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ChemoKnowings as Part of 21st Century *Bildung* and Subject Didaktik

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In this article, we elaborate on the construct ChemoKnowings as subject-specific powerful knowings for chemical agency in the Anthropocene era. Related to constructs such as critical chemical literacy, ChemoCapabilities, and eco-reflexive chemical thinking, we unpack the construct as an example of Carlgren's powerful knowings, which relates Young's powerful knowledge to the idea and tradition of *Bildung*. It means powerful knowledge containing embodied and relational (or tacit) dimensions. ChemoKnowings can therefore be described as embodied and relational knowledge in and about chemistry – (critical) chemical knowledge that matters meaningfully to the student, connecting them to themselves and the world, and conferring an ethical compass. By situating the teaching of ChemoKnowings within a vision for chemistry teaching as a part of a world-centered vision for schooling in the Anthropocene, ChemoKnowings are viewed as having the capacity to mobilise an ethico-socio-political action, that is, chemical agency. By focusing on student transformation of content for ChemoKnowings and integrating elements of a theoretical didaktik model for eco-reflexive chemistry education, we develop a vision-oriented didaktik model for ChemoKnowings. More generally, we argue that didaktik models for supporting teachers' consideration of student transformation of content for powerful subject-knowings are an important part of general subject didaktik. We present in the article vignettes that detail personal accounts for each of the three authors describing examples of chemistry-specific knowings that matter meaningfully to each of us, and which articulate our own embodied ethico-socio-political actions as students, teachers, researchers, and consumers. Inspired by Klafki's didaktik analysis, we end the article by proposing four areas of questions that the teacher can use in guiding their preparation and transformation of the content they bring into the classroom for promoting students' ChemoKnowings, and thus *Bildung* in the 21st century.

Keywords: didaktik, Anthropocene, powerful knowings, eco-reflexive *Bildung*, embodied knowledge, chemistry education, critical chemical literacy, agency

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INTRODUCTION

Scientists declared the era of our unsustainable ways of living the Anthropocene (Crutzen and Stoermer, 2000). The school needs to be reoriented toward navigating today's complexity and challenges stemming from the issues of socio-ecojustice and human impacts on the systems of the Earth resulting in, e.g., climate change, biodiversity loss, floods, and health-related issues.

However, at the same time schooling is increasingly impacted by an economic perspective that results in education being viewed as a cause of economic growth through human capital production (e.g., Sundberg and Wahlström, 2012; Gillies, 2014). Guided in part by the Organisation for Economic Co-operation and Development (OECD), this view manifests in the monitoring and measurement of learning outcomes (ibid.). However, in view of the idea that economic growth is also closely linked with increasing consumption and thus unsustainable ways of living (Kopnina, 2012), there is a risk that education for promoting the reorientation needed in the Anthropocene will go unrealised. Indeed, one example illustrating an expression of the risk created by schooling's entanglement with an economic perspective is what Biesta (2009) has called a trend in education toward "learnification," that is, a reduction of education to a discourse built upon a "language of learning" (p. 27) that determines how we describe teachers, students, teaching, and school. Crucially, a focus on education as an environment for the optimal production of learning, in which the teacher is conceived as a facilitator of individual learning outcomes or competencies, marginalises a focus on theories of teaching as well as on didaktik (e.g., Krogh et al., 2021). Thus, teachers' freedom of method in selecting content with the purpose of developing capacities in students that could open toward a critical stance and agency in relation to the Anthropocene are also marginalised. Therefore, when it comes to disciplinary education, specifically in chemistry education in our case, the risk is of school chemistry teaching being reduced to developing student's conceptual understanding of disciplinary chemistry knowledge, in part with a view to preparing future scientists and engineers, and in part to create consumers who place their belief in the products that scientists and engineers produce (see, e.g., Bencze and Carter, 2011 for a general discussion on this). Thus, what is needed is an approach to school chemistry teaching that takes its point of departure in the goals of schooling as a whole in the Anthropocene and that places focus on corresponding relevant content in teaching. We view 21st century *Bildung*, which is in the title of this article, as a part of a theoretically developed understanding of Environmental Citizenship in the 21st century (Hadjichambis et al., 2020). In this, "Knowledge is essential, but fostering knowledge alone in Education for Environmental Citizenship, without links to real life, personal experiences, competencies, and values, is insufficient and pointless for the sake of a sustainable world" (Smederevac-Lalic et al., 2020, p. 71).

