Science & Education
https://doi.org/10.1007/s11191-023-00471-2

ARTICLE

The Critical Role of Understanding Epistemic Practices in Science Teaching Using Wicked Problems

Hendra Y. Agustian[1]

Accepted: 4 September 2023

Abstract
Wicked problems have been characterised by their high epistemological and axiological complexities. These are the kinds of problems that may invade our classrooms because many of them concern many stakeholders, including our students. Several approaches have been developed to address wicked problems in various contexts. However, little is known about how they may translate into educational research and practice. This paper proposes a conceptual framework in which wicked problems are analysed from their ontological, epistemological, and ethical commitments. Subsequently, they are framed within post-normal science, drawing on critical discourse in science studies and science education. Chief to the arguments is a focus on epistemic practices that are strongly anchored in but also extend from disciplinary science and engineering education. Implications for research and practice in higher science education are presented.

Keywords Wicked problems · Post-normal science · Epistemic practices · Higher science education

1 Introduction

Over the past few years, the Covid-19 pandemic has presented us with a paradox. On the one hand, scientific progress related to epidemiology, immunology, and vaccine research offered real solutions and knowledge-in-the-making. On the other hand, apprehension and distrust towards science jeopardised the efforts to contain the spread of the mutating virus. Polarising views and attitudes occupied daily debates in person and on social media. Emerging public policies aimed at addressing the COVID-19 pandemic were a matter of life and death, but different beliefs and understandings of the issue impeded effective interventions. Uncoordinated efforts to address them were doomed to fail. Conversely,

---

Hendra Y. Agustian is Assistant Professor of Higher Science Education at Department of Science Education, Faculty of Science, University of Copenhagen. He has a BSc in Chemistry, an MA in Education, and a PhD in Chemistry Education.

✉ Hendra Y. Agustian
hendra.agustian@ind.ku.dk

[1] Department of Science Education, Faculty of Science, University of Copenhagen, Universitetsparken 5, 2100 Copenhagen, Denmark

Published online: 22 September 2023

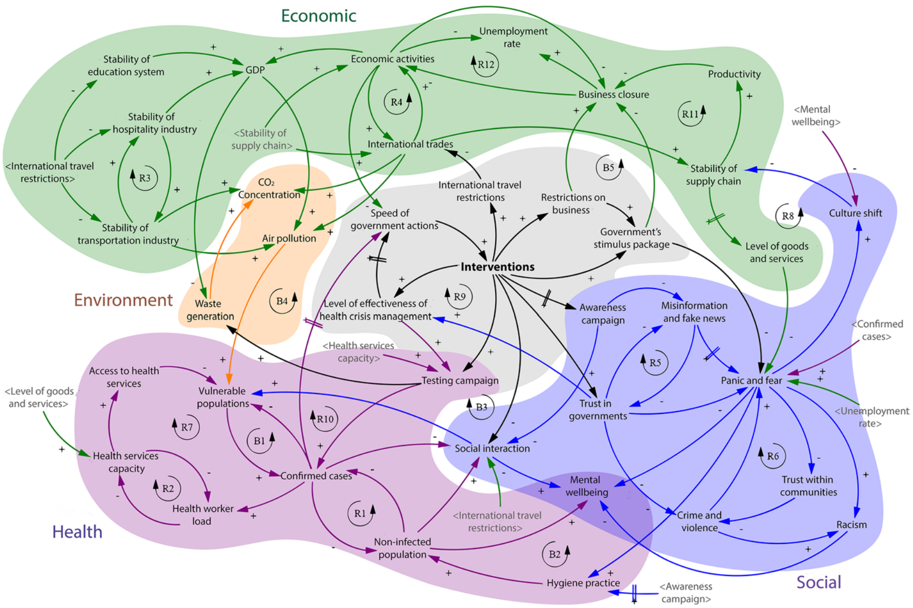

Fig. 1 Complexity and interconnectedness of the COVID-19 pandemic (Sahin et al., 2020)

coordination among many stakeholders was extremely difficult due to conflicting values and interests.

To illustrate, a few months into the pandemic, Sahin and colleagues (2020) map the complexity of this phenomenon, whereby intricate causal loops between various elements within and across health, social, economic, and environment systems complicated public policy interventions, as shown in Fig. 1. In this diagram, cause-and-effect links were identified through expert reviews of various governments' responses to the pandemic, supported by geographical data. At the centre, policy interventions aimed to mitigate the crisis had implications that transcended systems boundaries and necessitated trade-offs between the systems. For instance, they exerted influence on trust in governments and scientific input that fed into these interventions. Positive gain in trust in the system enhanced the effectiveness of health crisis management. However, lack thereof may have caused the spread of misinformation and fake news. The feedback loops between trust and misinformation represent two-way relationships between actions and consequences, which complicated the issues and led to a near-collapse effect in several countries (Sahin et al., 2020).

The abovementioned preliminary work situates several crucial aspects related to science literacy and science education, such as misinformation, trust, and awareness, in the broader context of interconnectedness and mess. Indicated in the diagram, awareness campaign policies were subjected to "post-truth" attacks, fuelled by various political, religious, and conspiracy theory agendas (Chinn et al., 2021; Kienhues et al., 2020). Amidst panic and fear, we observed how some of us resorted to emotions and gut feelings in deciding whether to follow regulations or not, or if any of them made sense at all. With so many contradictory findings (Briz-Redón & Serrano-Aroca, 2020), often worsened by different interpretations, scholars were concerned about science being undermined and deemed not trustworthy (Erduran, 2022; Kreps & Kriner, 2020; Sturgis et al., 2021). Recent work in this area shows that such a contradiction arises from the uncertainties and negotiations of scientific knowledge (Kienhues et al., 2020). To the informed scientific communities, this is regarded as a part of the normal dynamic of knowledge development in science, but to the lay public, this may look as if scientific knowledge was unreliable. Even worse, post-truthers exploit these "gateways" to advance their agenda. During the pandemic, this was worrying as efforts to develop vaccines began to deliver promising results.

Notwithstanding the perceived novelty of distrust in science and urgency regarding effective public policy issues, this was not a recent phenomenon. Laypeople's hesitancy towards science has been accompanying debates on climate change for decades. To date, lack of response to and downright inaction against the looming environmental catastrophe exist not only on an individual level but more pressingly are also institutional. Numerous explanations and arguments have been presented as to why this is the case, but science education is almost certainly playing a pivotal role in basic science literacy related to these real, complex issues (Erduran, 2021; National Academies of Sciences, 2021). As the degree of complexity of the aforementioned problems increased, they have been conceptualised as "wicked problems" (Kawa et al., 2021; Lönngren & van Poeck, 2021), and as such, problematised science and science education that typically operate within the context of "tame problems" (Schiefloe, 2021).

Given the reality of widespread misunderstanding and disinformation concerning wicked problems, scholars assert that STEM education must help equip individuals with the knowledge, skills, attitudes, and values needed to navigate such complexity (Gattie et al., 2011; Jones, 2020; Osborne & Pimentel, 2022). One way of helping "competent outsiders" to evaluate scientific information is by adopting a heuristic to accept or reject consensus, through which evidence for credibility and evidence for expertise are weighed (Osborne & Pimentel, 2022). Others highlight the potential role of philosophy of science and engineering in teaching for understanding how science and engineering work (Barak et al., 2022; Cunningham & Kelly, 2017; Erduran, 2020; Matthews, 2018). Recent studies in higher education suggest that wicked problem solving entails working within and across disciplines (both sciences and non-science), coming to terms with the complexity and messiness, and engaging diverse stakeholder perspectives (Kate et al., 2019; McCune et al., 2021). However, it is still unclear whether, and how, discipline-based higher science education has been playing a role and, indeed, could be empowered to help faculty address wicked problems in their teaching practice.

In this paper, I propose a conceptual framework for teaching science using wicked problems as an integral part of university science curricula, by focussing on the importance of understanding different ways of knowing and striving towards an open transdisciplinary inquiry (Brown, 2010). The framework incorporates an analysis of wicked problems from their ontological, epistemological, and ethical commitments, employing ideas from philosophy of science. The notion "post-normal science" will then be used to frame wicked problems in the critical discourse of Kuhnian philosophy. Subsequently, I will argue for a focus on epistemic practices that move beyond disciplinary science. With higher science education in mind, I will propose relevant methodological and pedagogical implications.

2 Conceptual Framework

2.1 Wicked Problems

The concept "wicked problems" has been used in various research fields since it was coined back in the 1970s, but the literature is dispersed among a variety of disciplines regarding its theoretical underpinnings, epistemological assumptions, rhetorical functions, and uses (Lönngren & van Poeck, 2021; Rittel & Webber, 1973). Likewise, the ontology of wicked problems has also been debated, from how they are defined to how they should be addressed in various contexts (Adam, 2016; Head, 2022; Tsey, 2019). The "wicked" characteristic is essentially attributed to the ill-formulated nature of the problems, exacerbated by conflicting findings and perspectives, which often lead to controversy, confusion, and messy solutions. Scholars have been critical of its utility for research, but at least in the context of climate change and the recent pandemic, the "wicked problem" framing has heightened the stakes and complexity of the issue, rendering attempts to address it problematic, because it entails many different stakeholders with opposing values and interests. The science underpinning wicked problems is rarely monopolised by a single discipline. Truly, it may be naïve to assume that wicked problems dwell primarily in any or all of natural sciences. Consider, for instance, a range of wicked problems such as poverty, energy and water demand, migration, and global health. The longstanding debates and controversies surrounding them demonstrate how science, politics, social policies, economic inequality, access to reliable information, and geographical positions are deeply entangled.

The adoption of the concept "wicked problems" to address highly complex societal issues is of course a matter of theoretical framing. Related notions such as "hyper-complex problems" (O'Brien, 2013; Serugendo et al., 2014), "risk society" (Ericson & Haggerty, 1997; Pietrocola et al., 2021), and "socioscientific issues" (Baytelman et al., 2020; Zeidler & Sadler, 2023) have been conceptualised. Indeed, the concept "socioscientific issues" (SSI) has been used in science education to describe problematic intertwine between science and society (Zeidler & Sadler, 2023), also in the same context with wicked problems (Pietrocola et al., 2021; Sadler et al., 2017; Shasha-Sharf & Tal, 2021). While these different lines of scholarship may have their own conceptualisation and empirical substantiation, they serve the same ideals of meaningfully engaging with societal problems in which science plays a significant role. What Zeidler and Sadler (2023) conceptualise as "evidence for cognitive and moral dissonance" embedded in SSI has been discussed in wicked problems literature as well (Adam, 2016; Carter, 2011; Rittel & Webber, 1973; Tromp, 2018). That said, wicked problems are broader than SSI, as they encompass a wider range of complex and multi-faceted problems beyond the specific intersection between scientific and social considerations that usually characterises SSI (See also, Cook, 2015; Murakami et al., 2017).

