al., 2018). A first step to be able to answer this question is to try to review, systematize, and critically analyze this large amount of scientific production. In this chapter, we continue the work started in previous handbooks and that was conducted recently by Kampourakis and Reiss (2018) and their many co-authors. Thus, we have reviewed trends and issues in biology teaching within the science education literature broadly, with some additions, such as the work of McComas et al. (2018), who recently considered "grand challenges" in biology education.

In the last decade, there have been important developments in biology education research, which may be corroborated with the publication of books on specific topics of learning and teaching biology, such as *Multiple Representations in Biological Education*, edited by Treagust and Tsui (2013); *Fostering Understanding of Complex Systems in Biology Education*, edited by Ben-Zvi Assaraf and Knippels (2022); and *Critical Thinking in Biology and Environmental Education*, edited by Puig and Jiménez-Aleixandre (2022). There have also been books dedicated to the teaching and learning of specific aspects of biology, such as *Evolution Education Re-considered*, edited by Harms and Reiss (2019), or *Genetics Education*, edited by Haskel-Ittah and Yarden (2021). In the same vein, there exists literature reviews on the teaching of genetics (Stern & Kampourakis, 2017), teaching and learning evolution

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(Glaze & Goldston, 2015), and those targeting an understanding of human biology (Peart, 2022). However, no single article or book chapter has systematized the research within biology didactics of the last decade (but see Kampourakis & Reiss 2018; Lazarowitz, 2014).

Therefore, we are pleased to provide a synthesis of what is known about research in biology teaching and learning with implication for how to improve biology understanding among students. Through our review of the research literature and the recommendations offered we hope to propose elements that may lead to the development of the pedagogical content knowledge (PCK) of biology teachers and highlight the most urgent avenues through which to continue advancing research on biological education. We are pleased to join the other 36 chapters in this handbook as one of four focused directly on a scientific discipline (chemistry, physics, biology, and earth sciences and astronomy).

The Nature of Biology as a Science

Erwin Schrödinger, in his landmark book *What Is Life?* (1946), defines the distinctiveness of the science of biology by stating that living matter works "in a manner that cannot be reduced to the ordinary laws of physics" (p. 76). On the other hand, Mayr (1996) proposes that biologists typically follow several distinct approaches to understanding complex biological phenomena (see also Peterson, 2020). In fact, Cleland (2020) makes a distinction between biologists working from historical perspectives (e.g., evolution, astrobiology, biogeography) and those engaged in experimental work (e.g., physiology, cell biology), and she proposed that the methods used by historical biology are as valid as those of experimental biology, because each practice is designed to exploit the information that nature makes available to them (see also Mayr, 1996). Furthermore, biology has been recognized as including both induction and deduction within its methods of generating knowledge (Marquet et al., 2014; Mayr, 1996; Peterson, 2020), and the progress in the field comes from the tension between empiricism and theory and the contribution of descriptive and explanatory investigations (Marquet et al., 2014).

However, biology not only has a unique focus (the living world) that distinguishes it from other sciences, but it also makes use of philosophical principles shared with other sciences but in interesting ways. For instance, laws or generalizations in some sciences are often seen to function invariably, but in biology it is to see these generalizations function more as probablities rather than the absolutes seen in the "hard" sciences. But this does not mean there are no laws in biology, just that they are nuanced. Furthermore, evolutionary biologist Ernest Mayr (1996) also reminds us that the way in which biology studies "the living" differs from that of other sister sciences, such as chemistry and physics. Just to name a few particularities with respect to biological research, Mayr includes the importance of probability, teleology, anthropomorphism, pluralism, emergence, and historical narration (Mayr, 1996). Furthermore, McComas (2018a), who takes the position that there are many elements of the nature of science tie all sciences together, highlights four philosophical aspects that can be interesting for discussion in biology class because they are somewhat unique in biology when compared with the "hard sciences", namely, reductionism, typology, determinism, and the challenges of universality. Therefore, all these features of biology research and biological knowledge could have explicit consequences for biology education (Kampourakis, 2013) and make discussions of the science of biology rich and nuanced.

One consequence of a study of biology is that it is a perfect environment for students to learn about the nature of science (NOS) (Kampourakis, 2013; Lederman, 2018; McComas, 2007, 2018a, b). Additionally, it is possible to propose that understanding biology necessarily implies understanding the nature of science, as many alternative ideas or myths about NOS can directly impact the understanding of biological concepts (e.g., evolution as "just a theory") (Scharmann, 2018) or biological disciplines (e.g., ecology as a less exact science because it does not conduct experiments) (Korfiatis, 2018). The second consequence is that biological instruction can include much space for argumentation and the review of socioscientific issues (e.g., Jiménez-Aleixandre & Evagorou, 2018; Korfiatis, 2018). Finally, because inquiry activities in secondary science classrooms are heavily weighted toward experimentation, understanding the diverse methodologies that are present in biology today (e.g., the distinction between experimental and historical biology) could improve the diversity of scientific methodologies represented in the science classroom and more accurately represent the science of biology (Gray, 2014).

Research About Teaching and Learning in Biological Content Areas

Different proposals for the content to be included in biology have coincided with the recognition that many are based on "core concepts" or "big ideas" about biology or life science (e.g., Duncan et al., 2017; Harlen, 2010; Millar & Osborne, 1998), which usually include cell, inheritance, evolution, and ecosystems. These big ideas also parallel many reports of research in biology education (Kampourakis & Reiss, 2018). However, the issue of the functioning and regulation within organisms, whether at the cellular or multicellular level, and their relationships with development, reproduction, nutrition, and health are ordered in a much more diverse way. For example, Kampourakis and Reiss (2018) review this topic in separate sections, such as human biology, reproduction and sexuality, development, and health and disease. Therefore, to synthesize both the literature on research in teaching biology and the most coherent organization of this content, in the following sections, we report our review of the research on teaching and learning of biology in six main "shown to be of major interest" among researchers, namely, cell, metabolism, human biology, genetics and inheritance, ecology, and evolution.

Considering Trends in Research on Biology Education

In this section, we will summarize an exploratory-descriptive analysis of trends in biology education research between March 2010 and March 2022. For this purpose, we have analyzed articles with empirical data published in five prominent international science education journals, one of which is dedicated specifically to biology education. These include the *Journal of Biological Education* (*JBE*), and the other four devoted to science education in general: *Journal of Research in Science Teaching* (*JRST*), *Research in Science Education* (RISE); *Science Education* (*SE*), and the *International Journal of Science Education* (*IJSE*). The entire abstract of the publication was reviewed to corroborate its status as empirical research on a biology education topic. Our intention with the review of these five journals is not to assume that it is a representative sample of all the research in the field, and certainly one limitation of our review is that interested research in biology pedagogy may well have been published outside our five journals and associated resources. However, our goal is to guide our analysis of the most important trends that we and other scholars in the field have recognized (e.g., Harms & Reiss, 2019; Haskel-Ittah & Yarden, 2021; Kampourakis & Reiss, 2018; McComas et al., 2018; Puig & Jiménez-Aleixandre, 2022; Ben-Zvi Assaraf & Knippels, 2022). In addition, the subsequent analysis in the next sections will not be restricted to the studies reported in these five journals, but we will include all those investigations that seem relevant to us to create a more coherent and meaningful synthesis.

Accordingly, 478 articles were recognized, which we classified into seven categories: genetics and inheritance, evolution, ecology (including plant biology), human biology (including physiology, development, and reproduction), cellular biology, metabolism (including also molecular biology), and general biology (studies that include a combination of the previous categories). In terms of the total articles, the discipline with the greatest research development appears to be evolution and ecology education (Figure 19.1). Importantly, the teaching of the cell, metabolism, and human biology have a low number of research studies compared to their important curriculum ubiquity and their great diversity of topics. On the other hand, the topics about science education that were more frequently identified were evolution and ecology.

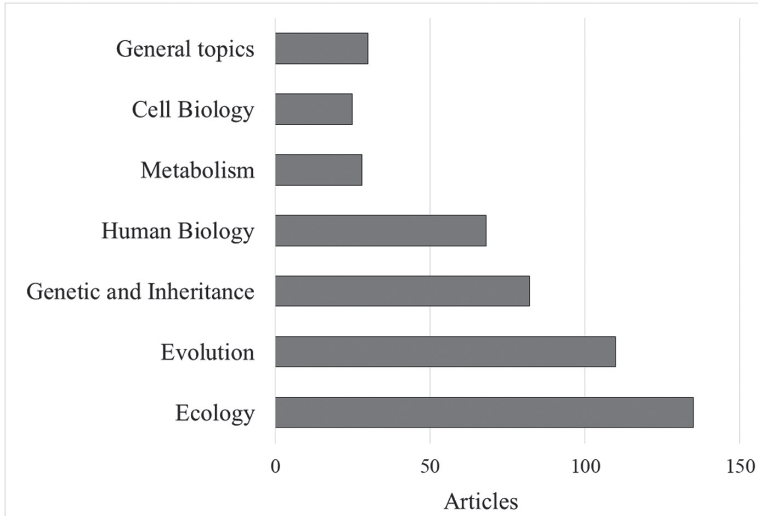

Figure 19.1 Number of articles assigned to any of the seven areas of biology education analyzed in this chapter. The general biology category included some very specific topics that were not assigned to any of the other areas (e.g., astrobiology) or were works that included more than one of the topics analyzed or the teaching and learning of biology in general was analyzed (e.g., initial education of biology teachers).