Serving as a bridge between natural sciences, life sciences and applied sciences (Mahaffy et al., 2019a), chemistry – a creative science analysing, synthesising, and transforming matter (Sevian and Talanquer, 2014) – contributes to the creation of medicines, materials, and chemicals that are recognised as having high societal value. Talanquer (2016, p. 4) writes: "The signature of chemistry is less its content than the practices that such knowledge enables. Chemistry is [. . .] a powerful way of thinking about and acting on the material world." Therefore, when knowledge in chemistry is applied, it can contribute to local and global environmental impact, as well as risks (e.g., Sjöström et al., 2016; Eilks et al., 2017), linking the discipline immutably with the idea of a risk society (e.g., Marks and Eilks, 2009; Marks et al., 2014; Sjöström et al., 2016; Eilks et al., 2017), and the Anthropocene (Mahaffy, 2014; Blatti et al., 2019; Mahaffy et al., 2019b; Zowada et al., 2019a,b).

Thus, as a discipline, chemistry should be viewed as being intimately tied to social, economic, political, environmental, and ethical dimensions (e.g., Sjöström et al., 2016). However, even though this is the case, teaching chemistry tends to focus on the explanation of isolated concepts without a purpose (e.g., Sevian and Talanquer, 2014). In an attempt to reconceptualise chemistry education, Talanquer (2019b) writes that chemistry knowledge can play a central role in understanding and solving global challenges. Such knowledge also encompasses engaging in decision-making in relation to sustainable action-taking. In developing a chemical systems thinking model, Talanquer (2019b) brought together a mechanistic-reasoning approach, a context-based approach, and a sustainable-action approach. However, even though there was an emphasis on the relevance of the content or the system under investigation to society, a clear educational goal or guidance for the criteria of content selection was absent. Similar to Talanquer, Mahaffy (2014) has also sought to create a more coherent link between chemistry education and global challenges. Discussing the use of chemistry knowledge in characterising the Anthropocene as a geological phenomenon, and discerning a link between postsecondary chemistry concepts and the chemistry of planetary boundaries (Steffen et al., 2015), Mahaffy et al. (2014, 2019b) have called for a more purposeful focus on the Anthropocene and planetary boundaries in chemistry education. In their view, attention needs to be paid to ideas linking humans and nature to foster action-taking citizens informed by these ideas. With a view to making sense of the current status of our planet and mitigating the human impact on the planetary boundaries, they provide examples of the underlying chemical concepts that are related to planetary boundaries for Anthropocene-aware chemistry education.

Clear in these examples is a linking of chemistry knowledge to the educated subject's agency in relation to sustainable action-taking in the Anthropocene. However, there is also a need for providing chemistry teachers with tools for actively supporting such an agency in chemistry teaching for the Anthropocene in a broad sense. Biesta (2009), argues that we need an ongoing discussion on the aims and goals of education. He writes:

"What is disappearing from the horizon [. . .] is a recognition that it also matters *what* pupils and students learn and what they learn it *for* – that it matters, for example, what kind of citizens they are supposed to become and what kind of democracy this is supposed to bring about [. . .]" (Biesta, 2009, p. 39).

Drawing upon contemporary views of *Bildung*, didaktik, and powerful knowings we seek in this article to develop an approach to chemistry teaching in the Anthropocene that re-awakens a discussion on the goals of chemistry education and the choice of content to be taught, providing thus a basis for supporting greater autonomy on the part of both teachers and students (of all ages) in a chemistry teaching in the Anthropocene. Of central importance in relation to achieving these aims will be our further development of the construct *ChemoKnowings* (first introduced in Herranen et al., 2021).