Due to their high complexity, wicked problems pose unprecedented epistemological challenges. In terms of knowledge generation, it is difficult to produce reliable knowledge because of conflicting perspectives. Expert and specialised knowledge, which is traditionally revered in its own domain, such as science, is no longer seen as the only authority (Kate et al., 2019). No matter how robust and established, it often represents only part of the story, as it is juxtaposed against community, organisational, and individual epistemologies (Brown, 2010). As such, it is more relevant than ever to acknowledge partiality, plurality, and provisionality of knowledge (Feyerabend, 1999; Foucault, 2002; Popper, 2005; Russell, 2010). However, as previously described, this epistemic limitation of science has been exploited by harmful post-truth agenda, particularly since the massive influence of social media and content creation platforms (Mackey, 2019; Moravčíková, 2020). More than ever, we need to educate for a nuanced understanding of how knowledge is constructed, negotiated, and evaluated. This is already a challenge that university science and engineering education is yet to meet, and the stakes are even higher when the said knowledge constitutes wicked problems.

Teaching knowledge related to wicked problems is equally challenging. As with any science teaching that incorporates a problem to solve or a case to investigate, traditional pedagogy centred on knowledge transfer is not suitable for wicked problems. Scholars in the field emphasise the importance of reconciliation of opposites (Adam, 2016), open and critical transdisciplinary inquiry (Brown, 2010; Colucci-Gray et al., 2013), and holistic thinking (Lehtonen et al., 2019). While variations of some of these approaches have been used in disciplinary science, such as systems thinking in chemistry education (Mahaffy et al., 2018) and socioscientific teaching in biology education (Tidemand & Nielsen, 2017), there is a large scope for designing and developing pedagogical devices that embrace, rather than ignore, the epistemic complexity of wicked problems. Previous works point to the importance of collaborative inquiry, transdisciplinarity, and knowledge integration. How this may manifest in the context of higher science education is, however, still unclear and underresearched.

Ramification of wicked problems across various layers of socio-economic structures, political ideologies, and planetary sub-systems such as the food-water-energy nexus (Tromp, 2018) also create ethical dilemmas. When addressing a wicked problem, what is the right and ethical course of action to take when there are conflicting values between local communities and government organisations, or between science and individuals? In a context where indigenous communities are faced with big corporations, how can power imbalances (ever) lead to equitable solutions? What about intergenerational equity associated with long-term consequences of climate change? Who is responsible for the future? These are some of the biggest ethical challenges that require accountability, justice, transparency, and continual critical reflections. The problem remains: How do we address this in our science teaching?

Wicked problems are not constitutive of a singular domain or discipline. It has been argued that "science alone cannot deal with wicked problems" (Turnpenny et al., 2011, p. 299). Similar argument for addressing harmful post-truth agenda has also been proposed (Kienhues et al., 2020). Essentially, a balancing mechanism is required to establish the epistemic authority of science, particularly regarding knowledge for which scientific evidence is overwhelming, while also engaging productively with the notions of values, ethics, and social nature of knowledge construction. Inquiries on wicked problems in practice often involve theoretical and methodological framing within social sciences and humanities, but for the purpose of this paper, they will be framed primarily within science studies and science education, as the following section illustrates.

2.2 Post-Normal Science

Following Kuhn's influential work, *The Structure of Scientific Revolutions* (Kuhn, 1962), scientists and philosophers of science were drawn to revisit scientific practices and ways in which scientific knowledge was created and evaluated. Kuhn's notion of scientific paradigms and paradigm shift challenged the dominant view of science in the mid-twentieth century as a unified and rational enterprise. Kuhn conceptualised the everyday working of science within these paradigms as "normal science". In science education, it also propelled research programmes in the nature of science, spearheaded among others by the National Science Foundation (Agustian, 2019). However, critics also came from within philosophy of science, particularly regarding his notion of incommensurability (Feyerabend, 1999; Laudan, 1996) and discontinuity of theory development, which was marked by scientific revolutions in a Kuhnian term (Lakatos, 1978). In his critique on scientific theories and methodologies, Laudan (1996) maintains that the Kuhnian concept of incommensurability, which refers to the supposed inability of advocates of rival theories to understand each other, leads to epistemic relativism. While most philosophers of science may be past the obsolete positivist paradigm, he argues that post-positivists are potentially guilty of either relativist ambiguity, naïve acceptance, or blind scepticism. It is thus possible, and even desirable in the context of highly complex and ambiguous problems, to demonstrate that certain methods are better than the others. Likewise, Lakatos (1978) argues that Kuhnian idea of irrational paradigmatic change that marks his notion of scientific revolution could also mean that "there is no explicit demarcation between science and pseudoscience, no distinction between scientific progress and intellectual decay, [and] there is no objective standard of honesty" (p. 4). Such an ontological position is of course not very productive for addressing wicked problems, combating post-truthism, or engaging with controversial socioscientific issues.

To this arsenal of philosophical critique, sociology and anthropology of science also added counterarguments and a more humanist view of science (Knorr-Cetina, 1991; Latour & Woolgar, 1986). In her extended ethnographic work on particle physics and molecular biology research groups, Knorr-Cetina (1999) describes how scientists establish cultural practices, through which they create and warrant knowledge. These epistemic cultures, she argues, are a structural feature in a transition of contemporary societies to knowledge societies. Sociological accounts of these cultures show that they are diverse among natural sciences, as opposed to a Kuhnian idea of scientific communities being homogeneous and isolated from external sociopolitical factors. Disunity of science therefore represents a different perspective from a consensus view early scholars in the nature of science aim to substantiate (e.g., Klopfer & Cooley, 1963; Lederman, 1992; Mackay, 1971; McComas et al., 1998).

In the 1980s, Ravetz's critique of Kuhn problematised the core of science epistemology, as he argued that a Kuhnian view of science was essentially anticritical, even though it was often portrayed as centred on rigorous peer review (Ravetz, 1986). In such a myopic view, scientific knowledge was derived from accumulation of hard facts, which fell short of its promises when faced with environmental problems. Likewise, engineering practices pertaining to solving design problems also showed inadequacy when faced with protective legislation and ethical constraints. Grounded in a large-scale project on sustainable development, his arguments substantiated how a reductionist view of normal science was no longer relevant for addressing complex problems, both in professional and educational practices.

Confounding quandary of highly complex environmental problems has been characterised as pertaining to "post-normal science" (Funtowicz & Ravetz, 1993, 2018). Post-normal science (PNS) refers to a new epoch but also a different form of science. As a new epoch, it represents a temporal notion of an age in which many systemic and environmental problems are caused by human. In this regard, PNS is closely related to the concept of "anthropocene", which is more than just a geological marker, but is also an age where the natural sciences, social sciences, and the wider public are brought into a conversation with each other (Reichel & Perey, 2018). As a temporal notion, post-normal science is characterised by paradoxes of progress and regress, as described in the opening paragraph of this paper. Harmful agendas in which facts are used to destabilise political discourse, conceptualised as "post-truth" agendas, are also more palpable, largely thanks to the massive influence of social media (Farrell, 2020). As a form of science, PNS is distinguished from core science, applied science, and professional consultancy.

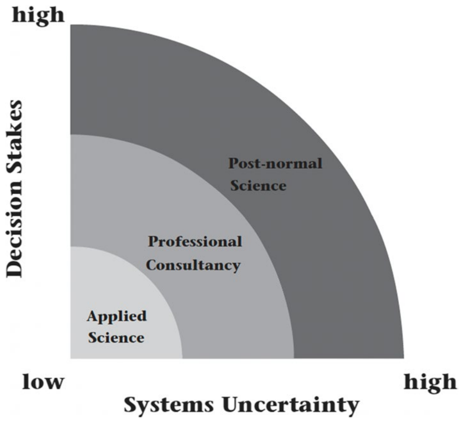

Fig. 2 Epistemic and axiological nexus of sciences beyond Kuhnian normal science (Funtowicz & Ravetz, 2018)

PNS is useful to frame meaningful discussions on wicked problems in at least two ways. First, it moves beyond the Kuhnian notion of normal science, where science is characterised by heavy reliance on technical work and puzzle-solving approach to problems. As argued previously, while some of these characteristics may still be relevant, they are far from adequate to understand the far-reaching implications and complications of wicked problems. Second, it frames both epistemic and axiological positions of science in an interplay, which is represented by systems uncertainty and decision stakes, respectively (see Fig. 2, henceforth referred to as PNS diagram).

The PNS diagram is rooted in a notational system for the management and communication of uncertainty in science for policy, proposed by Funtowicz and Ravetz (1990b), in which risk analysis, such as in the context of Three Mile Island nuclear power plant accident of 1979, was quantified (Funtowicz & Ravetz, 2018). It characterises different forms of science according to increasing systems uncertainty and decision stakes, as core science (represented by the intersection between both axes) expands in scope and complexity when it is applied and engages more stakeholders. With regard to the Kuhnian notion of normal science, it is argued that "if normal science typically occurs in university laboratories and is curiosity-driven, other forms of science connect it to the wider world in different ways" (Funtowicz & Ravetz, 2018, p. 443). As a concept, PNS highlights the centrality of uncertainty in understanding science epistemology, and by epistemology, I refer to its definition as theory of knowledge *and* one's construction of knowledge. The former is a formal association of the term as discussed in philosophy, whereas the latter represents how several science education scholars have used the term, such as "personal epistemology" (Elby et al., 2016; Yang & Tsai, 2012) and "practical epistemology" (Maeng, 2021; Sandoval, 2005). PNS diagram also entails axiology, which refers to the role of values tied to different societal and environmental stakes when making decisions based on scientific knowledge. The interplay between knowledge and values means that inquiries in these different forms of science should address not only the quality of knowledge but also whether it is important to engage now or later. As such, decision stakes in the diagram bring the notions of urgency and priority into the equation.

The notion of epistemic uncertainty has been discussed in the literature of philosophy of science (e.g., Boyd et al., 1991; Renn, 2020) and science education (e.g., Chen, 2022; Chen & Techawitthayachinda, 2021), but even more prominent in the literature on environmental studies and wicked problems (Alford & Head, 2017; Castree et al., 2018; Head, 2022; Lidskog & Lofmarck, 2015). An argument for focussing on uncertainty is that science should play a more proficient role in managing uncertainties, either in terms of knowledge generated through scientific research or behaviour of related stakeholders (Funtowicz & Ravetz, 1993). In science education with epistemic orientation, managing epistemic uncertainty is also high on the agenda. For instance, Chen (2022) proposes strategies that teachers can use, including critiquing and decomposing student epistemic uncertainty through argumentative practices to find possible solutions. This is an example of a purposeful investigation in a primary school context and, as such, is constrained within a tame problem of modelling. The arguments presented in the present paper suggest that when dealing with wicked problems, particularly in higher science education context, all of the variables such as epistemic uncertainty, decision stakes, urgency, and unpredictability will be more complex.