Research in Teaching and Learning Evolution

Evolution is one of the most studied topics within biology education (Figure 19.1), including more than 100 research articles published between 2010 and March 2022 in the five journals analyzed. This is fitting because evolution is both a difficult subject to teach and yet is the foundation for an understanding of biology.

Research literature in this topic includes specific ideas to teach about evolution in school settings, and what the most effective sequence should be when presenting this content to students. Some researchers have suggested that given the challenge faced by students in understanding the origin of species (macroevolution) through microevolutionary processes, such as natural selection, it might be convenient to review natural selection first and then move on to the processes of speciation and extinction (Nehm, 2018; Scharmann, 2018). For example, there are research results that show young students (5–8 years old) can understand natural selection (e.g., Emmons et al., 2016; Frejd et al., 2022). Another topic of discussion is the efficacy of reviewing inheritance and variability issues with students either before (Mead et al., 2017) or together with evolution issues (Homburger et al., 2019). Furthermore, there is research evidence that learning is benefited if evolution is included in biology curriculum as a central and integrating theme, instead of another isolated unit of content reviewed only after all other biological content has been covered (Pinxten et al., 2020). In a recent comparative study between university freshmen from Flanders, Belgium, and the Netherlands, Pinxten et al. (2020) found that Dutch graduates obtained a significantly higher score than Flemish graduates in a validated questionnaire about knowledge of natural selection, but the relative frequency of alternative conceptions was comparable in both student groups. On the other hand, additional international research has described the topics, depths, and emphases in which evolution is portrait in national standards (see Deniz & Borgerding, 2018, for a review). For example, it has been described that in France eight-year-old children learn about biodiversity, then about the classification of organisms from an evolutionary point of view, and finally, they learn about human evolution and evolutionary mechanisms (Quessada & Clément, 2018). In contrast, in other countries, such as Mexico, Germany, and South Africa, evolution is approached in a fragmented way, and the content is only in secondary school (Deniz & Borgerding, 2018). On the other hand, in terms of content topics, there are certain cross-cutting topics, such as adaptation or natural selection, that appear in much research, while other topics, which have been reported to be important in evolutionary education research, are less frequently investigated, as is the case for human evolution (e.g., Bravo & Cofré 2016; Pobiner et al., 2018) and phylogenetic relationships (Friedrichsen et al., 2016) (see also Table 19.1).

Learning Evolution

On the issue of student learning, researchers in evolution education have included a great diversity of topics (Table 19.1). Regarding the topic of alternative ideas, in recent years, the study of students' thinking about natural selection has moved from the identification and classification of alternative ideas (e.g., Cofré et al., 2016; Nehm, 2018) to a description and understanding of how this emergent

Table 19.1 Topics of Science Education and Content Present in the Studies Reviewed Across Five Science Education Journals Between March 2010 and March 2022 Targeting Evolution. The Concepts Are Ordered From Highest to Lowest Frequency.

Pedagogical Topics	*Disciplinary Topics*
Learning	
Alternative conceptions	Natural selection
Learning progression	Macroevolution
Conceptual change	Phylogenetic tree
Tree thinking	Deep time
Students' interests, knowledge, or reasoning	Origin of life
Ontological conceptual change	Human evolution
Indigenous knowledge	
Self-explanations	
Statistical reasoning	
Instructional strategies	
Argumentation	
ICTs, simulations, and visualization	
Teaching outside of school	
Models and representations	
Inquiry and practical work	
Conceptual maps	
Other issues	
Acceptance	
Assessment about knowledge and acceptance	
Nature of science	
Pedagogical content knowledge	
Teacher's attitude, beliefs, or knowledge	
Curricular issues	

process (Chi et al., 2012a) is explained (Evans et al., 2012; Nehm & Kampourakis, 2016; Parraguez et al., 2021; Zabel & Gropengiesser, 2011). For example, some studies have shown that in the transition between need-based reasoning and a true natural selection explanation, high school students mostly use the concept of variation and differential survival to explain evolution by natural selection (Evans et al., 2012). In accordance with this, Nehm and Kampourakis (2016) propose recognizing not only the different components of students' thinking (e.g., scientific and nonscientific elements) but also their structure and coherence (see also Nehm, 2018). After analyzing the composition of students' explanations, Nehm and Kampourakis (2016) established that a student can combine need-based reasoning with the scientific ideas of mutation and inheritance to build a mixed response (Cofré et al., 2016, 2018a, b; Parraguez et al., 2021). In a recent study, Parraguez et al. (2021) show that while students exhibit different trajectories of thinking that are idiosyncratic and context dependent, some patterns are also recognized, such as the proposal of teleological explanations by students; the initial use of key concepts, such as mutation, survival, and differential reproduction during the trajectories; the abundance of mixed explanations during and at the end of the instruction; the low coherence (*sensu*, Nehm & Kampourakis, 2016) in the structure of explanations, both in time and through the different contexts analyzed; and the greater frequency of a learning sequence that starts with the absence of explanations for evolution through intentionality and ends with explanations that are more focused on natural selection. Another line of research about students' thinking corresponds to analyses of students' alternative conceptions about natural selection focus on "the need of ontological conceptual change" (Chi et al., 2012a, b; Chi 2013; McLure et al., 2020). According to this approach, students understand the "population process" of natural selection as an "ontological event" in which change is driven and occurs at the individual level. Therefore, there is knowledge (students vs. scientist) belonging to different ontological models (Chi, 2013). In a recent quasi-experimental study, McLure et al. (2020), show significantly greater conceptual change in an experimental class (which focused on making students' aware of their currently held conceptual model and providing opportunities to transfer the understanding between models) than in a comparison class, in which students' written explanations adopted many aspects of the scientific ontological model. In the same vein, some learning progressions to support evolution education have been proposed (e.g., Evans et al., 2012; Wyner & Doherty, 2017; Zabel & Gropengiesser 2011). For example, Evans et al. (2012) suggested that understanding natural selection requires a "radical" conceptual change approach in which students must switch from a naïve psychological explanation that uses an anthropomorphic argument to a naturalistic explanation that avoids purpose and endorses the idea that species can undergo significant change. To address this monumental challenge, the authors developed a learning progression that includes four levels: (1) anthropomorphic reasoning external agent, (2) want-based reasoning intrinsic cause, (3) need-based reasoning, (4) natural selection, and (5) evolutionary origins. Other emerging studies on student learning include tree thinking (e.g., Seoh et al., 2016), Indigenous knowledge (Sánchez-Tapia et al., 2018), self-explanations (Neubrand & Harms 2017), and statistical reasoning (Fiedler et al., 2019) (see Table 19.1).

Teaching Evolution

In the topics of instructional strategies, argumentation, NOS, and inquiry, as well as the use of context and examples close to the daily lives of students, can have a good result in challenging alternative ideas and achieve conceptual change (e.g., Glaze & Goldston, 2015; Harms & Reiss, 2019; McLure et al., 2020; Núñez et al., 2022; see also Table 19.1). For example, Scharmann (2018) proposes that two things should be taught about the NOS in evolution classes, namely, that scientific theories are powerful tools for the advancement of science and that theories are applied to the field of science but not to other areas, such as faith or religion. If these two things are clear, this should lower the anxiety and discomfort levels of students who think that evolution is "against" their beliefs. On the other hand, students become interested when they face evidence of evolution in animal and plant populations by analyzing data (tables or graphs), watching documentaries of the work of real-life scientists, or simply reading news about the effect of evolution on their lives. In our experience, many of the students feel "astonished" to know that these changes are real and that there are many scientists who have contributed to the theory of evolution nowadays (Núñez et al., 2022). The application of this research coincides with a need that biology teachers in the United States have declared when they are asked what they lack to carry out better evolution classes, i.e., know research that uses real data and/or living organisms and have contemporary evolution examples (Friedrichsen et al., 2016). This approach of having students work with evidence goes hand in hand with other teaching strategies or approaches, such as inquiry, active learning, argumentation, and the review of examples of evolution in daily life. Another important element suggested is to incorporate examples of human evolution through inquiry-based teaching. Although the resistance to learning about human evolution is usually higher than the resistance to learning about evolution in other organisms, this approach has been shown to have good results in improving the interest and attitude of secondary students toward evolution, as well as the understanding of relevant aspects of the theory (e.g., Bayer & Luberda, 2016; Pobiner et al., 2018). On the other hand, although the use of models and representations is a recognized and widely used strategy in the teaching of biology, there is evidence that high school students may not learn the concept of natural selection using cut-and-paste activities, candy, or toothpicks to simulate within simulations (Sickel & Friedrichsen, 2012). In this work, through interviews with students after their participation in the modeling activity, the authors realized that students often do not understand the complexity of the natural selection process by engaging in an activity that is so far from reality. Therefore, a first step is not to present this as a practical activity or laboratory but simply as a model, analogy, or simulation (Sickel & Friedrichsen, 2012). Ultimately, what has been suggested is that students can use the models as tools for investigating and exploring natural phenomena and not simply as games. Malone et al. (2019) found in a study where population changes in real lizard species were simulated that the students of seven teachers who used the simulations gained a greater understanding and decreased their visions of need more significantly than did the students of the seven teachers who did not use this strategy.