TOWARD ECO-REFLEXIVE *BILDUNG*

In Sweden and the other Scandinavian countries, as well as in Germany, *Bildung* is a central element of the didaktik educational tradition (e.g., Sjöström and Eilks, 2018). The term didaktik is understood differently from how the word "didactics" is understood in English-speaking countries (Sjöström et al., 2017). Didaktik can be seen as the art, philosophy, and science of teaching and learning (Sjöström and Tyson, 2022; see also, e.g., Künzli, 2000; Wickman et al., 2020), which fundamentally concerns questions of *what* content is important to learn, *why* it should be taught, and *how* (e.g., Wickman, 2014). Didaktik "[...] concerns the analytical process of transposing (or transforming) human knowledge (the cultural heritage) like domain-specific knowledge into knowledge for schooling that contributes to [...] *Bildung*" (Duit et al., 2012, p. 16). German and Nordic didaktik distinguishes itself from the curriculum tradition common to English-speaking countries in some crucial ways (Friesen, 2018). For example, unlike the curriculum tradition, which creates a separation between curriculum (*what* is to be taught and *why*) and pedagogy (*how* something should be taught), didaktik opens for teachers having autonomy not only in choosing how to teach certain content but also in selecting content for teaching (based on their answering of *why* a particular content should be taught) (Gericke et al., 2018). The reason for this is because the curriculum in German and Nordic tradition, or *Lehrplan* (translation from German to English: Learning plan), was traditionally intended as a general guide to teaching, with the selection of content being left to teachers, who were understood to have a unique understanding of the specific needs of students in their local cultures and school context (Hopmann, 2015). Of importance in this regard was (and still is) the need of the teachers to come into a relationship with the *Lerhrplan* as "curriculum theorists" (Deng, 2021) so they might make selections of content for teaching that are both consistent with the goals of schooling and education as expressed through the *Lerhrplan*, and the unique learning needs of their particular students (Hopmann, 2015). In this way, the questions of *why* one should teach a particular content become central to didaktik. An additional aspect that distinguishes didaktik from the curriculum tradition is that didaktik acknowledges a distinction between content that is selected for teaching and the knowledge the student develops in their relationship with that content (Hopmann, 2007). In the curriculum tradition, such a distinction is not recognised (Hopmann, 2015). Teaching thus within didaktik opens for greater teacher autonomy when compared with teaching within the curriculum tradition, which more purposefully embodies content as disciplinary knowledge; this being a consequence of higher education institutions viewing such knowledge as a prerequisite for school students' later entry into higher education (Hopmann, 2015).

Describing the crucial connection between didaktik and *Bildung*, Künzli (2000, p. 46) writes that "*Bildung* serves didaktik as a cypher in its concern to synthesise into a consistently coherent whole everything happening within instruction." As an educational construct, *Bildung* dates back to the late 18th century. Its literal translation into English being "*becoming in the image of*." *Bildung* represents both an ideal image of something for humankind to become (Biesta, 2002; Gustavsson, 2014), and processes of subjectification (Biesta and Leary, 2012; Schneider, 2012) as well as an agency (Sjöström et al., 2017; Taylor, 2017; Eilks et al., 2018), that underlie/are driven by this ideal (see **Figure 1**, which will soon be described more in detail). *Bildung* envisions self-determination, participation, and solidarity (Klafki, 2000b), with the person's self-determination being bound to different ways of relating to themselves and the world (Rucker, 2020).

Significantly, the ideal image that *Bildung* represents is always bound to the culture and society in which the processes of subjectification and agency are a part (Taylor, 2017). Crucially, such processes are "understood as being in responsible relationship with other human beings and, by extension, with the natural world more generally" (Biesta, 2013, p. 739). To specify the meaning of *Bildung* today, we have to base it on the fact that we live in a globalised risk society with many global and ecological challenges (e.g., Straume, 2015). In an essay, Rowson (2019) discusses *Bildung* in relation to future education and sustainability issues. He expresses *Bildung* as being a values-driven applied philosophy of education and connects it to for instance spirituality, transdisciplinarity, and transformative education. He writes: "*Bildung* entails a dynamic world view that values the independence of mind and spirit grounded in ecological and social interdependence" (pp. 3–4).

During the last decade, ideas of less anthropo-centered versions of *Bildung*, where both relations and responsibility are emphasised, have evolved (e.g., Taylor, 2017; Sjöström, 2018). Rucker and Gerónimo (2017) have connected the concept to complexity, and Taylor (2017, 2020) to posthumanism. The latter author writes:

"A posthuman *Bildung* is a lifelong task of realising one's responsibility within an ecology of world relations, [... It] is a matter of spirituality and materiality which means that it is not an 'inner process' but an educative practice-oriented to making a material difference in the world. [... It is] education as an ethico-onto-epistemological quest for (better ways of) knowing-in-becoming." (Taylor, 2017, pp. 432–433).