Research on wicked problems demonstrates how values and ethics are inherent in problem solving strategies (Balint et al., 2011; Brown, 2010; Head, 2022; Lehtonen et al., 2019; Tromp, 2018), and PNS elevates the stakes involved regarding the urgency of decisions to make. As such, we need to rethink science and engineering education, so that it considers the complexity of real-world problems, their far-reaching implications, and immediacy of their effects. In relation to wicked problems, PNS provides a framework for democratisation of science in which students and teachers are part of the stakeholders.

Although there are substantial differences between normal and post-normal science, as well as applied science and professional consultancy, one factor applies to all: our effort to make sense of and respond to the evolving knowledge that stems from them. As a part of stakeholders affected by wicked problems, we want to know what is happening now and what could happen in the future. Indeed, we are expected to make decisions concerning not only ourselves but others. There is obviously more than one path, but the entire process accounts for what has been conceptualised as "epistemic practices." In the context of higher science education, epistemic practices are inherent in various inquiries tied to scientific problems (Agustian et al., 2022a; Hammer et al., 2008; Mogk & Goodwin, 2012). However, science education research in general suggests that despite this inherent character, the epistemic dimension is often left unattended (Duschl, 2008; Erduran & Kaya, 2019; Kirschner, 1992). Furthermore, Manz and colleagues (2020) argue that even curricular efforts that attempt to address this conundrum in K-12 science education, such as *Science and Engineering Practices* and *Next Generation Science Standards*, still do not make explicit the dynamic between the explanatory model of scientific phenomena, the empirical model, and the data model. Consequently, much of this underlying epistemic alignment is hidden in science classrooms (Manz et al., 2020; Pabuccu & Erduran, 2016), laboratories (Agustian, 2020; Jiménez-Aleixandre & Reigosa, 2006), and the field (Couper, 2023; Stodulka et al., 2019).

The argument for constructive epistemic alignment between phenomena, data, and explanatory models is centred on establishing science-as-practice in educational contexts, by which students are engaged in practices that reflect how scientists do science. While this is considered under-theorised in K-12 science education (Manz et al., 2020), it is even more so at tertiary level (Chen et al., 2020; Faber et al., 2022). Although science and engineering programmes often require students to conduct investigations, either laboratory-based, field-based, or computer-based, they do not necessarily engage them in reflection on epistemic alignment between phenomena, data, and explanatory models. This is often assumed rather than actually substantiated (Finne et al., 2021). Framing such alignment within the context of wicked problems and post-normal science elevates the stakes even higher, as what constitutes "evidence", "data", and "findings" may be diffused, misused, misunderstood, or even weaponised by post-truthers, as argued previously in this paper. Thus, it is even more important to engage students in epistemic practices and provide meaningful opportunities to reflect on various aspects of these practices, including how to manage uncertainties, how to identify and establish alignment between the aforementioned models, and how to address axiological queries such as moral and ethics. The next section elaborates on this concept as applied to wicked problems and post-normal science.

2.3 Epistemic Practices

In various cultural contexts, humans develop ways of knowing by means of reason, sense perception, experience, intuition, imagination, and language. An example of how this unfolds can be discerned by comparing the Temne farmers in Sierra Leone, West Africa, and the Inuit people of the Arctic Circle. Due to the differences in their geographic environments, the former being rich in colours and vegetation whereas the latter is bleak and monochromatic, the Inuit seem to have developed finer perceptual skills and knowledge that is useful for hunting and survival (Annis, 1982). In a more formal context, organisations also develop their own ways of knowing. For example, government organisations tend to follow specific protocols for gathering, analysing, and disseminating information. This may include surveys and database analyses, which may be shared through reports and public communication channels. They may also have established ways of engaging with stakeholders, such as public hearings or town hall meetings. Likewise, educational settings also provide various ways of knowing and evaluating knowledge claims, which is often formalised in terms of inquiry, modelling, experimentation, reasoning, and argumentation in science education.

A useful overarching concept for investigating these ways of knowing is "epistemic practices", which constitutes an established research tradition of its own and is underpinned by cognitive science, philosophy, anthropology, and rhetoric. In the context of science education, the concept refers to the processes and practices associated with how we propose, communicate, evaluate, and legitimise knowledge (Kelly & Licona, 2018; Manz et al., 2020). Around the time that Rittel and Webber coined the term "wicked problems", philosophical analyses of "epistemic practices" referred to an association with fallibilism (Meerbote, 1977) and critique of empiricism (Castells & de Ipola, 1976). On the one side of the debate, Meerbote argues that human knowledge and beliefs are uncertain and subject to revision based on new evidence. On the other side, Castells and de Ipola maintain that empirical evidence derived from observations and experiences is not neutral, as it is shaped by its historical and social contexts. Critical study of epistemic practices in professional science from a sociological perspective was marked by Knorr-Cetina's (1991, 1999) and Funtowicz and Ravetz's work (1990a, 1990b, 1993, 1994). Towards the end of the twentieth century, the literature on epistemic practices was thriving with multi-perspectivity encompassing science, religion, mathematics, and folkways (Alston, 1982; Azzouni, 1994; Barth, 1995; Goldman, 1993; Knorr-Cetina, 1991). However, it was not until somewhat later that the concept became explicit in science and engineering education.

In a substantial review of such a development, Duschl (2008) describes how science education goals have been shifting from a focus on content-process in the 1950s to discovery-inquiry in the 1980s and evidence-explanation in the twenty-first century. The shift is to some extent aligned with intellectual development in science studies and the learning sciences, but the reality of educational practice is often inconsistent with these contemporary scholarships. Nevertheless, some of the latest efforts to remedy such inconsistency have been reported to reduce heavy reliance on isolated, decontextualised content knowledge, and make room for more investigative and argumentative activities (Antink-Meyer & Arias, 2022; Koretsky et al., 2022; Shim & Thompson, 2022). For instance, Shim and Thompson (2022) focus on teachers' professional development aimed at fostering epistemic practices. Their longitudinal study shows that capacity building within professional learning communities seems to be an effective approach to move towards epistemic orientation in science teacher education. It also points to the potentials of such an orientation in the context of climate change education. But knowledge is still scarce as to how this could be done, particularly when climate change is conceptualised as a wicked problem. Accordingly, the introduction of wicked problems into the whole discourse adds another layer of complexity, when an approach such as transdisciplinary inquiry is to be enacted in educational settings.

The framing within post-normal science also suggests that discussions on the epistemological dimension of science, particularly when it comes to uncertainties, cannot be detached from the axiological dimension. If the fundamental argument for promoting epistemic education is to engage students in authentic, closer-to-real practices, then these two dimensions should be a part of research and instruction. In the following sub-sections, I will elaborate on how we can build on extant scholarship. To keep focus and consistency, I will refer back to the PNS framework wherever relevant.

2.3.1 Beyond Epistemic Practices in Science and Engineering Education

Discussions on epistemic practices in science education point to the importance of balancing the conceptual, social, and epistemic goals of science curricula and pedagogies (Duschl, 2008; Duschl & Grandy, 2013). I argue that technical goals should also be a part of this equation, especially in science disciplines that incorporate substantial element of practical work, be it in the laboratory, clinical settings, or out in the field. For decades, overly focus on canonical knowledge has been criticised as presenting a static image of settled science. While some of this knowledge defines disciplinary expertise and identities in higher science education, and as such, is still important to impart, it falls short when students have to grapple with unsettled science and knowledge that is still in the making (Ferguson et al., 2012), as described in the Introduction section.

The large corpus of scholarship on inquiry-based, context-based, and problem-based science education shows that learning *of* disciplinary science can be more effective when students learn to *do* science, by engaging in scientific practices such as hypothesising, experimenting, and problem solving (e.g., Agustian et al., 2022b; Dolmans et al., 2016; King, 2012; Lazonder & Harmsen, 2016; Seery, 2020). However, their implementation in practice is often still focussed on procedural processes of simplified contexts. Examples that describe this conundrum, and endeavours to resolve it, can be discerned from the literature in laboratory education and practical work (Agustian, 2022a; Dolmans et al., 2005; Hodson, 1996; Kirschner, 1992; Nicolaidou et al., 2019). This development subsequently leads to a focal shift to learning about science epistemologies through engagement in social and epistemic practices, as Duschl (2008) describes previously.

In a Kuhnian term, there seems to be a paradigmatic shift in science education from a focus on inquiry towards more epistemic orientation, centred on evidence and explanation. Important works in this area clearly demonstrate the central role of argumentation in bridging the investigative domain of science education (inquiry, experimentation, observations) with the explanatory domain (modelling and theory building) (Erduran, 2019; Erduran & Garcia-Mila, 2015; Erduran & Kaya, 2019; Jiménez-Aleixandre, 2014; Jiménez-Aleixandre & Crujeiras, 2017; Jiménez-Aleixandre & Reigosa, 2006; Kelly, 2010, 2018; Osborne, 2005). But even with such a remarkable development, research in this area is by and large contextualised in core science (the intersection between the axes in the PNS diagram, see Fig. 2), in which insights into the inner working of knowledge construction in normal science are explored in educational settings (e.g., Kelly, 2008; Mortimer & Araújo, 2014; Pabuccu & Erduran, 2016; Shim & Thompson, 2022). For instance, Mortimer and Araújo (2014) investigate epistemic practices in high school chemistry laboratories through the lens of productive disciplinary engagement, using discourse analysis of laboratory experiments in naturalistic settings. Their characterisation of epistemic practices associated with knowledge production, communication, and evaluation manifests in activities such as using different sources of data, arguing, and using data to evaluate hypothesis. However, there is a large scope for a focus on uncertainties, such as laboratory measurements and significant figures. Similar observation could also be said about empirical studies by Ageitos and colleagues (2019), Pabuccu and Erduran (2016), and Jiménez-Aleixandre and Reigosa (2006).

Evidently, a relevant body of knowledge can be discerned from a focus on epistemic uncertainty. For instance, Chen and colleagues have developed frameworks and tools to help teachers and students navigate and manage uncertainty (Chen, 2022; Chen & Qiao, 2020; Chen & Techawitthayachinda, 2021; Chen et al., 2019, 2020). In an argumentative context, which represents a key feature of epistemic practices, they suggest that teachers should indeed raise the issue of uncertainty and use it as an epistemic resource for students to collaboratively engage with. The goal is to actively find a way to reduce it, by connecting new understanding to existing knowledge, improving the coherence of arguments, and refining conceptual knowledge. Drawing on topics such as heat transfer, human body, and ecosystems, their studies show how the issue of epistemic uncertainty can be explored in K-12 core science. However, these empirical studies operate within a low uncertainty context, where the scientific knowledge with which the students engage is relatively established. To engage with very high uncertainty levels that characterise wicked problems, students will need to expand their epistemic resources. In a structured review of the norms and values of post-normal science, Kønig and colleagues (2017) argue that managing uncertainties is indeed one of the key recommendations for reflective negotiations of science advice. Within a PNS context, uncertainties are not only of epistemological but also technical, methodological, and ethical origins. Together, these are conceptualised as system uncertainties in the PNS diagram (Fig. 2).