Other Issues in Evolution Education

Finally, in other issues related with evolution education, the students' acceptance of the theory of evolution by natural selection (e.g., Cofré et al., 2018a, b), the development of assessment instruments for measuring the knowledge about natural selection (e.g., Nehm et al., 2012), the acceptance of the theory (e.g., Ha et al., 2019; Romine et al., 2017), and the different aspects of the knowledge about natural selection (e.g., Cofré et al., 2017; Dotger et al., 2018), feelings and beliefs (e.g., Hawley & Sinatra, 2019; Larkin & Perry-Ryder, 2015) of preservice and in-service biology teachers have been major topics in the field in the last decade (Table 19.1). For example, with respect to the issue of PCK targeting evolution, qualitative studies have been focused on describing some component of PCK of evolution, such as the learning of the students (Lucero et al., 2017), and others have studied the development of PCK of evolution in in-service (e.g., Bravo & Cofré 2016) and preservice biology teachers (Sickel & Friedrichsen 2018). An interesting aspect of this research is that both were qualitative studies that used the Magnusson et al. (1999) model to understand the change of the PCK component during a professional development program (e.g., Bravo & Cofré 2016) and initial education (Sickel & Friedrichsen 2018). In both studies, an improvement in PCK of evolution was described using content representations (CoRe) and PaP-eRs (pedagogical and professional experience repertoires) and the expansion, integration, and core concepts framework, respectively. On the other hand, quantitative instruments for assessing PCK in evolution have also been developed recently (Großschedl et al., 2019; Becerra et al., 2022).

In summary, evolutionary education is one of the most vigorous areas of research within biology education, both in student learning and teaching, and there is even a large development of studies on different aspects of professional teacher education in this content (e.g., Sickel & Friedrichsen, 2013). Nevertheless, there are still frontiers to explore, especially around teaching and learning of evolutionary content other than a mechanistic view of natural selection and how the integration of this content with other areas of biology might lead to a more holistic learning of life sciences.

Research on Teaching and Learning Genetics and Inheritance

Due to its central importance to understanding biology and other issues present in our everyday lives (e.g., genetic testing, genetically modified food, gene therapy, forensic investigations), coupled with the natural curiosity that students have about inheritance itself, the field of genetics and inheritance is a central focus of biological literacy (e.g., Boerwinkel et al., 2017; Duncan et al., 2017; Stern & Kampourakis, 2017) and one of the most vigorous branches of research within biology education (Figure 19.1) (see also Haskel-Ittah & Yarden, 2021). An important part of this literature is focused on what should be taught and in what sequence (Table 19.2), even recognizing three conceptual

Table 19.2 Topics of Science Education and Content Present in the Studies Reviewed Across Five Science Education Journals between March 2010 and March 2022 Targeting Genetics and Inheritance. The Concepts Are Ordered From Highest to Lowest Frequency.

Pedagogical Topics	*Disciplinary Topics*
Learning	
Alternative conceptions	Molecular genetics
Learning progression	Human genetics
Conceptual change	Genetic determinism
Students' attitudes and beliefs	Biotechnology and genetic engineering
Students' moral reasoning	Mendelian genetics
	Genetically modified organisms
Instructional strategies	Three models of inheritance
Argumentation	Meiosis and cytogenetics
SSI and critical thinking	Genetic variation
ICTs, simulations, and computer-based games	ADN and protein synthesis
Models and representations	
Inquiry-based instruction	
Lab and practical work	
Authentic research practices	
Teaching outside of school	
Other issues	
Curricular issues	
Pedagogical content knowledge	
Teachers' attitude, beliefs, or knowledge	
Textbook analysis	
Development and validation of assessment	

models in genetics (meiosis, Mendelian inheritance, and molecular genetics) (e.g., Freidenreich et al., 2011). In addition, some authors have proposed that the teaching of genetics should include a change in the curricular sequence, i.e., starting with the teaching of quantitative traits (e.g., height in our species), which are typically explained by the action of more than one gene and by environmental factors, and then moving on to simpler traits (Dougherty, 2009). Indeed, this geneticist and educator believes:

> Given what we know about the deficiencies in the current curriculum and student understanding and armed with a better understanding of the genetics of complex traits, there is no longer a compelling reason to maintain the historical sequence of our curricula.
>
> *(Dougherty, 2009, p. 8)*

The same conclusion is reached as result of a Delphi study conducted by Boerwinkel et al. (2017), which proposes that Mendelian genetics should be presented in the curriculum as "the exception rather than the rule". These proposals do not mean that single gene trait inheritance is inaccurate but imply that this view should be included with caution to avoid reinforcing the misleading idea of one-gene-to-one trait is the norm (Kampourakis, 2021). According to Wolfe (2012), there is a curricular oversimplification of the gene–trait relationship as being one-to-one (including in biology textbooks); from its inception, the chromosomal theory of inheritance has been presented as a complex process of interactions between various genes and the environment.

Learning Genetics and Inheritance

There are multiple challenges to understanding genetics, which has been described as one of the most complex topics for students to understand (Aivelo & Uitto, 2021; Bahar et al., 1999; Gericke & El-Hani, 2018). Some reasons given by a sample of English students and teachers for ranking genetics as the most difficult content to understand within biology were the complicated language, including terms such as allele, gene, and homologs; the mathematical content of Mendelian inheritance exercises; and the complexity of the process of meiosis and its similarity to mitosis (Bahar et al., 1999). In the issue of students' learning and thinking, many alternative ideas about inheritance and variation have been reviewed (Gericke & El-Hani, 2018; Haskel-Ittah & Yarden, 2021; Stern & Kampourakis, 2017), for instance, students often have (1) difficulty distinguishing between genotype and phenotype; (2) a deterministic view of genes associated with racism; (3) a lack of knowledge about where genes are located or their relationship to DNA, chromosomes, and alleles; (4) a tendency to attribute specific and stereotyped functions to a gene (e.g., intelligence gene); (5) associating dominant alleles with those most commonly found in the population; (6) making the assumption that all inheritance is monogenetic; and (7) a failure to recognize the role of biological variation (see also Aivelo & Uitto, 2021; Alred et al., 2019; Castéra et al., 2008; Castéra & Clement, 2014; Krüger & Santibáñez 2021; Stern et al., 2020). Of these alternative ideas, genetic determinism seems to be a main obstacle to achieving genetic literacy because it is widely observed in not only students' alternative ideas but also school texts (Castéra et al., 2008) and teachers' thinking (Castéra & Clement, 2014). In the latter study, which includes 8,285 in-service and preservice teachers from 23 countries, the findings show that genetic determinism is present in relation to both individuals (e.g., to justify intellectual likeness between relatives) and groups of humans (e.g., to justify gender differences or the superiority of some human groups). The study also shows that more determinism is present among African and Lebanon teachers than in teachers from Brazil, Australia, and European countries. Research in genetics education has also shown that there are at least five views of the gene presented in school textbooks, which range from a traditional view that assumes the inheritance of characteristics to a view that proposes multiple means of gene regulation (Gericke & Hagberg, 2007). Considering this background, a migration from a deterministic conception of the gene to a more realistic view has been proposed, in which the gene is understood as a developmental resource, i.e., a molecular entity that provides proteins by transcription and translation through biosynthesis processes, in which its expression is variable and subject to complex relationships (Moss, 2003).

With respect to the development of a learning progression in genetics and inheritance, studies conducted by Ravit Duncan and colleagues (Duncan et al., 2009, 2016) have proposed that the teaching of genetic inheritance should start from basic or primary education to successively incorporate new concepts and greater depth regarding both the inheritance of traits and the variability of traits (see also Todd et al., 2017, 2019). According to Duncan et al. (2009), there is sufficient information on the teaching and learning of genetics to propose that students from sixth grade onward can understand basic aspects of molecular genetics, which suggests that the classical, meiotic, and molecular models can be taught from this same level through the end of secondary school. Duncan et al. (2016) propose that reviewing aspects of molecular genetics before classical genetics results in better learning outcomes than reviewing classical Mendelian inheritance and then following up with molecular genetics. This two-year study, which included 117 seventh-grade students from two schools, finds a positive correlation between students' performance after learning molecular genetics and their understanding at the end of the next unit that includes Mendelian genetics. However, the authors state that additional studies are required because the learning achieved in the classical sequence is also significant, only to a lesser degree. A similar result has been found by Deutch (2018) at the university level. In this study, a comparison of two sequential courses with similar groups of students indicates that there are no statistically significant differences in exam scores or final grades between the two approaches (i.e., Mendelian genetics or molecular genetics first). Therefore, it is likely best to include a progression of the three models over time to create the best context for understanding abstract concepts, such as alleles, heterozygotes, or genes.