Building upon Taylor's (2017) contribution to developing a posthuman understanding of *Bildung*, Clucas et al. (in preparation) has sought to further develop such an understanding of the construct. In their development of a posthuman understanding of *Bildung*, the authors build upon a fundamental view of the construct as standing for both an ideal image of something for humankind to become (Biesta, 2002; Gustavsson, 2014), and processes of subjectification (Biesta and Leary, 2012; Schneider, 2012) and agency (Sjöström et al., 2017; Taylor, 2017; Eilks et al., 2018) that underlie/are driven by this ideal. Presented as a novel posthuman understanding for *Bildung*, these two aspects of the construct are viewed as being intimately related, being defined as (1) a process of subjectification that involves the *Bildung* entity intentionally opening to being renewed through embodied connection with the world, and (2) a process of crafting *Bildung* as an ideal image with a view to the *Bildung* entity guiding itself and others toward relationships for renewal (Clucas et al. in preparation). **Figure 1**

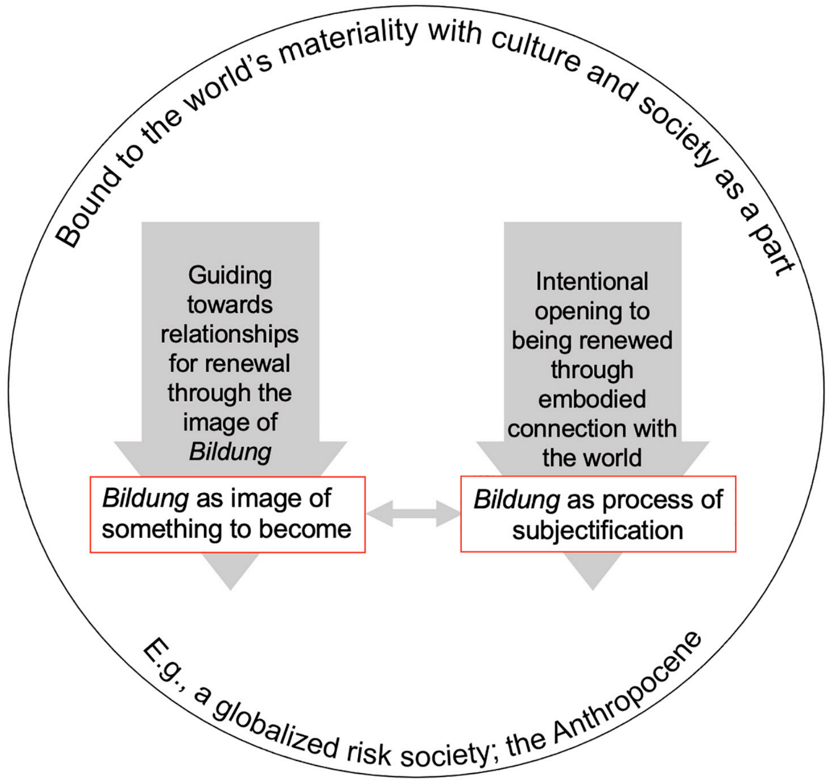

FIGURE 1 | Simplified model of a posthuman understanding of *Bildung* (Clucas et al. in preparation).

shows a simplified representation of the authors' posthuman understanding of *Bildung* that captures these two fundamental aspects. Also shown in the model is the idea that these two aspects of *Bildung* are always situated within, and thus bound to, the world's materiality of which culture and society are a part (Horlacher, 2016), which today would be a globalised risk society and the Anthropocene (Brondizio et al., 2016).

As has perhaps already become clear for the reader, *Bildung*, at least in relation to the nature of learning it specifically entails, can be understood differently depending upon which perspective is used to frame it, and the context *Bildung* is situated within (Horlacher, 2016). We wish therefore to conclude this brief presentation of *Bildung* by distinguishing two (complementary) perspectives that have become valuable to us: *Bildung* seen as a counter-concept, and Sjöström and colleagues' critical- and eco-reflexive *Bildung* construct for chemistry (and science) education.

Bildung as a Counter-Concept

The idea of *Bildung* as a counter-concept finds its origins in the emergence of *Bildung* as a pedagogical construct in the modernising era of 18th century Germany (Alves, 2019). Conceived in the face of developments in the sciences, new technologies, increased division of labour, and knowledge specialisation, the emergence of *Bildung* as a pedagogical construct was a reaction against a perceived fragmentation of knowledge and society (ibid.). *Bildung* became thus a pathway for people to become reconnected to the idea of humanity and be integral or whole "in a world increasingly similar to a vast machine" (ibid., p. 5). As a critical and resistant counter-concept, *Bildung* is seen therefore as an illuminating factor that threatens to reduce or narrow human beings' perception and constitution of reality (Wimmer, 2003). If we compare this description of *Bildung* to the model in **Figure 1**, a view of *Bildung* as a counter-concept reflects an ideal image of something to become, that being the capacity for resisting a narrowing of the entity's perception of reality. Seen in the context of the Anthropocene, the role of *Bildung* as a counter-concept (as an ideal image of something to become) might reasonably be viewed as being critically important in education. This is because it is associated with the idea of education as having a broader value, and not something that can be characterised in instrumental terms only (e.g., Schnack, 2008).