To advance the research agenda on wicked problem inquiries and epistemic orientation in higher science education, the PNS framework suggests that we need to consider other forms of science where system uncertainties and decision stakes are higher. As mentioned previously, beyond core science, one should look into applied science, professional consultancy, and PNS itself. Timely, the literature on epistemic practices in science education has recently been accompanied by a synergistic development in engineering education (Antink-Meyer & Arias, 2022; Cunningham & Kelly, 2017; Koretsky et al., 2022). Cunningham and Kelly (2017) categorise epistemic practices in engineering that may be relevant for education, viz.

- Embedding engineering in social contexts.
- Using data and evidence to make decisions.
- Employing tools and strategies for problem solving.

- Finding solutions through creativity and innovation.

The abovementioned development is important for critical discussions on wicked problems and post-normal science, because engineering already moves beyond core disciplinary science, as the PNS framework in Fig. 2 represents. Comparison between epistemic practices in science and engineering education highlights similarities such as using systems thinking in dealing with a problem and embedding the problem in its social context, but there is a higher level of system uncertainty and decision stakes involved in engineering process designs (Clift, 2006; Funtowicz & Ravetz, 1993). In the following section, some of these ideas will be developed further to advance our understanding of epistemic practices that could be relevant for teaching using wicked problems in higher science education.

2.3.2 Towards Epistemic Practices in Post-Normal Science Education

To characterise epistemic practices in post-normal science that may be relevant for higher science education, I draw on theoretical and empirical knowledge development in inquiries into wicked problems and their implementation in education. Substantial works include Brown (Brown, 2015; Brown et al., 2010; Hocking et al., 2016), Block (Block et al., 2018, 2019, 2022), and Head (Head, 2019, 2022; Head & Alford, 2015). Akin to a host of other scholars in this field, they seem to agree that a collective, reflexive, and transdisciplinary approach is paramount to a productive, dignified, and meaningful inquiry into wicked problems (Colucci-Gray et al., 2013; Kate et al., 2019; Kønig et al., 2017; Lehtonen et al., 2019; McCune et al., 2021; Veltman et al., 2019). Higher science education is typically discipline-based, with core sciences such as chemistry, physics, and biology being taught within monodisciplinary structures and cultures (Lindvig et al., 2019). While there may be interdisciplinary courses and programmes, these deeply entrenched structures are known to be rather resistant to transformation (Lindvig, 2018; Lindvig et al., 2019; Woiwode & Froese, 2021). Transdisciplinary approach heightens the challenge even more, as it may require non-academic engagement, as shown in Fig. 3.

The diagram in Fig. 3 is drawn from empirical studies on using sustainability issues as a wicked problem in higher education (Block et al., 2019, 2022). In these studies, sustainability issues are framed, defined, and investigated within four disciplinary approaches. Representing traditional higher science education, a monodisciplinary approach draws on only one scientific discipline. In contrast, a multi-disciplinary approach investigates the issue from several disciplinary perspectives, but without crossing the boundaries between them. An interdisciplinary approach is characterised by cross-fertilisation between several scientific disciplines, visualised by the intertwined helix in the diagram. A transdisciplinary approach is different from interdisciplinary in that it may involve non-academic environment. As the diagram suggests, the latter two highlight the importance of transcending boundaries (Block et al., 2022; Lawrence, 2010).

The characterisation of multi-, inter-, and transdisciplinarity as described here represents one school of thought in the literature of disciplinarity. Others, such as Klein (2008) and Collin (2009), emphasise the transcendental aspect of transdisciplinarity, as a result of a more extended collaboration that leads to a synthesis of conceptual and methodological frameworks. Within this school of thought, interdisciplinarity is characterised by 'neighbouring disciplines with compatible epistemologies' (p. S117), whereas transdisciplinarity involves a wider range of stakeholders in society. Ontological variations in conceptualising disciplinarity are relevant for a more nuanced understanding of the notions and their

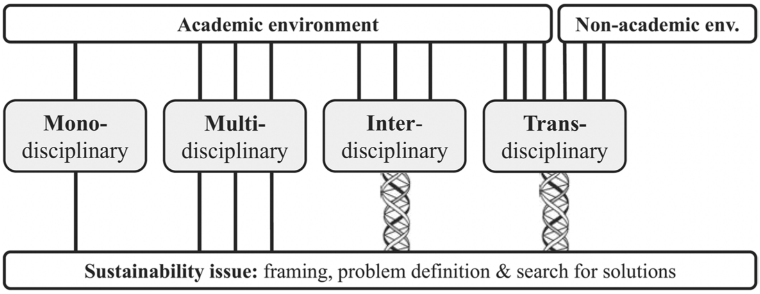

Fig. 3 Transdisciplinary vis-a-vis other disciplinary approaches to wicked problems in sustainability (Block et al., 2022)

application in educational research and practice. The diagram in Fig. 3 is presented as an example of these variations, mainly due to the proximity of contexts between sustainability issues and wicked problems. However, it is not the only possible framing. Useful insight could also be drawn from von Wehrden and colleagues (2019), as they propose five basic building blocks for inter- and transdisciplinary research, viz. (1) collective glossaries, (2) definition of boundary objects, (3) problem- and solution-oriented approaches, (4) inter- and transdisciplinary facilitator, and (5) reflexivity.

The central argument for advancing epistemic practices in post-normal science education is that research and instruction in this area should be strongly anchored in a discipline-based science education, such as in a study programme of BSc in Chemistry, but they should also meaningfully engage other relevant disciplines, not only within science, but also non-science and non-academic fields. The literature on wicked problems and post-normal science suggests that this could be done with either interdisciplinary (Brossard et al., 2019; Kate et al., 2019; Kawa et al., 2021; McCune et al., 2021) or transdisciplinary approach (Block et al., 2022; Brown, 2010, 2015; Hendriks, 2019; Shasha-Sharf & Tal, 2021). One could of course argue that wicked problems could be taught within monodisciplinary structure and culture that constrain traditional higher science education. Indeed, the educational implications in the next section are partly proposed with that in mind. In professional practices of wicked problem inquiries, the role of disciplinary expertise cannot be understated (Kawa et al., 2021). However, as argued throughout this paper, it cannot stand on its own. In either inter- or transdisciplinary approach, a synthetic and systemic view of knowledge and values are considered, and as such, higher science education with epistemic orientation focussing on wicked problem inquiries should also consider such a view.

In particular, the blend of academic and non-academic engagement in transdisciplinary inquiry commands a novel way of looking at epistemic practices. Brown (2010) intimates that such an engagement entails personal/individual, local community, specialised, and organisational epistemologies. As argued in the previous section, each of these ways of knowing has their own characteristics, but the overlaps between them and the shared epistemic goals in addressing the problem may serve as a common ground on which a new, integrated knowledge is generated. Brown refers to this novel synthesis as holistic epistemology (2010). The increasing epistemic complexity in transdisciplinary inquiry also reflects the increasing system uncertainty in post-normal science argued earlier (see Fig. 2). One could view engineering as a representation of applied science, whereas non-government organisation could play a professional consultancy role. In the context of post-normal science, Kønig and colleagues (2017) argue that “the acknowledgement and management of plural legitimate perspectives involves among other things a framework for making it possible for stakeholders to engage in constructive and open dialogue cultivating mutual learning despite different disciplinary backgrounds, conflicting interests, and value disputes” (p. 13).

To date, implementations of transdisciplinary approach still leave a sizeable scope for elucidating how the shared epistemic goals translate to research-based instruction. Equally important, knowledge is still scant as to how such a complex inquiry learning can be assessed. A recent scoping review in this journal (Daneshpour & Kwegyir-Afful, 2022) points to the need for institutional support and faculty training. Similar to the central argument presented in this section, they also argue that transdisciplinary approach to education has the potential to contribute to the development of innovative and sustainable solutions to wicked problems, as well as prepare students to become effective problem solvers and change agents in their professional and personal lives.

In the context of post-normal science education, the most enduring challenge with regard to epistemic practices is how to make sure that different epistemologies can be evaluated and legitimised in a way that respects the differences without falling into relativism, where anything goes (Brown, 2010), or tokenism, where diversity is just a skin-deep impression (Niemann, 2016). Several proponents of the focal shift to epistemic practices in education emphasise dialogic and dialectical approach (Cunningham & Kelly, 2017; Koretsky et al., 2022; Odden & Russ, 2018; Wagner, 2018), whereas others hint towards the potentials of rhetorical approach (Ageitos et al., 2019; Kelly et al., 2001). The challenge is, in a context where different sciences and non-science are to establish a meaningful discourse, how can productive, reflective, and critical inquiry be attained?

Although transdisciplinary inquiry is characterised by its complex, non-linear, and reflexive process aimed at knowledge synthesis drawn from different epistemologies (Lawrence, 2010), epistemic practices in post-normal science education should still be strongly anchored in disciplinary expertise. This needs to be asserted, lest we undermine the specialised knowledge, skills, and competences we seek to develop in our students. At the same time, the stakeholders ought to surrender some of their epistemic authority, in the spirit of knowing the other sides of the story. As previously stated, this is consistent with the principle of knowledge partiality (Feyerabend, 1999). Rarely explored educational virtue such as intellectual humility (Ballantyne, 2021) may prove to be essential in alleviating potential tensions arising from authoritative standpoints, both from science and non-science.

Science in the post-normal age brings axiology into the equation. As depicted in Fig. 2, this aspect is inevitable and inseparable from the epistemic axis. It is beyond the scope of this paper to also incorporate axiological analysis, but it does generate some implications for educational research and practice, as the following section elaborates.

3 Implications

3.1 For Educational Research

Research into epistemic practices in education has so far been predominated by science and engineering education. The conceptual framework proposed in this paper demonstrates that in the context of wicked problems, we need to extend this line of research. One of the principles of tackling wicked problems in a real-world practice is engaging different stakeholders in the process (Balint et al., 2011; Block et al., 2019; Raisio et al., 2018; Tromp, 2018). This may include professional consultancy, such as (non-)government organisations and sustainability consultants, but also local community that may have a stake in the issue, including indigenous community. Funtowicz and Ravetz (1993) argue that an extended peer community, consisting of all those with a stake in the dialogue on the issue, should be deployed to ensure the quality of scientific input related to those policies. However, the extremely diverse capacities and competences possessed by the stakeholders in such a community may complicate the process.

Therefore, we need to understand how the increasing epistemic complexity in the context of wicked problems can be addressed in a productive, dignified, and meaningful way. While this has been explored in real-life practices, albeit with crash and burn (Brown et al., 2010), higher science education is yet to make meaningful intellectual contribution. McCune and colleagues (2021) have attempted to substantiate perspectives from faculty members teaching wicked problems in different disciplines, framed within the notion of ways of thinking and practising in disciplinary contexts. There are some overlaps with ways of knowing that typify epistemic practices such as skilled communication using key concepts and particular genres of the discipline. But their study was conducted within separate disciplinary structures and cultures, so there is a scope for transdisciplinary synthesis. In that regard, research programmes on epistemic practices in post-normal science education at the university level are needed. These programmes could explore various avenues, including but not limited to:

- Characterisation of epistemic practices in post-normal science that are applicable to discipline-based higher science education.
- Enactment of these practices and investigations into its effect on the stakeholders, in terms of learning and lived experiences.
- Taxonomical classification of wicked problems in all science disciplines.
- Stakeholders' participatory research on transdisciplinary inquiry into a wicked problem pertaining to a local context.
- Investigation of how the notion of intellectual humility may alleviate the tensions arising from epistemic authority.
- Exploration of the role of ignorance in the face of epistemic complexity.