Teaching Genetics and Inheritance

In the topics of teaching genetics, multiple strategies have been developed to improve students' understanding at different educational levels, including scientific inquiry, the use of dramatizations and analogies, the use of computer programs for problem solving, modeling, computer-based game, socioscientific questions, and argumentation (e.g., Donovan et al., 2019; Duncan et al., 2011; Gericke & El-Hani, 2018; Jiménez-Aleixandre & Evagorou, 2018; Puig & Jiménez-Aleixandre, 2011; Puig et al., 2017; Sadler et al., 2015; Schwartz et al., 2021; Smith et al., 2009; Tal et al., 2011; see also Table 19.2). For example, discussion or argumentation among peers has been used in many studies to challenge the alternative idea of genetic determinism (e.g., Donovan et al., 2019; Jiménez-Aleixandre et al., 2000; Puig et al., 2017; Zohar & Nemet, 2002). For example, in a case study that involved tenth-grade students ($n = 20$) engaged in the practices of modeling and argumentation, Puig et al. (2017) show that the use of evidence as part of argumentation helps students to relate the three worlds of knowledge (i.e., theory, representation, and natural world). Using a teaching sequence comprising eight tasks on genetics and evolution of human diseases, the authors conclude that a relationship exists among the number of interactions between modeling and argumentation, the connections between the worlds of knowledge and students' capacity to develop a more sophisticated representation. In a quantitative study focused on genetic determinism and racism, Donovan et al. (2019) study three different samples, namely, 8th–9th-grade students ($n = 166$), 9th–12th-grade students ($n = 721$), and adults ($n = 176$), with the aim of studying the relationship between learning scientific information about genetic variation both within and between US census racial groups and a reduction in genetic essentialism and racial stereotyping in participants. The authors found that the participants' systematic analysis of human genetic variation data helped them develop the ability to critique essentialist genetic beliefs about race. Donovan et al. (2019) report that learning about the social and quantitative complexities of human genetic variation research could prepare students to become genetically literate. Furthermore, Aivelo and Uitto (2021) have recently described that teaching approaches that place an emphasis on a one-to-one relationship from genes to traits or textbooks with stronger Mendelian emphasis result in students with stronger beliefs in genetic determinism, while teaching approaches that emphasize epigenetics and complex human traits lead to lower genetic determinism.

Other Issues in Genetics Education

Finally, about professional development and practices for the teaching of genetics, there are several studies that have developed instrument for assessing PCK (Großschedl et al., 2019), described the integration of the components of PCK of biology teachers (e.g., Park et al., 2012), as well as the decisions they make regarding the use of different teaching strategies (e.g., use of multimodal representations of molecular genetics concepts to engagement students in critical discussion [Nichols, 2018]), and specific content and context to teach genetics at school (e.g., including human context or not [Aivelo & Anna Uitto, 2019]) (Table 19.2).

In summary, genetics education is represented in a significant line of research with a long tradition within biology education, which includes a large variety of content and strategies to develop student learning. Currently, it seems interesting to continue advancing in the investigation of how the understanding of abstract concepts that are far from daily life can lead to scientific literacy and citizenship (e.g., Donovan et al., 2019, 2020; Upadhyay et al., 2020).

Research on Teaching and Learning Ecology

Research in ecology teaching and learning is one of the most studied topics within biology education (Figure 19.1), including topics such as global climate change, ecosystems, food chain, carbon cycling, flow of matter and energy, and the loss of biodiversity (Korfiatis, 2018; Table 19.3). However, the topic of ecology is sometimes avoided or not covered by biology teachers due to time constraints and because this topic is often included at the end of many biology books, thus falling late in the school year when time is lacking (McComas, 2003). In the same study, McComas (2003) found that there are important concepts within the discipline that are either absent or presented at low frequencies, such as biodiversity, succession, biospheres, conservation issues, or the relationship between ecology and evolution.

Learning Ecology

On the issue of students' learning, research literature has showed that some fundamental concepts are poorly understood by students, including the species idea, population, ecosystem, energy flow, biodiversity, food chain, equilibrium, greenhouse effect, and the causes of climate change (e.g., Anderson & Doherty, 2017; Bermudez & Lindemann-Matthies, 2020; Jordan et al., 2009, 2014; Korfiatis, 2018; McComas, 2002; Reinfried & Tempelmann, 2014; Rousell & Cutter-Mackenzie-Knowles, 2020; Varela et al., 2020). Therefore, it is unsurprising that many high school students face great challenges to understand more complex concepts, such as the flow of nutrients and energy, at different biological levels (Jin & Anderson 2012; Mohan et al., 2009). According to the study reported by Jin and Anderson (2012), in a group of nearly 2,000 students between the 4th and 11th grades, less than 10% achieved a high level of understanding (Level 4) in a learning progression about matter cycles and energy flows. Other popular alternative ideas include the idea that plants obtain their food or energy from the soil, that energy is reused by plants, and that matter and energy cycle in the same way (e.g., Anderson & Doherty, 2017; Harm & Bertsch, 2018; Wernecke et al., 2018). Similarly, research literature has shown that students of all ages hold a great number of alternative

Table 19.3 Topics of Science Education and Content Present in the Studies Reviewed Across Five Science Education Journals Between March 2010 and March 2022 Targeting Ecology. The Concepts Are Ordered From Highest to Lowest Frequency.

Pedagogical Topics	*Disciplinary Topics*
Learning	
Alternative conceptions	Climate change and global warming
Learning progression	Ecosystem
Conceptual change	Environmental issues
System thinking	Biodiversity
Students' interests, beliefs, or attitudes	Plant biology
Students' drawings	Carbon cycling
	Food chain and food web
Instructional strategies	Energy and matter flow
Argumentation	Marine environment
SSI	Animal ecology
Teaching outside of school	Species interactions
Tics and simulations	
Inquiry-based instruction	
Models and modeling	
Lab and practical work	
Other issues	
History and nature of science	
Professional development programs	
Teachers' attitude, beliefs, or knowledge	
Curricular issues	

ideas in understanding other models of natural ecosystems, such as the food chain, food webs, and the food pyramid (Bravo-Torija & Jiménez-Aleixandre, 2012; Butler et al., 2015; Korfiatis, 2018; McComas, 2002). Some of these alternative ideas include notions like (1) the largest organism in a food web is always the top predator and that the smallest is the producer, (2) changes in populations in a food chain occur only in a bottom-up manner and not in a top-down process, (3) natural resources are infinite and therefore species can easily shift from one resource to another, (4) nature tends to balance itself, and (5) the meaning of arrows in a food chain or food web are confused and interpreted as going from predator to prey (Anderson & Doherty, 2017; Gotwals & Songer, 2009; Hovardas & Korfiatis, 2011; Korfiatis, 2018).

Additionally, students seldom recognize feedback loops and indirect relations in ecosystems (Hogan, 2000); while they are aware of structures, students seldom reason about the behaviors and functions of complex systems (Hmelo-Silver et al., 2007). All these learning challenges can prevent students from making important decisions in their lives and preferring more sustainable ways of life. For example, they do not understand that it is more efficient to feed or raise organisms at lower levels of the pyramid or the food web (for example, it is more efficient to eat small pelagic fish than top predators, such as salmon or tuna) (Bravo-Torija & Jiménez-Aleixandre, 2012). Regarding the issue of middle and secondary students' conceptions of biodiversity, literature from very different countries supports the same pattern. For example, Menzel and Bögeholz (2009), in a sample of 16–18-year-old Chilean and

German students, found that students generally define biodiversity as the variety of plants and animals. A similar view has been demonstrated by most of the 321 secondary students from 13 Argentinean schools who participated in the study by Bermudez and Lindemann-Matthies (2020). The students' responses strongly center on species richness and undervalue population size, functional characters, and species evenness. All these studies show that genetic diversity is neglected as an integral part of biodiversity. A study conducted in South America also finds that this simple view of biodiversity has no influence on school location (urban vs. rural) or gender (Bermudez & Lindemann-Matthies, 2020). On the other hand, in the big issue of global climate change, many important alternative ideas have been described, such as understanding greenhouse effect as a harmful phenomenon *per se*; the idea that ozone depletion is a causal factor of global warming; students' confusion among the different types of radiation, such as solar and terrestrial radiation or ultraviolet and infrared radiation; and the belief that generic actions, such as not polluting, can mitigate climate change (e.g., Reinfried & Tempelmann 2014; Rousell & Cutter-Mackenzie-Knowles 2020; Varela et al., 2020).