Sjöström and Colleagues' Critical- and Eco-Reflexive Bildung Construct for Chemistry (and Science) Education

Of importance to chemistry (and science) education, Sjöström and colleagues have drawn from the works of Hans-Georg Gadamer (1900–2002), Paul Ricoeur (1913–2005), and the German educational philosopher Wolfgang Klafki (1927–2016) in developing a *Bildung* construct for the

Anthropocene which they term critical- or eco-reflexive *Bildung* (Sjöström et al., 2016, 2017; Sjöström and Eilks, 2018). Posited as a metatheory, critical- or eco-reflexive *Bildung* includes ideas of critical reflexivity, emancipation, critical-democratic awareness, socio-ecojustice, and socio-political action (Sjöström et al., 2016, 2017; Sjöström and Eilks, 2018). As a framework for critically and sustainability-oriented chemistry and science teaching, it suggests a chemistry (and science) teaching that orients student's in "a critical stance toward the modern risk society, an understanding of the complexity of life and society and their interactions, and a responsibility for individual and collective actions toward socio-ecojustice and global sustainability" (Sjöström et al., 2016, p. 336). In developing their framework, Sjöström and his colleagues have closely related critical- and eco-reflexive *Bildung* to a critical view of science education and scientific literacy which they term Vision III (Sjöström et al., 2017; Sjöström and Eilks, 2018). It is a critical scientific literacy relating to urgent socio-political issues and in doing so also emphasises relevant knowledge in and about science and technology in the Anthropocene.

POWERFUL KNOWLEDGE AND KNOWINGS

While criticising the loss of content discourse within educational research, Young and his colleagues have introduced and unpacked the idea of *powerful knowledge*, building on the social realism perspectives of Bernstein and Durkheim (Young, 2013; Young and Muller, 2013). Situated within the curriculum tradition, powerful knowledge is conceived as a curriculum principle, being also strongly aligned with the subject disciplines (Muller and Young, 2019). Significant in this regard, powerful knowledge has two characteristics that differentiate it conceptually from other forms of knowledge: first, it is specialised knowledge within the boundaries of the disciplines, which separates it from general knowledge. Second, it is separate from everyday experiences that the students carry which differentiates it from everyday knowledge (Young, 2013). Significantly, Young and his colleagues draw a distinction between powerful knowledge and what they term "Knowledge of the powerful" (KOTP), where the latter refers to power structures that utilise knowledge to create or uphold domination or "power over" (Muller and Young, 2019). In contrast, powerful knowledge is conceived as the knowledge that gives the holder "power to" act in a manner that generates human value (ibid.). Powerful knowledge is thus "available to all who acquire it [. . . and] infinitely transferable" (Muller and Young, 2019, p. 198). It is a knowledge that allows students "to understand and interpret the world. [. . .] it transcends and liberates [them] from their daily experience" (Young, 2013, pp. 117–118).

Recently, a number of authors have attempted to situate powerful knowledge within the didaktik tradition (Gericke et al., 2018; Carlgren, 2020; Deng, 2021; Hordern, 2022). Of value in this context is that situating powerful knowledge in this way opens to pedagogical questions that are not normally open to examination in the curriculum tradition, namely, questions of *what* content should be selected for teaching and *why*. In this way, the question of what powerful knowledge might be is no longer restricted to subject discipline knowledge, but rather, it becomes an idea for teachers and students to examine and define also (Gericke et al., 2018). Indeed, it becomes an issue for examination and definition in relation to the purpose of schooling as a whole (Hordern, 2022). As a vision for education, and embodied in the curriculum of the didaktik tradition, such a whole is not derived from the separate disciplines, but rather, "through an analysis of the whole life culture" (Künzli, 2000, p. 44). Thus, subject teaching becomes something broader and more integrated than simply teaching subject knowledge (e.g., Gericke et al., 2018), and opens to the possibility of teaching "with an object in view that is complete in itself" (Weniger, 2000, p. 116), e.g., an education that can initiate students in tackling unresolved societal challenges in the Anthropocene (Kvamme, 2021). Significantly, in the didaktik tradition, *Bildung* is commonly viewed as embodying the educational outcome that such a vision for education represents (e.g., Rucker, 2020; Deng, 2021; Kvamme, 2021).