On top of the scant knowledge on the epistemic axis of the PNS nexus (see Fig. 2), we also have scarce understanding of how the axiological axis comes into play in the epistemic practices associated with wicked problems. Knowledge development in this area is understandably focussed on the epistemic aspect, but in an epoch where 'facts are uncertain, values in dispute, stakes high, and decisions urgent' (Funtowicz & Ravetz, 1993), investigations into epistemic practices should also incorporate the notions of values, ethics, and presumably also aesthetics. Specifically, how some of the cornerstones of epistemic practices (proposing, communicating, evaluating, and legitimising knowledge) affect and are affected by values, ethics, and aesthetics. In a transdisciplinary context, we may not even refer to a single knowledge, but knowledges (Brown, 2010), each with its own epistemology, underlying assumptions, biases, and limitations of knowledge. The role of philosophy of science is crucial (Jacobsen & Børsen, 2019), and further work can build on Tromp (2018), in which they argue for incorporating a more holistic, systems-based view of the world. Creative approaches using art and storytelling may also shed some light on how our values are partly shaped by aesthetics and imagination (Brown et al., 2010; Turan & Cetinkaya, 2022). There is so much to substantiate, and considering the high stakes involved in the post-normal science, higher science education can play a prominent role in leading the way forward.

3.2 For Curriculum Development

Higher science education curricula are defined by and, to a large extent, confined within monodisciplinary structures and cultures. Therefore, the introduction of transdisciplinary approach to wicked problems may require some structural and cultural adjustments. Curriculum developers in each discipline may revisit their existing curricula first and foremost to identify areas in which a potential wicked problem could be investigated in a transdisciplinary context.

They may wish to collaborate with educational researchers and consultants to scaffold this development process. Trade-offs may need to be made, but the principle of balancing the conceptual, technical, social, and epistemic goals in designing intended learning outcomes applies here.

As with any other curriculum development efforts in higher education, the process can be scaffolded at different levels (Biggs & Tang, 2011). At a course level, course leaders and their teams could look into topics that may include a wicked problem pertaining to their discipline. For example, in chemistry, one could look into chemical pollution in the environment and how it may affect various communities. The curriculum could incorporate both laboratory work and fieldwork, by which students conduct investigations and engage with stakeholders. The complication of this problem with public policy, such as described by Allen (2013), could be used as a case to investigate. Within a transdisciplinary framework, the case can be investigated in a collective inquiry involving other students from other STEM (science, engineering, technology, and mathematics) and HASS (humanities, arts, and social sciences) departments, as well as representatives from a local community affected by the issue and a non-government organisation that may be active in the field.

At a programme level, curriculum developers within and across faculties may wish to design an entire course on wicked problems. To date, several universities such as University of Sydney,[1] University of Melbourne,[2] and Aarhus University[3] offer a course on wicked problems. While designing an entire course like this may take much more into considerations, it is worth deliberating, if higher education is really striving towards meeting the challenges of today's world of wicked problems (Kawa et al., 2021). Furthermore, at least insofar as higher science education is concerned, the process of curriculum development aimed at transdisciplinarity may need to be institutionalised at the university level with both STEM and HASS disciplines coming together to engage in collective epistemic practices. The involvement of HASS disciplines in the inquiries may prove to be powerful in addressing the axiological axis of the PNS nexus, as argued previously.

[1] Wicked Problems and Policy Innovation, https://www.sydney.edu.au/units/GOVT4603

[2] Thinking Tools for Wicked Problems, https://handbook.unimelb.edu.au/subjects/unib10019

[3] Wicked Problems: Environmental Communication, Media, and Justice in the Anthropocene, https://international.au.dk/education/admissions/summeruniversity/course/wickedproblems

3.3 For Instruction

The centrality of problem in the entire discussion on wicked problems implies that instruction could largely benefit from problem-based learning (PBL) pedagogy. In particular, research-based instructional approaches can be discerned from PBL in inter- and transdisciplinary higher education settings (Jensen et al., 2019; Savin-Baden, 2016; Stentoft, 2017). Initially, PBL emerged "as a response to the identified need in educational practices of building bridges between science and academia and the complexities of real-world problems" (Jensen et al., 2019). Thus, the foundational philosophy of PBL is indeed fit for purpose in our discussion on wicked problems and post-normal science education. PBL has long been used in monodisciplinary contexts, primarily in medical education (Neville, 2008), but it typically deals with tame problems (Belland, 2019), and although there may be elements of interdisciplinarity, students do not necessarily engage in a collective inquiry involving other disciplines (Hall & Weaver, 2001). The same could be said about PBL in other sciences such as chemistry (Williams, 2019), biology (Carrió et al., 2011), and physics (Raine & Symons, 2012). So, there is a large scope for its development within transdisciplinary contexts.

Surely, the ontology of the problem matters. Traditional PBL instructions may already deal with complex problems. For example, in their extended work on PBL, Moust and colleagues (2021) typify "dilemma problems", as a kind of problem that can be used in PBL instruction in which students are asked to take a critical stance towards a subject. Likewise, Belland (2019) uses "ill-structured problems" in which students are required to critically synthesise information from multiple, credible sources. However, as described in Sect. 2.1, wicked problems are different from these tame problems in terms of their high degree of uncertainty, ambiguity, and interconnectedness. Tame problem can be complex, but they can typically be tackled using the existing PBL heuristics. The dichotomy of tame and wicked problems bifurcates PBL instructions. While much is known about the effectiveness of various PBL instructional designs (see, e.g., edited volumes by Moallem and colleagues (2019) and Walker and colleagues (2015), less is known about wicked problem solving. So, faculty interested in scholarship of teaching and learning may wish to develop their pedagogy in this area.

As many faculty can testify, balancing pedagogical approaches in teaching practices is not an easy task to accomplish, particularly when we are so used to operate within a familiar, presumably convenient framework. In a typically crowded, academic-centred university science curriculum, how much room can we feasibly make for an inter- or transdisciplinary approach to wicked problem inquiries? In a course module on Environmental Chemistry, for example, how many cases pertaining to wicked problems should be allocated for an optimal result? While there is no straightforward answer to these questions, and empirical findings are scant, faculty could draw inspiration from Tawfik and colleagues (2020) on case-based reasoning in PBL instruction using case libraries of complex, ill-structured problems. Grounded in cognitive learning theories, their findings suggest that case libraries are effective in developing students' knowledge structures pertaining to a particular complex problem, especially when they are designed to generate relevant recommendations for students to focus on. This means that students may need more than one case to engage with, to be able to build coherent schemata with which they can engage in argumentation and collaborative reflection more effectively.

PBL is of course not the only possible instructional framework in which wicked problems can be taught. Other inductive and investigative frameworks may also be effective, including inquiry-based, context-based, and ultimately research-based teaching frameworks. Whichever is chosen, the focus on epistemic practices within PBL instruction implies that all stakeholders involved in the collective inquiry into the chosen wicked problem should continually reflect on their assumptions, biases, and limitations of knowledge. As described before, the presumably different epistemologies at stake may cause tensions and conflicts. Therefore, externalisation of thinking and reasoning during group deliberations may help alleviate some of these tensions. As mentioned previously, virtues such as intellectual humility and open-mindedness are essential. In their work on transdisciplinary PBL, Jacobsen and Børsen (2019) show that students negotiate discursive positioning of self and others during a collective inquiry, but those from academic background seem to perceive themselves higher than those from professional background. They ground their perception on several aspects, notably their greater qualifications within philosophy of science. As argued throughout this paper, the role of philosophy of science and science studies in general is indispensable in advancing our knowledge of how epistemic practices in higher science education could be expanded as to encompass non-science and non-academic epistemologies. In turn, this should also inform science teaching and learning.

3.4 For Assessment

In terms of student learning, the principle of constructive alignment (Biggs, 2014) applies. Assessment on wicked problems has to be designed according to the formulated goals and in keeping with the instructional design. As mentioned before, faculty should strive to strike a balance between the conceptual, technical, social, and epistemic learning goals. Coherence and scaffolding within and across curricula are paramount to ensure that students can make sense of the assessment tasks they are given. Due to the complexity of the issue and the complication it may create in terms of students' affect and conation, conceptions of learning that depart from cognitivism are relevant to consider (Agustian et al., 2022a; Illeris, 2018). The widely substantiated notions of active and constructivist learning are applicable. But also, empirical works on wicked problem inquiries in practice point to pertinent notions such as collaborative learning, action learning, sociocultural learning, and transformative learning (Balint et al., 2011; Block et al., 2022; Brown et al., 2010; Head, 2022; Tromp, 2018). While some of these notions are not necessarily easy to assess, student learning around the core concept of wicked problems that is focussed on epistemic practices could be assessed according to the following principles.

First, departure from cognitivism means that assessment methods should consider the social, cultural, and contextual factors that influence learning, rather than acquisition of knowledge and skills in isolation. They need to be authentic and contextualised in real-world scenarios. Second, individual and collective reflections are required to verbalise students' reasoning and thinking, particularly with regard to their values, assumptions, and biases. This may be done in written formats, such as essays and reports, but more importantly also during the collaborative inquiry. The formative aspect of assessment is crucial. Likewise, feedback practices that foster self-reflection and constructive peer community are useful. This may also include extended peer community, consisting of non-academic stakeholders, as Funtowicz and Ravetz (1993) suggest.

4 Conclusion

I have presented a conceptual framework for teaching using wicked problems by focusing on epistemic practices. Philosophical analysis of wicked problems indicates that the framing of post-normal science could be useful in advancing our understanding of epistemic practices in higher science education. I have done so by extending the existing work in science and engineering education. The notion of transdisciplinarity arises from the epistemic and axiological complexity inherent in wicked problems. This has several implications for educational research on epistemic practices, as the current scholarship tends to be confined within disciplinary structures. It also necessitates stakeholder engagement in the process. The typical monodisciplinary structures and cultures in higher science education may become a challenge in fostering productive, dignified, and meaningful transdisciplinary inquiries into wicked problems, but several possible avenues for scholarship of teaching and learning in this area have been proposed. The high stake decisions characterising post-normal science highlight the imperative nature of addressing wicked problems, and higher science education can make meaningful contribution to the advancement of the understanding of epistemic practices in this context.

Acknowledgements The author would like to thank the University Science Education and the History and Philosophy of Science research groups at University of Copenhagen, Professor Kristine Harper, Professor Sibel Erduran, and Professor Hanne Andersen for their valuable feedback on this paper.