Research about learning progression in ecology have included some of the core concepts reviewed previously. For example, regarding the flow of matter and energy through an ecosystem, investigations have proposed postponing teaching about this topic explicitly until middle school but reviewing only simpler ideas at elementary levels (Anderson & Doherty, 2017; Jin & Anderson, 2012; Mohan et al., 2009). According to Anderson and Doherty (2017), elementary students can learn to distinguish matter from nonmatter and recognize that living organisms are composed of the same matter as nonliving objects. Middle and high school students can learn more detail about the carbon transformation process in ecosystems if they become more able to associate energy with familiar organic molecules (i.e., glucose, ATP, etc.) and potentially understand the nature of chemical bonds to describe the energy within foods, fuels, and body tissues as "chemical energy" (Jin & Anderson, 2012). In a noteworthy result, Opitz et al. (2017) show that this more sophisticated student learning of the energy concept can be applied in not only a biological context but also a chemistry and physics context, which can have notable curricular consequences. For other important issues of ecology education, such as the understanding of community and population phenomena, it has been noted that elementary students can learn that all ecosystems contain different types of organisms, that different organisms have different life cycles, that there exist different types of interactions among species (e.g., predation, mutualism, competition), and that changes in one population in a food chain will affect other populations (e.g., Anderson & Doherty, 2017).

Ecology learning progressions have been also proposed for food chain understanding in preschool students (Allen, 2017) ecosystem thinking (Hokayem & Gotwals 2016; Mambrey et al., 2020), carbon cycling (Mohan et al., 2009), and global climate change understanding (Varela et al., 2020). The development of multiple learning progressions about energy and the flow of nutrients in food webs or ecosystems includes rubrics, open questions, interviews, or context tasks that permit evaluation of different students' achievements (e.g., Bravo-Torija & Jiménez-Aleixandre, 2012; Gotwals & Songer, 2009; Hmelo-Silver et al., 2007; Hogan, 2000; Hokayem & Gotwals, 2016; Jin et al., 2019). For example, Jin et al. (2019) used a 12-item instrument, including four constructed-response items and eight two-tier items (the two-tier items require students to choose an option and then explain their choice) to evaluate secondary students' understanding of ecosystems (the high school form contains 11 items, and the middle school form contains 9 items). The assessment requires that students use discipline-specific systems thinking concepts, such as feedback loops or energy pyramids, to analyze and explain the interdependent relationships in ecosystems and the impact of humans on those relationships.

Teaching Ecology

With respect to ecology instruction, there exists consensus that the topic is challenging to teach without going out into the field or investigating the environment (Anderson & Doherty, 2017;

Korfiatis, 2018). However, many effective strategies have been described in the literature in addition to teaching outside of school (Table 19.3). Importantly, learning outside the classroom must be combined with strategies that can challenge the different alternative ideas and cognitive challenges that we have reviewed herein. There are many examples of research that show that certain instructional interventions, including inquiry-based instruction and simulations, are successful in developing system thinking in not only middle and secondary school students (e.g., Hmelo-Silver et al., 2015; Jordan et al., 2014) but also in elementary school students (e.g., Hokayem & Gotwals, 2016). For example, Hmelo-Silver et al. (2015) studied what may be called the "aquarium mental model" of 145 middle school students from two suburban public schools in the United States before and after an intervention, including a classroom aquarium (installed and maintained approximately one month before), function-oriented hypermedia for background information and reference, and NetLogo simulations for computer-supported collaborative inquiry learning. After participating in an instructional unit, students were shown to understand more about the structures, behaviors, and functions of the ecosystem (aquarium); in addition, in both classes, between 63% and 77% of the students demonstrated improved mental models, according to the five models developed by Hmelo-Silver et al. (2007).

Regarding the issue of energy, nutrient flows and food webs, learning should focus on the study of food chains, while the metaphor of the balance of nature should be avoided (Korfiatis, 2018). Demetriou et al. (2009) propose a simple strategy for allowing students to construct a food web using data collected from the field, following three steps: (1) identifying the species in the ecosystem, (2) defining the relationships between the species, and (3) constructing the food web. After applying this intervention to a small group of fourth graders in a school in Cyprus, students were found to be able to construct quite precise and complicated webs, including many species, and to draw multiple trophic connections in a better way than students in the control group. To teach energy and nutrient flows in food webs in secondary school, Wernecke et al. (2018) propose using learning from alternative ideas by inserting an error in an ecological energy flow diagram derived from prevalent alternative ideas about energy. The results of their study, which included 304 ninth-grade students in Germany, show that students who successfully identify and explain the error achieve larger gains in conceptual knowledge than those students who learn with a correct diagram. Conversely, a preponderance of the results in the literature show that the inclusion of socioscientific issues, as well as argumentation and modeling, creates productive teaching contexts for challenging alternative ideas and promotes both positive and active attitudes toward caring for the environment issues, climate change, and biodiversity among students (e.g., Bravo-Torija & Jiménez-Aleixandre, 2012; Dawson & Carson 2020; Gotwals & Songer, 2009; Osborne et al., 2017; Sadler et al., 2015; Zangori et al., 2020). For example, Zangori et al. (2020), in a study with four US thirrd-grade classrooms (54 students in total), showed that the intertwining of modeling and SSI served as an important bridge to support students in considering causal relationships within ecosystems.

Other Issues in Ecology Education

In relation to other topics within ecology education, research has focused on the study of the effect of professional development programs on the improvement of practices associated with topics such as climate change (e.g., Drewes et al., 2019), but there is still much to be done in terms of the development of the PCK of other content reviewed in this section (but see Großschedl et al., 2019). However, an interesting topic to point out, different from the teaching and learning of ecological content, is the inclusion of topics related to the nature of science, either in the context of teaching climate change (e.g., Khishfe et al., 2017) or in other topics related to the ecosystem (e.g., Herman, 2018; Schizas et al., 2021). Apparently, the sum of SSI and environmental issues are a favorable context for learning about NOS.

In summary, ecology education is the field of research in biology education with the biggest development (Figure 19.1), but with a high prevalence of topics, such as climate change, biodiversity, and ecosystem thinking (Table 19.3). A broad avenue that can be traveled in the future is to combine studies on environmental issues with the understanding of other central concepts of ecology, such as populations dynamics and the interactions between species (Korfiatis 2018).

Research on Teaching and Learning Human Biology

Different life experiences (from pregnancy to illness and exercise) logically lead many students to wonder how their body works and, more importantly, which decisions to make to maintain health. Therefore, it is crucial to investigate ways to improve student literacy in this area. However, human biology is one of the least study topics in biology education (Figure 19.1, see also Ben-Zvi Assaraf & Snapir 2018). If we add to this lower development of research in this area, the fact that within human biology we find the greatest diversity of subtopics within six contents studied (Table 19.4), the consequence is that there are areas within this content that present almost no research, such as development (Kampourakis & Stasinakis, 2018) or the nervous system (Ben-Zvi Assaraf & Snapir 2018). Thus, most of the research in this content concentrates on the study of the concept of system in general, where the best-known systems are often used as examples (circulatory or respiratory system) and the anatomy or structure of the human body as a whole (Table 19.4).

Table 19.4 Topics of Science Education and Content Present in the Studies Reviewed Across Five Science Education Journals Between March 2010 and March 2022 Targeting Human Biology. The Concepts Are Ordered From Highest to Lowest Frequency.

Pedagogical Topics	*Disciplinary Topics*
Learning	
Alternative conceptions	System thinking (usually respiratory or circulatory)
System thinking	Human body (anatomy or structure and function)
Students' interests and knowledge	Reproduction and sexuality
Learning progression	Nutrition and body health
	Circulatory system
Instructional strategies	Respiratory system
Models and representations	Digestive system
ICTs, simulations, and visualization	Diseases, microorganisms, and immune system
Teaching outside of school	System and regulation
Lab and practical work	Neurobiology
Inquiry-based instruction	Health and body
Argumentation	
Role play	
SSI	
Videogaming	
Case study strategy	
Other issues	
Teachers' attitude, beliefs, or knowledge	

Learning Human Biology

On the issue of students' learning, the study of alternative ideas has been one of the major research topics in the area. For example, students' knowledge and conceptions have been described regarding the circulatory system (e.g., Fančovičová & Prokop, 2019; Özgür, 2013), respiratory system (e.g., Garcia-Barros et al., 2011; Reinoso et al., 2019), digestive system (e.g., Allen et al., 2021; Garcia-Barros et al., 2011), obesity (Weissová & Prokop, 2020), reproduction and sexuality (e.g., Reiss, 2018; Sirovina & Kovačević 2019), microorganisms and disease (Byrne & Grace 2018; Prokop et al., 2009), health-related biotechnology applications (van Lieshout & Dawson 2016), and homeostasis (e.g., Zion & Klein, 2015). For example, Özgür (2013) investigated the persistence of alternative ideas on the topic of the human blood circulatory system among students in four grades (319 fifth and seventh graders and 400 preservice science teachers). The results show that many alternative ideas among school students are no longer present in the responses of preservice teachers; however, the frequency of others is not significantly different across the different educational levels studied. Analogously, in a study of students' ideas of the body's internal structure, Andersson et al. (2020) show that the number of internal organs that students can draw increases with age. In the study, which included a group of 170 students between 4 and 13 years old who individually produced drawings, the six internal organs most frequently indicated were the heart, brain, skeleton, stomach, blood, and lungs, whereas other organs, such as the pancreas, cecum, vocal cords, and tonsils, were mentioned by very few students (but see Dempster & Stears, 2014). Regarding this issue, Patrick and Tunnicliffe (2010) found that a group of 71 in-service science teachers from the United States demonstrated a similar pattern to that shown by students (see Andersson et al., 2020 for a review of previous studies), i.e., the teachers can draw individual organs, but they are unable to draw the entire organ system. Notably, the number of years a teacher has taught and the use of dissection in their classroom appear to positively influence students' scores.