In her situating of powerful knowledge within the didaktik tradition, Carlgren (2020) relates powerful knowledge to *Bildung* by developing the idea of *powerful knowings*. Importantly, when Carlgren is speaking of powerful knowings she is referring to the knowing that the student has come to know through the teachers' teaching of "knowns," that is, the specific knowledge the teacher wants their students to learn. For Carlgren, "knowings" can be distinguished from "knowns" in that they include what she describes as tacit dimensions that are in addition to the "knowns" (Carlgren et al., 2015). However, it is important to point out here that the "knowns" in relation to powerful knowledge may be understood differently according to the teaching tradition a particular teacher is situated within. For example, in the didaktik tradition, "knowns" might be viewed as contents of education for *Bildung* (*Bildungsinhalt*), whereas in the Anglo-Saxon curriculum tradition, "knowns" might be disciplinary knowledge as curriculum content. The factor impacting these differences is the teacher's transformation of curricular content for teaching and the fact that – if taking it to its extreme – in the didaktik tradition the teacher is given freedom in relation to the selection of content that the teacher in the Anglo-Saxon curriculum tradition is not. Crucially, it is through Carlgren's inclusion of tacit dimensions that she is able to relate Young and colleagues' conceptualisation of powerful knowledge to *Bildung* (Carlgren, 2020). Importantly, Carlgren ties tacit knowledge and thus powerful knowings to the idea of knowledge as something "incorporated into our bodies [. . .] which connects us with the world and functions as a tool to widen our interface with it" (p. 326). Therefore, through tacit dimensions of knowing, the idea of powerful knowings can be viewed as containing an embodied and relational view of knowledge, with such a view being also consistent with the idea of *Bildung* (ibid.).

Thus, a core outcome of situating powerful knowledge within the didaktik tradition is of opening powerful knowledge to a discussion on knowledge transformations (Gericke et al., 2018; Carlgren, 2020; Deng, 2021; Hordern, 2022). Critically, such transformations take place both inside and outside of educational settings (Gericke et al., 2018). In this article, we are especially interested in knowledge transformations that take place in relation to chemistry classroom teaching, specifically, students' transformation of content for *ChemoKnowings* and the need for teachers' transformation of content to take such a transformation into consideration. First introduced by Herranen et al. (2021), ChemoKnowings are a specific form of powerful knowings in chemistry education that the student comes to know in the context of the classical didaktik triangle. Of significance in this regard is the crucial role the teacher plays in creating the conditions for students coming into a relationship with a subject matter that can be transformed into powerful knowings as ChemoKnowings. Indeed, this we view as a central task of chemistry didaktik. Situating powerful knowledge within the context of a *Bildung*-centered didaktik, Deng (2021) points to the fact that the teachers' didaktik work is the crucial arena for the transformation of content for *Bildung*. Deng argues thus for teachers' use of Klafki's didaktik analysis in relation to knowledge transformation at the classroom level (ibid.). Developed in 1958, and formulated as five questions, Klafki (2000a) developed his didaktik analysis approach to support teachers' work to transform content for *Bildung*:

I. What general sense, basic phenomena or fundamental principle does this content exemplify and open up to the learner? (Exemplary Significance)
II. What significance does the content in question already possess in the minds of the children in my class? (Contemporary Significance)
III. What constitutes the topic's significance for the children's future? (Future Significance)
IV. How is the content structured (which has been placed in a specific pedagogical perspective by questions 1–3)? (The Structure of the Content)
V. What are the special cases, phenomena, situations, and so forth in terms of which the structure of the content in question can become interesting, stimulating, and approachable for children? (Accessibility) (from Bladh, 2020, p. 210)

In view of the connection between the idea of powerful knowings and *Bildung*, we believe Klafki's questions open to the idea of our discussion on knowledge transformations for powerful knowings (as ChemoKnowings) approaching an outlining of its own question areas for guiding teachers' work in transforming curriculum content. That is, transforming curriculum content to come to understand which "knowns" the teacher wishes to teach for students' intended "knowings." Of central importance in this regard is that any such question areas need to guide teachers in creating the conditions through which students, in their relationship with chemistry teaching content, are enabled in transforming "knowns" toward ChemoKnowings. That is, a knowing in chemistry education (in a broad sense) that includes embodied and relational (or tacit) dimensions in addition to the "knowns" (both in and about the subject, in our case chemistry).