Funding Open access funding provided by Royal Library, Copenhagen University Library

Declarations

Conflict of Interest The author declares no conflict of interest.

References

Adam, R. J. (2016). *Education for wicked problems and the reconciliation of opposites: A theory of bi-directional development*. London: Routledge.

Ageitos, N., Puig, B., & Colucci-Gray, L. (2019). Examining reasoning practices and epistemic actions to explore students' understanding of genetics and evolution. *Science and Education, 28*(9–10), 1209–1233.

Alford, J., & Head, B. W. (2017). Wicked and less wicked problems: A typology and a contingency framework. *Policy and Society, 36*(3), 397–413.

Allen, J. H. (2013). The wicked problem of chemicals policy: Opportunities for innovation. *Journal of Environmental Studies and Sciences, 3*(2), 101–108.

Alston, W. P. (1982). Religious experience and religious belief. *Noûs, 16*(1), 3–12.

Annis, D. B. (1982). Epistemology naturalized. Source. *Metaphilosophy, 13*(3), 201–208.

Antink-Meyer, A., & Arias, A. M. (2022). Teachers' incorporation of epistemic practices in K-8 engineering and their views about the nature of engineering knowledge. *Science and Education, 31*(2), 357–382.

Agustian, H. Y. (2019). Systematic review of research in the nature of science, 1963-2019. *North American Association for Philosophy and Education Conference*.

Agustian, H. Y. (2020). Students' understanding of the nature of science in the context of undergraduate chemistry laboratory. *Electronic Journal of Research in Science and Mathematics Education, 24*(2), 56–85.

Agustian, H. Y., Finne, L. T., Jørgensen, J. T., Pedersen, M. I., Christiansen, F. V., Gammelgaard, B., & Nielsen, J. A. (2022a). Learning outcomes of university chemistry teaching in laboratories: A systematic review of empirical literature. *Review of Education, 10*(2), e3360.

Agustian, H. Y., Pedersen, M. I., Finne, L. T., Jørgensen, J. T., Nielsen, J. A., & Gammelgaard, B. (2022b). Danish university faculty perspectives on student learning outcomes in the teaching laboratories of a pharmaceutical sciences education. *Journal of Chemical Education, 99*(11), 3633–3643.

Azzouni, J. (1994). *Metaphysical myths, mathematical practice: The ontology and epistemology of the exact sciences*. Cambridge: Cambridge University Press.

Balint, P. J., Stewart, R. E., Desai, A., & Walters, L. C. (2011). *Wicked environmental problems: Managing uncertainty and conflict*. Washington: Island Press.

Ballantyne, N. (2021). Recent work on intellectual humility: A philosopher's perspective. Journal of Positive Psychology, 1–21.

Barak, M., Ginzburg, T., & Erduran, S. (2022). Nature of engineering: A cognitive and epistemic account with implications for engineering education. Science & Education.

Barth, F. (1995). Other knowledge and other ways of knowing. *Journal of Anthropological Research, 51*, 65–68.

Baytelman, A., Iordanou, K., & Constantinou, C. P. (2020). Epistemic beliefs and prior knowledge as predictors of the construction of different types of arguments on socioscientific issues. *Journal of Research in Science Teaching, 57*(8), 1199–1227. https://doi.org/10.1002/tea.21627

Belland, B. R. (2019). Technology applications to support teachers' design and facilitation of, and students' participation in PBL. In M. Moallem, W. Hung, & N. Dabbagh (Eds.), *The Wiley Handbook of Problem-Based Learning*. Wiley Blackwell: Hoboken.

Biggs, J. (2014). Constructive alignment in university teaching. *HERDSA Review of Higher Education, 1*, 5–22.

Biggs, J., & Tang, C. (2011). *Teaching for quality learning at university* (4th ed.). Maidenhead: Open University Press.

Block, T., Goeminne, G., & Van Poeck, K. (2018). Balancing the urgency and wickedness of sustainability challenges: Three maxims for post-normal education. *Environmental Education Research, 24*(9), 1424–1439.

Block, T., Provè, C., Dehaene, M., Abeele, P. V., & Beeckmans, L. (2022). Understanding urban sustainability from mode 2 science and transdisciplinary education: How master thesis ateliers of the Ghent Stadsacademie tackle wicked issues. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-022-02657-0

Block, T., Van Poeck, K., & Östman, L. (2019). Tackling wicked problems in teaching and learning. Sustainability issues as knowledge, ethical and political challenges. In K. Van Poeck, L. Östman, & J. Öhman (Eds.), *Sustainable Development Teaching*. London: Routledge.

Boyd, R., Gasper, P., & Trout, J. D. (Eds.). (1991). *The philosophy of science*. Cambridge: The MIT Press.

Briz-Redón, Á., & Serrano-Aroca, Á. (2020). The effect of climate on the spread of the COVID-19 pandemic: A review of findings, and statistical and modelling techniques. *Progress in Physical Geography, 44*(5), 591–604.

Brossard, D., Belluck, P., Gould, F., & Wirz, C. D. (2019). Promises and perils of gene drives: Navigating the communication of complex, post-normal science. *Proceedings of the National Academy of Sciences of the United States of America, 116*(16), 7692–7697.

Brown, V. A. (2010). Collective inquiry and its wicked problems. In V. A. Brown, J. A. Harris, & J. Y. Russell (Eds.), *Tackling wicked problems: Through the transdisciplinary imagination* (pp. 61–83). Earthscan.

Brown, V. A. (2015). Utopian thinking and the collective mind: Beyond transdisciplinarity. *Futures, 65*, 209–216.

Brown, V. A., Harris, J. A., & Russell, J. Y. (2010). *Tackling wicked problems: Through the transdisciplinary imagination*. London: Earthscan.

Carrió, M., Larramona, P., Baños, J. E., & Pérez, J. (2011). The effectiveness of the hybrid problem-based learning approach in the teaching of biology: A comparison with lecture-based learning. *Journal of Biological Education, 45*(4), 229–235.

Carter, L. (2011). Gathering in threads in the insensible global world: The wicked problem of globalisation and science education. *Cultural Studies of Science Education, 6*, 1–12.

Castells, M., & de Ipola, E. (1976). Epistemological practice and the social sciences. *Economy and Society, 5*(2), 111–144.

Castree, N., Hulme, M., & Proctor, J. D. (Eds.). (2018). *Companion to environmental studies*. London: Routledge.

Chen, Y. C. (2022). Epistemic uncertainty and the support of productive struggle during scientific modeling for knowledge co-development. *Journal of Research in Science Teaching, 59*(3), 383–422.

Chen, Y. C., & Qiao, X. (2020). Using students' epistemic uncertainty as a pedagogical resource to develop knowledge in argumentation. *International Journal of Science Education, 42*(13), 2145–2180.

Chen, Y. C., & Techawitthayachinda, R. (2021). Developing deep learning in science classrooms: Tactics to manage epistemic uncertainty during whole-class discussion. *Journal of Research in Science Teaching, 58*(8), 1083–1116. https://doi.org/10.1002/tea.21693

Chen, Y. C., Benus, M. J., & Hernandez, J. (2019). Managing uncertainty in scientific argumentation. *Science Education, 103*(5), 1235–1276.

Chen, Y. C., Aguirre-Mendez, C., & Terada, T. (2020). Argumentative writing as a tool to develop conceptual and epistemic knowledge in a college chemistry course designed for non-science majors. *International Journal of Science Education, 42*(17), 2842–2875.

Chinn, C. A., Barzilai, S., & Duncan, R. G. (2021). Education for a "post-truth" world: New directions for research and practice. *Educational Researcher, 50*(1), 51–60.

Clift, R. (2006). Sustainable development and its implications for chemical engineering. *Chemical Engineering Science, 61*(13), 4179–4187.

Collin, A. (2009). Multidisciplinary, interdisciplinary, and transdisciplinary collaboration: Implications for vocational psychology. *International Journal for Educational and Vocational Guidance, 9*, 101–110.

Colucci-Gray, L., Perazzone, A., Dodman, M., & Camino, E. (2013). Science education for sustainability, epistemological reflections and educational practices: From natural sciences to trans-disciplinarity. *Cultural Studies of Science Education, 8*(1), 127–183.

Cook, K. (2015). Grappling with wicked problems: Exploring photovoice as a decolonizing methodology in science education. *Cultural Studies of Science Education, 10*, 581–592.

Couper, P. R. (2023). Interpretive field geomorphology as cognitive, social, embodied and affective epistemic practice. *Canadian Geographer*. https://doi.org/10.1111/cag.12821

Cunningham, C. M., & Kelly, G. J. (2017). Epistemic practices of engineering for education. *Science Education, 101*(3), 486–505.

Daneshpour, H., & Kwegyir-Afful, E. (2022). Analysing transdisciplinary education: A scoping review. *Science and Education, 31*(4), 1047–1074.

Dolmans, D. H. J. M., De Grave, W., Wolfhagen, I. H. A. P., & Van Der Vleuten, C. P. M. (2005). Problem-based learning: Future challenges for educational practice and research. *Medical Education, 39*(7), 732–741.

Dolmans, D. H. J. M., Loyens, S. M. M., Marcq, H., & Gijbels, D. (2016). Deep and surface learning in problem-based learning: A review of the literature. *Advances in Health Sciences Education, 21*(5), 1087–1112.

Duschl, R. A. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. *Review of Research in Education, 32*, 268–291.

Duschl, R. A., & Grandy, R. (2013). Two views about explicitly teaching nature of science. *Science and Education, 22*(9), 2109–2139.

Elby, A., Macrander, C., & Hammer, D. (2016). Epistemic cognition in science. In J. A. Greene, W. A. Sandoval, & I. Bråten (Eds.), *Handbook of Epistemic Cognition* (Issue October, pp. 113–127). London: Routledge.

Erduran, S. (2020). Science education in the era of a pandemic: How can history, philosophy and sociology of science contribute to education for understanding and solving the Covid-19 crisis? *Science and Education, 29*(2), 233–235.

Erduran, S. (2021). Science education and the pandemic, 1 year on. *Science and Education, 30*(2), 201–204.

Erduran, S. (2022). Trust in science and science education — Part 1. *Science and Education, 31*(5), 1101–1104.

Erduran, S., & Garcia-Mila, M. (2015). Epistemic practices and thinking in science: Fostering teachers' development in scientific argumentation. In R. Wegerif, L. Li, & J. C. Kaufman (Eds.), *The Routledge International Handbook of Research on Teaching Thinking* (pp. 412–425). Routledge.

Erduran, S., & Kaya, E. (2019). *Transforming teacher education through the epistemic core of chemistry: Empirical evidence and practical strategies*. Dordrecht: Springer.

Erduran, S. (2019). *Argumentation in chemistry education: research, policy and practice* (S. Erduran, Ed.). London: The Royal Society of Chemistry.

Ericson, R. V., & Haggerty, K. D. (1997). *Policing the risk society*. University of Toronto Press.