In the issue of alternative ideas about reproduction and sex education, Reiss (2018) notes that there is extensive literature but unclear conclusions regarding this issue. For example, he notes that many students struggle to relate the moment of conception to uterine structures and do not relate the processes of menstruation, ovulation, and the probability of implantation of a fertilized egg. On the other hand, Macintyre et al. (2015) explore sources of information and learning among adolescents between 16 and 19 years old in relation to sexual health and sexuality. They conduct semi-structured interviews to determine adolescents' understanding of pregnancy, sexually transmitted infections (STIs), and contraception. The findings suggest that traditional taboos restricting dialogue on topics such as sexual diversity and abortion appear to be falling and that certain traditional gender classifications may be changing, while challenges to discussing topics such as emergency contraception, sexual violence, and sexual pleasure persist and must be addressed in teaching.

Regarding the topic of research about learning progression to support human body content, a limited amount of literature exists compared with the large number of concepts and issues available about organismal biology (e.g., Ben-Zvi Assaraf & Snapir, 2018; Reiss & Tunnicliffe, 2001; Rogat et al., 2017). The most studied topic in this respect is the understanding of the human body as a complex system (e.g., Ben-Zvi Assaraf et al., 2013; Gilissen et al., 2020; Hmelo-Silver et al., 2007; Tripto et al., 2018; see also Ben-Zvi Assaraf & Snapir, 2018; Verhoeff et al., 2018 for a review). For this concept, at least three learning progressions or states of understanding have been proposed, namely, the structure–behavior–function (SBF) theory (e.g., Hmelo-Silver et al., 2007); the components, mechanisms, and phenomena (CMP) conceptual framework (Snapir et al., 2017); and the system thinking hierarchy (STH) model (Tripto et al., 2018). For example, using the human respiratory system as a model, Hmelo-Silver et al. (2007) studied the mental model of 21 middle school children, 20 preservice teachers, and 13 experts. They found five states of the system models recognized (1=egocentric, 2=simple healthy lung, 3=healthy body, 4=pragmatic expert, and 5=hierarchical expert), which progress from simple and structure-based models to those that are more elaborate, interconnected, and increasingly consider behaviors and functions. Notably, both middle school students and preservice teachers showed to have representations that rank between levels 1 and 3, while experts (respiratory therapists and pulmonary physicians) showed to use only levels 4 and 5. On the other hand, Wenderoth et al. (2020) offer a learning progression about ion movement using the following six contexts: plant tropism, plant transport, neuromuscular, renal, cardiovascular, and respiratory physiology.

Based on interviews from 90 participants and short-answer surveys from over 4,000 college students, they propose a five-level learning progression. Students at the first level (L1), provide explanations that tell stories in a non-mechanistic way that often contain teleological ideas. In L2, students use limited mechanistic reasoning and attempt to explain the "why" or "how" by using relevant concepts in a limited way. In L3, students use emergent principle-based reasoning and address ideas about chemical and electrical gradients, but they make errors when integrating the components. In L4, students use principle-based reasoning with an incomplete consideration of the relationships among interacting components. Lastly, in L5, students use principle-based reasoning with full consideration of the relationships among interacting components. On the topic of the anatomical structure of the human body, the pioneering work of Reiss and Tunnicliffe (2001) describes how students improve their understanding about their body with age. First, students learn that they contain some individual organs, and then they realize that these organs are in specific locations. Afterward, they come to know that certain organs are joined together in functional units; finally, students learn that a few organs are joined into an entire organ system.

Teaching Human Biology

In the issue of instructional strategies, research suggests that biology teachers must promote the understanding of the human body and that of any organism as a complex system (e.g., Ben-Zvi Assaraf & Snapir, 2018; Gilissen et al., 2020). According to these authors, teaching the human body as a complex system must uphold the following four principles: (1) presentation of present human body systems in a conceptual framework that organizes all the systems components and their relationships; (2) providing a means of externalizing their own mental system models; (3) providing a guide for using system language and for drawing clear connections between the various aspects of the systems; and (4) emphasizing connections between the hierarchical levels of the system. In accordance with the literature published in recent years, these principles can be implemented using various resources and strategies, including simulations, physical models, drawings, and concept maps (e.g., Ben-Zvi Assaraf & Snapir, 2018; Gilissen et al., 2020; Liu & Hmelo-Silver, 2013; Rogat et al., 2017). For example, Liu and Hmelo-Silver (2013) use two different versions of hypermedia to teach about the human respiratory system. There was a function-centered version (called F-hypermedia) and a structure-centered version (S-hypermedia) offered to 20 college students in the United States. The results showed that students in F-condition provided more elaboration, asked more explanatory questions, made more connections to their prior knowledge, and demonstrated more metacognitive processing compared to the dyads in the S-condition. Recently, Gilissen et al. (2020) proposed seven system characteristics (boundary, components, interactions, input and output, feedback, dynamics, and hierarchy) in classroom practice to teach human body systems. Using a lesson study as their research design, the authors evaluated two lessons in two small upper-secondary biology classes (15–16-year-old students). After using different instructional strategies in many activities (e.g., use a tangram with seven system traits, create representations, perform role-play, draw graphs, ask questions). Findings showed that most students were able to name and apply the seven characteristics in a glucose regulation system.

Regarding the issues of teaching sexuality and reproduction, research has shown that traditional instruction and information-seeking activities for students are predominant (e.g., Eisenberg et al., 2013). However, a more significant strategy is the inclusion of socioscientific problems (e.g., Brotman et al., 2011; Dawson, 2011) and argumentation (Orlander & Lundegård, 2012). The latter authors used argumentation as a strategy to address abortion with 15-year-old students in Sweden and report on how scientific content becomes relevant to students and how students shift the disciplinary focus to the development of scientific skills, such as argumentation, despite their low achievement in the application of scientific concepts. In another example, Orlander (2016) generated spaces for critical discussion on notions of femininity and masculinity and their comparison between humans and animals and focuses on metaphors that have their origin in the animal world. The study recorded the classroom interactions of 16 years (n=32) of age over the course of one semester. The results show that students can understand that reproduction in animals presents many elements that humanize animal behavior and that these elements contribute to forming constructions of concepts of femininity and masculinity in people.

Other Issues in Human Biology Education

There are few issues other than those related to learning and teaching human biology (Table 19.4). For example, studies on teachers are few compared to other topics reviewed (e.g., evolution or genetics) and generally focus on describing alternative ideas of some topic (see previous discussions). One exception is the study by Schmelzing et al. (2013) reporting on the development of a questionnaire to assess the PCK of the circulatory system, or the study by Werner et al. (2019), which investigated the implementation of two model-based lessons on the topic neurobiology in grade nine by 32 biology teachers. In addition, there seems to be no research that evaluates the explicit connection between the understanding of concepts of human biology and the nature of science (but see Großschedl et al., 2019). There are only a few investigations in which some topics are used as a context for teaching NOS, for example, infectious diseases (e.g., Pavez et al., 2016; Won et al., 2011).

In summary, human biology education is represented by a diverse area of research within biology education but contains with an unequal development of research focus. Underdeveloped areas include a lack of descriptions of students' alternative ideas even as other areas, such as the study of some systems, have reached an important level of sophistication. Among the central themes of such research is the issue of systems thinking, the development of learning progressions, and the implementation of different teaching strategies. A topic that might also be explored relates to the best curricular sequence to support student understanding of body system functioning. In this context, there are also important possibilities in the integration of descriptive studies of body systems and the interaction between concepts such as nutrition, health, regulation, and the immune function all within systems thinking models (e.g., Gilissen et al., 2020). An unresolved question is whether the understanding of human development should be integrated into this level of education or if, on the contrary, it should be included in the teaching of heredity and evolution (Kampourakis & Stasinakis, 2018).