In our view, Klafki's original questions do not sufficiently open for teachers, in their transformation of curriculum content, to take into consideration the volition of students in relation to their own transformations of content for *Bildung*. For Gericke et al. (2018), however, both teachers and students play a role in determining what powerful knowledge is. The student's own role in determining whether or not a particular chemical content knowledge becomes for them a ChemoKnowing must therefore be included. In his recent description of *Bildung*-oriented teaching, Rucker (2020) explored the process of transformation for *Bildung* from the perspective of the student. Rucker describes teaching as an act of summoning the student's self-activity, and the student as developing the ability to self-determination "in the confrontation with a resistant world [. . .] with cultural objects that do not submit to every judgement and action" (p. 56). For Rucker, such a resistant confrontation with content is what opens the possibility of *Bildung*. Recently, Biesta (2022) opened an existential discussion on students and what they might do with taught content. Education needs to encourage students to be in and with the world and it is up to the students how to do so, although guided by the teacher. For students to exist as subjects in and with the world, they need to acknowledge that they navigate within the frame of the world, nature, and the social. Such acknowledgement may call for the kind of confrontation that Rucker is describing. Significantly, and citing Benner (2015), Rucker (2020) writes that "teaching can only be *Bildung*-supportive if it leaves room for the self-relationship of the learner with what is being learned and taught" (p. 59). Thus, placing themselves critically in relation to particular content, the student purposefully examines the content's claim to validity, also making a judgement of what value that content has for the student themselves (ibid.). The student thus has the opportunity to decide for themselves whether or not a particular content is both convincing and of meaningful personal value. Importantly, it is only when both conditions are satisfied that we can speak of a transformation for *Bildung*, which Rucker defines as "the ability to act in light of objective insights and one's own value judgements" (p. 59). Drawing from these ideas, we consider the student's examination of validity claims as well as value judgements in their self-relationship with chemistry teaching content to be crucial to their coming to know as ChemoKnowings. Drawing on different theoretical perspectives, our focus in this article is to begin an exploration of what ChemoKnowings might be in the Anthropocene, and thus to approach outlining some different didaktik models that can support student's transformation of content for ChemoKnowings through the opening to the teacher considering such a transformation in their chemistry didaktik praxis. We will start by briefly exploring three concepts that are related to ChemoKnowings: critical chemical literacy, eco-reflexive chemical thinking, and ChemoCapabilities, respectively.

THREE RELATED CONCEPTS TO ChemoKnowings

In the next section we will elaborate further on the construct *ChemoKnowings* based on ideas of eco-reflexive *Bildung* and powerful knowledge and knowings, and also present a new "vision model," that includes student transformation of content, and which aims to broadly guide teachers in promoting ChemoKnowings and "chemical agency" in their teaching. However, before doing so, we will briefly explore previously discussed ideas and concepts that also have had the ambition to point at relevant chemistry knowledge (in and about) and what to (be able to) do as a citizen with such chemistry-related knowledge. Such related concepts are chemical literacy and chemical thinking. And inspired by the concept GeoCapabilities – suggested in relation to geography education – we will mention the corresponding concept ChemoCapabilities. All these three conceptual ideas are – more or less – related to ChemoKnowings as an idea and construct. However, our focus in this article is on the latter concept, so we will only give short introductions to the three other concepts, as a background to previous research inside the same area of research interest. The three other constructs can also provide theoretical insight into what might be meant (in a broad sense) by ChemoKnowings.

Critical Chemical Literacy

When searching (2022-01-25) on Google Scholar for "chemical literacy" there were 1300 hits. In the top three regarding citations were three articles by Shwartz, Ben-Zvi, and Hofstein published in 2005 and 2006 in IJSE, JCE, and CERP (Shwartz et al., 2005, 2006a,b). The CERP paper (Shwartz et al., 2006b) had about 300 citations in Google Scholar. The authors refer to Bybee (1997) and his definition of multidimensional scientific literacy. In addition to the concepts of scientific disciplines and procedures of scientific investigation, such a view of scientific literacy also includes philosophical, historical, and social dimensions of science and technology.

Shwartz et al. (2006b, p. 206) formulated a definition of chemical literacy consisting of four domains: (1) scientific and chemical content knowledge; (2) chemistry in context; (3) higher-order learning skills; and (4) affective aspects. Domain one is about understanding chemistry as an experimental discipline that tries to explain the structure and dynamics of our material world. Domain two is about the role of chemistry in everyday life. Domain three is about meta-cognitive aspects and domain four is about affective aspects connected with the individuals' view of chemistry and chemical-related issues, e.g., impartiality and interest.