Faber, C. J., Kajfez, R. L., Lee, D. M., Benson, L. C., Kennedy, M. S., & Creamer, E. G. (2022). A grounded theory model of the dynamics of undergraduate engineering students' researcher identity and epistemic thinking. *Journal of Research in Science Teaching, 59*(4), 529–560.

Farrell, K. N. (2020). Untrol: Post-truth and the new normal of post-normal science. *Social Epistemology, 34*(4), 330–345. https://doi.org/10.1080/02691728.2019.1706117

Ferguson, L. E., Bråten, I., & Strømsø, H. I. (2012). Epistemic cognition when students read multiple documents containing conflicting scientific evidence: A think-aloud study. *Learning and Instruction, 22*(2), 103–120.

Feyerabend, P. K. (1999). *Knowledge, science and relativism* (J. Preston, Ed.; Vol. 3). Cambridge: Cambridge University Press.

Finne, L. T., Gammelgaard, B., & Christiansen, F. V. (2021). When the lab work disappears: Students' perception of laboratory teaching for quality learning. *Journal of Chemical Education, 99*, 1766–1774.

Foucault, M. (2002). *Archaeology of knowledge*. Routledge.

Funtowicz, S. O., & Ravetz, J. R. (1990a). A new scientific methodology for global environmental issues. In R. Costanza (Ed.), *Ecological Economics: The Science and Management of Sustainability* (pp. 137–153). Columbia University Press.

Funtowicz, S. O., & Ravetz, J. R. (1990b). *Uncertainty and quality in science for policy*. Kluwer Academic Publishers.

Funtowicz, S. O., & Ravetz, J. R. (1993). Science for the post-normal age. *Futures, 25*(7), 739–755.

Funtowicz, S. O., & Ravetz, J. R. (1994). The worth of a songbird: Ecological economics as a post-normal science. *Ecological Economics, 10*, 197–207.

Funtowicz, S. O., & Ravetz, J. R. (2018). Post-normal science. In N. Castree, M. Hulme, & J. D. Proctor (Eds.), *Companion to Environmental Studies* (pp. 443–447). Routledge.

Gattie, D. K., Kellam, N. N., Schramski, J. R., & Walther, J. (2011). Engineering education as a complex system. *European Journal of Engineering Education, 36*(6), 521–535.

Goldman, A. I. (1993). Epistemic folkways and scientific epistemology. *Philosophical Issues, 3*, 271–285.

Hall, P., & Weaver, L. (2001). Interdisciplinary education and teamwork: A long and winding road. *Medical Education, 35*(9), 867–875.

Hammer, D., Russ, R. S., Mikeska, J., & Scherr, R. (2008). Identifying inquiry and conceptualizing students' abilities. In R. A. Duschl & R. Grandy (Eds.), *Teaching Scientific Inquiry*. Leiden: Brill.

Head, B. W. (2019). Forty years of wicked problems literature: Forging closer links to policy studies. *Policy and Society, 38*(2), 180–197.

Head, B. W., & Alford, J. (2015). Wicked problems: Implications for public policy and management. *Administration and Society, 47*(6), 711–739.

Head, B. W. (2022). *Wicked problems in public policy: Understanding and responding to complex challenges*. Cham: Palgrave Macmillan.

Hendriks, S. L. (2019). Food security policy analysis as a key element in attaining SGD2 and addressing food policy failures of the past. In S. L. Hendriks (Ed.), *Food Security Policy, Evaluation and Impact Assessment* (pp. 3–8). Routledge.

Hocking, V. T., Brown, V. A., & Harris, J. A. (2016). Tackling wicked problems through collective design. *Intelligent Buildings International, 8*(1), 24–36.

Hodson, D. (1996). Practical work in school science: Exploring some directions for change. *International Journal of Science Education, 18*(7), 755–760.

Illeris, K. (2018). A comprehensive understanding of human learning. In K. Illeris (Ed.), *Contemporary Theories of Learning: … in Their Own Words* (pp. 1–14). Routledge.

Jacobsen, A. J., & Børsen, T. (2019). Students' positioning in transdisciplinary project-based learning. In A. A. Jensen, D. Stentoft, & O. Ravn (Eds.), *Interdisciplinarity and Problem-Based Learning in Higher Education* (pp. 117–132). Springer.

Jensen, A. A., Stentoft, D., & Ravn, O. (Eds.). (2019). *Interdisciplinarity and problem-based learning in higher education*. Dordrecht: Springer.

Jiménez-Aleixandre, M. P. (2014). Determinism and underdetermination in genetics: Implications for students' engagement in argumentation and epistemic practices. *Science and Education, 23*(2), 465–484.

Jiménez-Aleixandre, M. P., & Crujeiras, B. (2017). Epistemic practices and scientific practices in science education. In K. S. Taber & B. Akpan (Eds.), *Science Education: An International Course Companion* (pp. 69–80). Sense Publishers.

Jiménez-Aleixandre, M. P., & Reigosa, C. (2006). Contextualizing practices across epistemic levels in the chemistry laboratory. *Science Education, 90*(4), 707–733.

Jones, K. (2020). Fake news, artificial intelligence, mobile divisions, likely futures? Debates on digital technologies in mathematics education. In G. Ineson & H. Povey (Eds.), *Debates on Mathematics Education* (pp. 155–168). Routledge.
Kate, H., James, J., & Tidmarsh, C. (2019). Using wicked problems to foster interdisciplinary practice among UK trainee teachers. *Journal of Education for Teaching, 45*(4), 446–460.
Kawa, N. C., Arceño, M. A., Goeckner, R., Hunter, C. E., Rhue, S. J., Scaggs, S. A., Biwer, M. E., Downey, S. S., Field, J. S., Gremillion, K., McCorriston, J., Willow, A., Newton, E., & Moritz, M. (2021). Training wicked scientists for a world of wicked problems. *Humanities and Social Sciences Communications, 8*(1), 1–4.
Kelly, G. J. (2008). Inquiry, activity, and epistemic practice. In R. A. Duschl & R. E. Grandy (Eds.), *Teaching Scientific Inquiry* (pp. 99–201). Sense Publishers.
Kelly, G. J. (2010). Scientific literacy, discourse and epistemic practices. In C. Linder, L. Östman, D. A. Roberts, P.-O. Wickman, G. Ericksen, & A. MacKinnon (Eds.), *Exploring the Landscape of Scientific Literacy* (pp. 71–83). Routledge.
Kelly, G. J. (2018). Developing epistemic aims and supports for engaging students in scientific practices. *Science and Education, 27*(3–4), 245–246.
Kelly, G. J., Crawford, T., & Green, J. (2001). Common task and uncommon knowledge: Dissenting voices in the discursive construction of physics across small laboratory groups. *Linguistics and Education, 12*(2), 135–174.
Kelly, G. J., & Licona, P. (2018). Epistemic practices and science education. In *Science: Philosophy, History and Education* (pp. 139–165). Dordrecht: Springer.
Kienhues, D., Jucks, R., & Bromme, R. (2020). Sealing the gateways for post-truthism: Reestablishing the epistemic authority of science. *Educational Psychologist, 55*(3), 144–154.
King, D. (2012). New perspectives on context-based chemistry education: Using a dialectical sociocultural approach to view teaching and learning. *Studies in Science Education, 48*(1), 51–87.
Kirschner, P. A. (1992). Epistemology, practical work and academic skills in science education. *Science and Education, 1*(3), 273–299.
Klein, J. T. (2008). Evaluation of interdisciplinary and transdisciplinary research: A literature review. *American Journal of Preventive Medicine, 35*(2), S116–S123.
Klopfer, L. E., & Cooley, W. W. (1963). The history of science cases for high schools in the development of student understanding of science and scientists: A report on the HOSG instruction project. *Journal of Research in Science Teaching, 1*(1), 33–47.
Knorr-Cetina, K. D. (1991). Epistemic cultures: Forms of reason in science. *History of Political Economy, 23*(1), 105–122.
Knorr-Cetina, K. D. (1999). *Epistemic cultures: How the sciences make knowledge*. Cambridge: Harvard University Press.
Kønig, N., Børsen, T., & Emmeche, C. (2017). The ethos of post-normal science. *Futures, 91*, 12–24.
Koretsky, M. D., Nefcy, E. J., Nolen, S. B., & Champagne, A. B. (2022). Connected epistemic practices in laboratory-based engineering design projects for large-course instruction. *Science Education, 106*, 674–705.
Kreps, S. E., & Kriner, D. L. (2020). Model uncertainty, political contestation, and public trust in science: Evidence from the COVID-19 pandemic. *Science Advances, 6*(43), 1–12.
Kuhn, T. S. (1962). *The structure of scientific revolutions*. Chicago: The University of Chicago Press.
Lakatos, I. (1978). *The methodology of scientific research programmes* (J. Worrall & G. Currie, Eds.). Cambridge: Cambridge University Press.
Latour, B., & Woolgar, S. (1986). *Laboratory life: The construction of scientific facts*. Princeton: Princeton University Press.
Laudan, L. (1996). *Beyond positivism and relativism: Theory, method, and evidence*. Westview Press.
Lawrence, R. J. (2010). Beyond disciplinary confinement to imaginative transdisciplinarity. In V. A. Brown, J. A. Harris, & J. Y. Russell (Eds.), *Tackling Wicked Problems: Through the Transdisciplinary Imagination* (pp. 16–30). Earthscan.
Lazonder, A. W., & Harmsen, R. (2016). Meta-analysis of inquiry-based learning: Effects of guidance. *Review of Educational Research, 86*(3), 681–718.
Lederman, N. G. (1992). Students' and teachers' conceptions of the nature of science: A review of the research. *Journal of Research in Science Teaching, 29*(4), 331–359.
Lehtonen, A., Salonen, A. O., & Cantell, H. (2019). Climate change education: A new approach for a world of wicked problems. In J. W. Cook (Ed.), *Sustainability, Human Well-Being, and the Future of Education*. Cham: Palgrave Macmillan.
Lidskog, R., & Lofmarck, E. (2015). Managing uncertainty: Forest professionals' claim and epistemic authority in the face of societal and climate change. *Risk Management, 17*(3), 145–164.

Lindvig, K. (2018). The implied PhD student of interdisciplinary research projects within monodisciplinary structures. *Higher Education Research and Development, 37*(6), 1171–1185.

Lindvig, K., Lyall, C., & Meagher, L. R. (2019). Creating interdisciplinary education within monodisciplinary structures: The art of managing interstitiality. *Studies in Higher Education, 44*(2), 347–360.

Lönngren, J., & van Poeck, K. (2021). Wicked problems: A mapping review of the literature. *International Journal of Sustainable Development and World Ecology, 28*(6), 481–502.

Mackay, L. D. (1971). Development of understanding about the nature of science. *Journal of Research in Science Teaching, 8*(1), 57–66.