Research on Teaching and Learning Cell Biology

In addition to the theme of evolution, the cell is often reported as one of the most fundamental concepts in biology (McComas, 2018b) because its study provides us with the answers to what life is and how it works (Alberts et al., 2019). Learning about cells is complex, and the ideas that students obtain regarding their structure, organization, and function have been addressed by research literature (e.g., Fernández & Jiménez-Tejada, 2019; McComas, 2018b; Table 19.5). In addition to the difficulty that this theme shares with others at the microscopic level, the influence of the typical models used to teach about the cell presents an additional challenge to its learning (e.g., Fernández & Jiménez-Tejada 2019; Vlaardingerbroek et al., 2014). However, research development in cell education the last decade has been lower than other biology topics examined (Figure 19.1).

Table 19.5 Topics of Science Education and Content Present in the Studies Reviewed Across Five Science Education Journals Between March 2010 and March 2022 Targeting Cell Biology. The Concepts Are Ordered From Highest to Lowest Frequency.

Pedagogical Topics	*Disciplinary Topics*
Learning	
Alternative conceptions	Cell structure
Students' interests and knowledge	Cell process
Learning progression	Microorganisms
	Stem cell
Instructional strategies	Cancer
Models and representations	Cell division
ICTs, simulations, and visualization	
Lab and practical work	
Inquiry-based instruction	
Argumentation	
SSI	
Other issues	
Teachers' attitude, beliefs, or knowledge	

Learning Cell Biology

On the issue of learning about cells, several authors have collected and described alternative ideas from students and teachers (e.g., Allen, 2010; Fernández & Jiménez-Tejada 2019; Gonzalez-Weil & Harms, 2012; McComas, 2018b; Vijapurkar et al., 2014). Among these ideas, the following are some that may have greater consequences in the understanding of other phenomena or may have received less attention from researchers: (1) confusion regarding atoms, molecules, and cells, as well as not understanding the relationship between them; (2) cells are flat; (3) cells possess organs, such as miniature replicas of human organs, while plant cells have (only) chloroplasts, just as animals have mitochondria; (4) the energy within the cell is used only for activities such as movement and growth; and (5) prokaryotic cells have no nucleus, which means that they lack DNA. Student ideas that cells are two-dimensional can be particularly difficult to modify in elementary (Vijapurkar et al., 2014) and secondary (McComas, 2018b) education; furthermore, there is evidence that even after learning about cells, high school students can maintain a dissociated vision between organisms and the cells that comprise them (González-Weill & Harms, 2012).

Difficulties may also be associated with representations in textbooks, as shown by Vlaardingerbroek et al. (2014), who verify the problems that high school students have in estimating the scale of cells and their internal structures by misinterpreting the classic diagrams that appear in textbooks. Various studies have shown that some students' alternative ideas are also present in their teachers. For example, in a study with 192 preservice teachers, Nawaf et al. (2015) show that up to 22% of the participants accepted that a semipermeable membrane is required for diffusion or that once a substance has dissolved in water, its particles stop moving (both invalid ideas). On the other hand, valid instruments have been developed to gauge high school students' understanding of cellular processes (Sesli & Kara, 2012) confirming the thinking that students have when they are finished with their formal educational process experience. Although multiple-choice diagnostic tests have been the norm in studies on the assessment of knowledge about cells, drawings and diagram interpretation have also been used. For example, Vlaardingerbroek et al. (2014) evaluate the interpretation of cell diagrams and confirm that several years of school education generates distorted views about cell size and scale in college students.

Teaching Cell Biology

Some of the challenges faced in learning about cells and their structure and function requires students' ability to understand objects and processes that are both three-dimensional and essentially invisible. Therefore, textbooks usually start with basic microscopy or by introducing the use of magnifying glasses starting in kindergarten. However, many schools lack the infrastructure to teach cells based on laboratory practices; therefore, they end up using paper and pencil activities to teach about cells (McComas, 2018b). This phenomenon and the classical cell representations used in elementary and secondary school education lead to the acquisition or strengthening of alternative ideas about the dimensions and scales of cell structures and their internal components (Vlaardingerbroek et al., 2014). In this respect, the diversification of cell biology teaching strategies has been identified as a need in the preparation of university courses (Veselinovska et al., 2011). In fact, according to the compilation presented by McComas (2018b), in middle school, the practical activities used are quite repetitive, and multiple versions can be observed in textbooks. A good review of different and specifically designed strategies for teaching about cells appears in Allen and Tanner (2003). In the last years, research has been conducted on the use of highly diverse strategies, highlighting case studies (e.g., Veselinovska, 2011), role-playing (e.g., Cherif et al., 2016), modeling and representations (Verhoeff et al., 2008), the elaboration of arguments (e.g., Choi et al., 2010), SSI (e.g., France et al., 2012), and inquiry context (e.g., Matuk et al., 2019; Röllke et al., 2021) (See also Table 19.5). For example, Matuk et al. (2019), incorporated qualitative graphing activities into a seventh-grade web-based inquiry unit about cell division and cancer treatment to perform two studies lasting two academic years. Findings from the first year (n = 30 students) showed that students gain understanding about cell division, cancer, and cancer treatment after the intervention. The second study (n = 117 students), which included two versions of the same unit (one that students construct graphs and one that they critique graphs), showed that both activities improved students' integrated understanding of graphs and cell content. Improving understanding of processes that are invisible and dynamic may be supported with strategies based on dynamic computer visualizations (Oliver et al., 2019). This study showed that high school students gain understanding in cellular processes of diffusion, osmosis, and filtration after a one-year intervention. Teaching cell theory has also been especially approached throughout the history of science (Camacho et al., 2012) and has been proposed as an excellent context by which to approach (and discuss) theory concepts from an epistemic perspective. According to McComas (2003, 2018b) and others (e.g., Lewis 1972), cell theory, a label commonly included in secondary books, is best defined as a law, generalization, or principle instead of a theory, which it is not. Interestingly, many college and university textbooks call this important idea the "cell principle", a more appropriate name.

Other Issues in Cell Biology Education

There are few papers related to topics in cell biology education other than teaching and learning (Table 19.5). Only recently have there been studies related to the development of instruments to assess subject-matter knowledge about cell (Suwono et al., 2021) and PCK of this content and other disciplines in biology (Großschedl et al., 2019). In summary, despite the great importance of the study on the understanding and teaching of the functional unit of life, there is less research development compared to other areas (e.g., evolution, genetics, or ecology). A possible way to invigorate this line could be to continue the development of a more contextualized teaching, for example, by conducting more studies on the teaching of SSI in the context of stem cells, cancer, or other cellular issues (Table 19.5). In addition, although there are few examples on learning progressions (Verhoeff et al., 2008), further development on cell-specific processes (e.g., division, differentiation) should be encouraged.

Research on Teaching and Learning Metabolism

There exists a literature consensus that energy is a central idea for teaching and learning biology and that the processes of photosynthesis and respiration are crucial to understanding it (e.g., Duncan et al., 2017; Harms & Bertsch, 2018; NGSS, 2013; Opitz et al., 2017; Schramm et al., 2018). However, this area of biology education is one of the least developed in the research literature examined (Figure 19.1) and least represented in suggestions for instructional approaches (Table 19.6).

Learning about Metabolism

On the issue of student learning about metabolism, numerous articles have been published over the past 20 years on alternative ideas possessed by learners (e.g., Beals et al., 2012; Opitz et al., 2017; Wernecke et al., 2018; Wilson et al., 2006). These studies highlight the existence of serious challenges in teaching and learning about energy, photosynthesis, and respiration, while also arousing great interest among researchers who have proposed ideas to address these issues by focusing primarily on the aim of knowing what the most widespread alternative ideas are and targeting them (Bergan-Roller et al., 2020; Kubsch et al., 2020; Opitz et al., 2017; Parker et al., 2012; Ryoo & Linn, 2012).

Among the most reported alternative ideas are (1) plants obtain their food from the soil through their roots; (2) photosynthesis occurs during the day, while respiration occurs at night; (3) it is not known where the energy obtained as a result of photosynthesis is contained; (4) plants do not breathe; (5) respiration is synonymous with gas exchange; (6) animal respiration differs from plant respiration; (7) it is not known that respiration is a source of energy; (8) energy is recycled and absorbed as a result of photosynthesis; and (9) plants do not breathe, but the air is recycled and absorbed by plants

Table 19.6 Topics of Science Education and Content Present in the Studies Reviewed Across Five Science Education Journals Between March 2010 and March 2022 Targeting Metabolism. The Concepts Are Ordered From Highest to Lowest Frequency.

Pedagogical Topics	*Disciplinary Topics*
Learning	
Alternative conceptions	Cellular respiration
Students' interests and knowledge	Photosynthesis
Learning progression	Protein synthesis
Instructional strategies	
Models and representations	
ICTs, simulations, and visualization	
Lab and practical work	
Inquiry-based instruction	
Other issues	
Teachers' attitude, beliefs, or knowledge	

(e.g., Beals et al., 2012; Harms & Bertsch, 2018; Opitz et al., 2017; Parker et al., 2012; Park et al., 2018; Schwartz & Brown, 2013; Wernecke et al., 2018; Wilson et al., 2006; Zangori et al., 2017). For example, Parker et al. (2012) presents a diagnostic test that evaluates the knowledge of photosynthesis in university students who were enrolled in an introductory biology course with large enrollment classes between 2004 and 2009. These authors also conducted interviews to complete the information obtained in the tests. The results indicate that many college students lack both a basic understanding of photosynthesis and the ability to reason with scientific principles of the conservation of matter and energy and the hierarchical nature of biological systems. Regarding cellular respiration, a recent study by Bergan-Roller et al. (2020) uses concept maps as instruments to evaluate previous knowledge in 182 undergraduate students enrolled in an introductory biology course. The authors also interviewed a small number of students, and the obtained information is used to corroborate the inferences made from the concept maps. Results indicate that students have a simplified understanding of cellular respiration and its processes, as is evident based on the quantities of schemas that were vaguely connected and organized by the subjects in this study.

Teaching Metabolism

Regarding learning challenges faced in teaching metabolism, Harms and Bertsch (2018) highlight two characteristics presented by metabolism concepts, namely, (1) their abstract nature makes tangible teaching and learning resources mandatory, very often using school texts, which, according to the authors, are not used to their full potential, and (2) the high complexity of the concepts increases as they interrelate with each other, which, according to the authors, could be intensified by the fact that energy is also a cross-cutting concept in the disciplines of biology, chemistry, physics, and engineering. In the same vein, various teaching strategies are described in the research literature (Table 19.6). For example, in a quasi-experimental study including eighth-grade students (n = 30), Kubsch et al. (2020) targeted energy representation and found that the construction of energy transfer models helps students apply the systems transfer perspective successfully to explain phenomena. Similarly, Orbanić et al. (2016) compared the constructivist teaching of photosynthesis with traditional instruction. Based on a design including 201 Slovenian elementary school students (in fifth-grade classes) divided into control and experimental groups, the authors report that constructivist teaching targeting students' prior ideas improves the learning of photosynthesis and fosters the development of higher-order thinking in students, thus increasing the level of scientific literacy (Orbanić et al., 2016).

With respect to teaching strategies targeting respiration, Schramm et al. (2018) used a learning progression, including inquiry-based activities, to improve the understanding of photosynthesis, respiration, and biosynthesis processes among 563 middle and high school students. Their study examined the impact of a two-week intervention and demonstrated that students achieve a better understanding of photosynthesis and respiration in a way that avoids many common alternative ideas generally held about these processes. In another study including the understanding of photosynthesis and respiration, Schwartz and Brown (2013) use multiple representations to encourage a view of biological nested systems in three preservice science teachers. The authors use three tasks that include concept maps, drawings, concrete models, and guiding questions as instructional guides that can help scaffold student thinking about photosynthesis and cellular respiration within and across biological levels. According to the qualitative results presented, Schwartz and Brown (2013) propose that these activities can be used to identify alternative ideas and develop more sophisticated systems views, as well as formative assessments.

Other Issues in Metabolism Education

On the topic of teachers' knowledge about metabolism, several studies report investigations of subject-matter knowledge (SMK) and PCK (e.g., Akçay, 2017; Brown & Schwartz, 2009; Käpylä et al., 2009; Park & Chen 2012; Park et al., 2011, 2018; Großschedl et al., 2019). For example, Käpylä et al. (2009) investigated the effect of the amount and quality of SMK on PCK about photosynthesis, comparing ten primary and ten secondary (biology) teacher students. The main finding of the study was that primary preservice teachers were not aware of students' conceptual difficulties and had problems choosing the most important content. Neither of the groups had knowledge of suitable experiments and demonstrations for teaching photosynthesis. In a more recent work, Park et al. (2018) developed two different instruments for assessing PCK about photosynthesis. The authors included two components of the PCK in their instruments, knowledge of student understanding (KSU) and knowledge of instructional strategies and representations (KISR). Two interesting results of the study were that although KSU and KISR are theoretically conceptualized as separate constructs constituting PCK, they were not loaded separately by PCA analysis and that a linear connection between teachers' SMK, PCK, and classroom practice is not possible of state.

In summary, despite the importance of research on understanding metabolic processes, for example, to understand processes at higher levels of biological organization (e.g., the ecosystem), learning progressions such as those described in previous sections have not yet been developed. The diversification in the study of the teaching of other metabolic processes (e.g., protein synthesis), as well as the connection with other levels of organization (Brown & Schwartz, 2008; Schwartz & Brown 2013), or even other disciplines, in the subject of understanding the flow of energy (Harms & Bertsch, 2018) seem possible ways to develop this line of research.

Conclusions and Future Directions in Biology Education Research

In this chapter, we endeavored to provide a synthesis of the most prominent research topics in the area of biology education or didactics of biology of the last ten years, guided by the exhaustive review of five prominent science education journals but also by our experience as biology teachers, biology teacher educators, and researchers in some specific areas of biology education. And while we recognize that our effort may have weaknesses and be incomplete, we believe that some interesting patterns have emerged from our analysis.

On the issue of biology topics, while some topics are especially developed, such as teaching and learning about evolution, genetics, and ecology, others appear particularly deficient from a biology education research perspective, including cell biology, metabolism, and some aspects of human biology, such as development, the immune system, and the nervous system. These last topics and others should be addressed by future researchers (See Tables 19.1 to 19.6).

The viral pandemic that began in 2020 and the continuing environmental catastrophes brought about by climate change have placed various issues of biology into the everyday language of the media and the public. The means available by which to access biological knowledge have multiplied, and popular science texts on these issues are also multiplying. However, it has become apparent that all this exposure has not allowed individuals and governments to make decisions that are consistent with the evidence. It is possible that the underlying problem is that the time available for the study of biology in schools is insufficient, particularly if it fails to include the scope and nature of science (NOS). As many authors argue, biology is an ideal context in which to address the NOS and scientific argumentation and provide better bases for decision-making. We need additional studies on the importance (or not) of including aspects of the NOS in biology teaching. While there seems to be sufficient evidence to suggest that the teaching of evolution benefits from this knowledge, other areas of biology could also potentially benefit from such knowledge, such as inheritance, neuroscience, ecology, or climate change.

Although we have detailed knowledge of students' alternative ideas in almost every piece of biology content taught in school, learning progressions have not yet been developed for all the big ideas. The topics most urgently in need of development are human biology, cell biology, and metabolism.

We must take better advantage of the knowledge that we have about biology learning to identify and describe the most relevant teaching strategies for understanding each content. Doing this will assist students in providing explanations and hold understanding vital for effective decision-making. This approach is especially relevant in human health and physiology issues, such as nutrition and sexuality, where little research has been done about teaching and learning, and many public policy initiatives are designed without the use of research evidence that promotes safer and healthier behaviors. It may be that teaching strategies that seem effective in other areas (e.g., evolution, genetics, or ecology) may also be effective regarding these topics.

More research is needed to show the real benefit (or not) of doing practical/laboratory work that brings biological phenomena closer to students. While there is evidence of the contribution of the use of empirical data and interactions with real systems and contexts in ecology and evolution, the benefit of empirical work with macro-level phenomena for the understanding of microsystems (e.g., cell, genetics, or physiology) seems less clear. For these topics, there is significant evidence of the teaching effectiveness of using models and representations, although more research is suggested to assess the importance of model understanding and modeling skills. Finally, teaching strategies that are widely used in content such as genetics, evolution, and ecology, such as argumentation and the inclusion of socioscientific issues, could also be investigated in topics related to the functioning of human biology, cell biology, and metabolism.

Although the efforts of those who have conducted research in biological education are valued, too often these recommendations do not make it into practice in schools. Thus, the current chapter may present an opportunity that favors the incorporation of several recommendations that modify the most common curricular modes, i.e., teaching molecular genetics before Mendelian genetics; teaching an integrated approach to human body systems by systems thinking, instead of teaching each system separately; the concept of development as an articulating axis; and other learning progressions described in physiology, ecology, and evolutionary topics. In a broader sense, it would be strategic to redouble the collective efforts so that certain core concepts can be studied transversally between subjects, such as energy or complex systems, which have been shown to have similar learning progressions during different school grades. It is even more urgent that several historically exclusive concepts of biology be reviewed with a multidisciplinary approach, as occurs with sexual education, genetics, or ecosystems.

The goal for all those interested in biology education is that we devise teaching and assessment strategies to help students guide their learning about the biological world and help them achieve biological literacy and are anxious that biology teachers and researchers work together in moving toward this goal.

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