Mackey, T. P. (2019). Empowering metaliterate learners for the post-truth world. In T. P. Mackey & T. E. Jacobson (Eds.), *Metaliterate Learning for the Post-Truth World* (pp. 1–32). American Library Association.

Maeng, S. (2021). Explicating epistemic process in elementary students' language use by practical epistemology and discourse register analyses. *Research in Science Education, 51*(1), 153–170.

Mahaffy, P. G., Krief, A., Hopf, H., Mehta, G., & Matlin, S. A. (2018). Reorienting chemistry education through systems thinking. *Nature Reviews: Chemistry, 2*(4), 1–3.

Manz, E., Lehrer, R., & Schauble, L. (2020). Rethinking the classroom science investigation. *Journal of Research in Science Teaching, 57*(7), 1148–1174.

Matthews, M. R. (2018). *History, philosophy and science teaching - New perspectives*. Springer.

McComas, W. F., Almazroa, H., & Clough, M. P. (1998). The nature of science in science education: An introduction. *Science & Education, 7*(6), 511–532.

McCune, V., Tauritz, R., Boyd, S., Cross, A., Higgins, P., & Scoles, J. (2021). Teaching wicked problems in higher education: Ways of thinking and practising. *Teaching in Higher Education*. https://doi.org/10.1080/13562517.2021.1911986

Meerbote, R. (1977). Fallibillism and the possibility of being mistaken. *Philosophical Studies, 32*, 143–154.

Moallem, M., Hung, W., & Dabbagh, N. (Eds.). (2019). *The Wiley Handbook of Problem-Based Learning*. Hoboken: Wiley Blackwell.

Mogk, D. W., & Goodwin, C. (2012). Learning in the field: Synthesis of research on thinking and learning in the geosciences. *Special Paper of the Geological Society of America, 486*, 131–163.

Moravčíková, E. (2020). Media manipulation and propaganda in the post-truth era. *Media Literacy and Academic Research, 3*(2), 23–37.

Mortimer, E. F., & de Araújo, A. O. (2014). Using productive disciplinary engagement and epistemic practices to evaluate a traditional Brazilian high school chemistry classroom. *International Journal of Educational Research, 64*, 156–169.

Moust, J., Bouhuijs, P., & Schmidt, H. (2021). *Introduction to problem-based Learning*. Groningen: Noordhoff Uitgevers.

Murakami, C. D., Hendrickson, M. K., & Siegel, M. A. (2017). Sociocultural tensions and wicked problems in sustainable agriculture education Advanced Practices of Sustainable Agriculture. *Agriculture and Human Values, 34*(3), 591–606.

National Academies of Sciences. (2021). *Call to action for science education: Building opportunity for the future*. Washington, DC: The National Academies Press.

Neville, A. J. (2008). Problem-based learning and medical education forty years on: A review of its effects on knowledge and clinical performance. In *Medical Principles and Practice* (Vol. 18, Issue 1, pp. 1–9). https://doi.org/10.1159/000163038

Nicolaidou, V., Nicolaou, P., & Nicolaou, S. A. (2019). Transforming a cookbook undergraduate microbiology laboratory to inquiry based using a semester-long PBL case study. *Advances in Physiology Education, 43*(1), 82–92.

Niemann, Y. F. (2016). The social ecology of tokenism in higher education. *Peace Review, 28*(4), 451–458.

O'Brien, K. (2013). Global environmental change III: Closing the gap between knowledge and action. *Progress in Human Geography, 37*(4), 587–596.

Odden, T. O. B., & Russ, R. S. (2018). Sensemaking epistemic game: A model of student sensemaking processes in introductory physics. *Physical Review Physics Education Research, 14*(2), 20122.

Osborne, J., & Pimentel, D. (2022). Science, misinformation, and the role of education. *Science, 378*(6617), 246–248.

Osborne, J. (2005). The role of argument in science education. In K. Boersma, M. Goedhart, O. e Jong, & H. Eijkelhof (Eds.), *Research and the Quality of Science Education.* Dordrecht: Springer.

Pabuccu, A., & Erduran, S. (2016). Investigating students' engagement in epistemic and narrative practices of chemistry in the context of a story on gas behavior. *Chemistry Education Research and Practice, 17*(3), 523–531.

Pietrocola, M., Rodrigues, E., Bercot, F., & Schnorr, S. (2021). Risk society and science education: Lessons from the Covid-19 pandemic. *Science & Education, 30*(2), 209–233.

Popper, K. (2005). *The Logic of Scientific Discovery*. Routledge.

Raine, D., & Symons, S. (2012). Problem-based learning: Undergraduate physics by research. *Contemporary Physics, 53*(1), 39–51.

Raisio, H., Puustinen, A., & Vartiainen, P. (2018). The concept of wicked problems: Improving the understanding of managing problem wickedness in health and social care. In *The Management of Wicked Problems in Health and Social Care* (pp. 3–20). London: Routledge.

Ravetz, J. R. (1986). Usable knowledge, usable ignorance: Incomplete science with policy implications. In W. C. Clark & R. E. Munn (Eds.), *Sustainable Development of the Biosphere* (pp. 415–434). Cambridge University Press.

Reichel, A., & Perey, R. (2018). Moving beyond growth in the Anthropocene. *Anthropocene Review, 5*(3), 242–249.

Renn, J. (2020). *The evolution of knowledge: Rethinking science for the anthropocene*. Princeton: Princeton University Press.

Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sciences, 4*(2), 155–169.

Russell, J. Y. (2010). A philosophical framework for an open and critical transdisciplinary inquiry. In V. A. Brown, J. A. Harris, & J. Y. Russell (Eds.), *Tackling Wicked Problems: Through the Transdisciplinary Imagination* (pp. 31–60). Earthscan.

Sadler, T. D., Foulk, J. A., & Friedrichsen, P. J. (2017). Evolution of a model for socio-scientific issue teaching and learning. *International Journal of Education in Mathematics, Science and Technology, 5*(1), 75.

Sahin, O., Salim, H., Suprun, E., Richards, R., Macaskill, S., Heilgeist, S., Rutherford, S., Stewart, R. A., & Beal, C. D. (2020). Developing a preliminary causal loop diagram for understanding the wicked complexity of the COVID-19 pandemic. *Systems, 8*(2), 1–9.

Sandoval, W. A. (2005). Understanding students' practical epistemologies and their influence on learning through inquiry. *Science Education, 89*(4), 634–656.

Savin-Baden, M. (2016). The impact of transdisciplinary threshold concepts on student engagement in problem-based learning: A conceptual synthesis. *Interdisciplinary Journal of Problem-Based Learning, 10*(2), 1–22.

Schiefloe, P. M. (2021). The corona crisis: A wicked problem. *Scandinavian Journal of Public Health, 49*(1), 5–8.

Seery, M. K. (2020). Establishing the laboratory as the place to learn how to do chemistry. *Journal of Chemical Education, 97*(6), 1508–1511.

Serugendo, M. D. G., Risoldi, M., & Solemayni, M. (2014). The social computer. In J. Pitt (Ed.), *The Computer After Me: Awareness and Self-Awareness in Autonomic Systems* (pp. 159–172). Imperial College Press.

Shasha-Sharf, H., & Tal, T. (2021). Who benefits from the natural gas in Israel? Using a public debate to teach all components of education for sustainable development. In *Contributions from Science Education Research* (Vol. 8, pp. 121–147). Dordrecht: Springer.

Shim, S. Y., & Thompson, J. (2022). Four years of collaboration in a professional learning community: Shifting toward supporting students' epistemic practices. *Science Education, 106*(3), 674–705.

Stentoft, D. (2017). From saying to doing interdisciplinary learning: Is problem-based learning the answer? *Active Learning in Higher Education, 18*(1), 51–61.

Stodulka, T., Dinkelaker, S., & Thajib, F. (2019). Fieldwork, ethnography and the empirical affect montage. *Analyzing Affective Societies: Methods and Methodologies* (pp. 279–295). Abingdon: Taylor and Francis.

Sturgis, P., Brunton-Smith, I., & Jackson, J. (2021). Trust in science, social consensus and vaccine confidence. *Nature Human Behaviour, 5*(11), 1528–1534.

Tawfik, A. A., Kim, K., & Kim, D. (2020). Effects of case library recommendation system on problem solving and knowledge structure development. *Educational Technology Research and Development, 68*(3), 1329–1353. https://doi.org/10.1007/s11423-020-09737-w

Tidemand, S., & Nielsen, J. A. (2017). The role of socioscientific issues in biology teaching: From the perspective of teachers. *International Journal of Science Education, 39*(1), 44–61.

Tromp, C. (2018). *Wicked philosophy: Philosophy of science and vision development for complex problems*. Amsterdam: Amsterdam University Press.

Tsey, K. (2019). *Working on wicked problems: A strengths-based approach to research engagement and impact*. Dordrecht: Springer Nature.

Turan, F. K., & Cetinkaya, S. (2022). The role of aesthetics and art in organizational sustainability: A conceptual model and exploratory study in higher education. *Sustainable Development, 30*(1), 83–95.

Turnpenny, J., Jones, M., & Lorenzoni, I. (2011). Where now for post-normal science?: A critical review of its development, definitions, and uses. *Science, Technology and Human Values, 36*(3), 287–306.

Veltman, M. E., Van Keulen, J., & Voogt, J. M. (2019). Design principles for addressing wicked problems through boundary crossing in higher professional education. *Journal of Education and Work, 32*(2), 135–155.

Wagner, P. A. (2018). Warranted indoctrination in science education. In M. R. Matthews (Ed.), *History, Philosophy and Science Teaching* (pp. 307–315). Springer.

Walker, A., Leary, H., Hmelo-Silver, C., & Ertmer, P. A. (2015). *Essential Readings in Problem-based Learning: Exploring and Extending the Legacy of Howard S. Barrows*. Purdue University Press.

von Wehrden, H., Guimarães, M. H., Bina, O., Varanda, M., Lang, D. J., John, B., ... & Lawrence, R. J. (2019). Interdisciplinary and transdisciplinary research: Finding the common ground of multi-faceted concepts. *Sustainability Science, 14*, 875–888.

Williams, D. P. (2019). Context- and problem-based learning in chemistry in higher education. In M. K. Seery & C. McDonnell (Eds.), *Teaching chemistry in higher education: A Festschrift in honour of Professor Tina Overton* (pp. 123–136). Creathach Press.

Woiwode, H., & Froese, A. (2021). Two hearts beating in a research centers' chest: How scholars in interdisciplinary research settings cope with monodisciplinary deep structures. *Studies in Higher Education, 46*(11), 2230–2244.

Yang, F.-Y., & Tsai, C.-C. (2012). Personal epistemology and science learning: A review on empirical studies. In B. J. Fraser, K. G. Tobin, & C. J. McRobbie (Eds.), *Second International Handbook of Science Education*. Cham: Springer Science & Business Media.

Zeidler, D. L., & Sadler, T. D. (2023). Exploring and expanding the frontiers of socioscientific issues. In *Handbook of Research on Science Education* (pp. 899–929). London: Routledge.