The 15-year-old framework has merits, but also limitations. For example, concentration and transportation aspects as well as technological aspects are not present in the framework. The latter is crucial because chemistry is as much a technology as it is natural science (Sjöström, 2007a; Chamizo, 2013). In addition to understanding and explaining the world, chemistry also aims at making new molecules, materials, product formulations, sustainable industrial processes, etc. (e.g., Sjöström and Talanquer, 2014; Talanquer, 2016; Marcelino et al., 2019). Concentration and transportation aspects are central in relation to environmental issues.

A more general critique of the framework is that there is a need for a socio-critical-political framing. Such humanistic perspectives on chemistry education toward "multifaceted problematisation" are highlighted by Sjöström and Talanquer (2014). It requires problematisation of chemistry content (*in* chemistry) and problematisation of chemistry from humanistic perspectives (*about* chemistry). Such a critical-reflexive approach to chemistry highlights reflecting on the relationship between chemistry, technology, environment, and society within social, historical, and philosophical framings. In addition to understanding, problematising, and reflecting, it also covers decision-making and action taking toward issues framed by chemistry, technology, environment, and society (Sjöström and Talanquer, 2014).

The term "critical chemical literacy," which we believe is pointing in the same direction as ChemoKnowings, has almost not at all been used before, and when so has been done it was used for framing of chemistry by broad societal perspectives and pluralism (Sjöström and Stenborg, 2014). Both "critical chemical literacy" (as used by Sjöström and Stenborg, 2014) and ChemoKnowings are being importantly linked to what can be called eco-reflexive *Bildung*.

Eco-Reflexive Chemical Thinking

When searching (2022-01-25) on Google Scholar for "chemical thinking" there were 1800 hits. In the top six regarding hits and/or citations were articles (co)authored by Vicente Talanquer (Sevian and Talanquer, 2014; Banks et al., 2015; Sjöström and Talanquer, 2018; Talanquer, 2018, 2019a; Freire et al., 2019). The CERP-paper (Sevian and Talanquer, 2014) had more than 200 citations in Google Scholar. In this article, chemical thinking is defined as "the development and application of chemical knowledge and practices with the main intent of analysing, synthesising, and transforming matter for practical purposes" (ibid., pp. 10–11). This idea mainly supports chemistry professionals in a broad sense, but may also be useful as a background in layman decision-making in diverse situations (e.g., Cullipher et al., 2015). Mainly based on ideas of what can be called "sustainability agency" and considerations of the impact of chemical actions – risks and benefits – Sjöström and Talanquer (2018) elaborated on what they called eco-reflexive chemical thinking and action. They related their ideas to eco-reflexive *Bildung* and also discussed implications for education. We believe the term "eco-reflexive chemical thinking" (43 hits in the Google Scholar search, mainly due to references to the article by Sjöström and Talanquer, 2018) is pointing in the same direction as ChemoKnowings, although probably embodied and relational dimensions are even more pronounced in the latter construct, as we will describe more in detail below.

As already mentioned above, Talanquer (2019a) has also discussed the need for chemistry knowledge and chemical thinking in relation to global challenges. Such knowledge encompasses engaging in decision-making in relation to sustainable action-taking. As also mentioned above, Talanquer has developed a chemical systems thinking model, later applied in relation to, for instance, COVID-19 (Talanquer et al., 2020).

ChemoCapabilities

Inspired by the concept GeoCapabilities (e.g., Lambert et al., 2015; Bladh, 2020) – suggested in relation to geography education – we here suggest the new corresponding construct ChemoCapabilities. More generally, what can be called

"SubjectCapabilites" may be viewed as related to subject-specific powerful knowledge. The GeoCapabilities approach seeks to explain human development through education, more specifically through school subject geography. Through its emphasis on engagement in disciplinary knowledge, the GeoCapabilities approach rejects generic 21st-century skills. Through their engagement with disciplinary knowledge, students develop:

[a] A deep descriptive world knowledge. [b] A critical conceptual knowledge that has explanatory power and systematicity, providing a relational understanding of people living on the planet. [c] A propensity to think through alternative social, economic, and environmental futures in specific place and locational contexts (Lambert et al., 2015, p. 732).

The term Capabilities has been developed in relation to *Bildung*-ideas, mainly those by Amartya Sen and Martha Nussbaum. More recently, Bladh (2020) connected it also to the *Bildung*-ideas in Klafki's didaktik analysis. Based on Klafki's more recent thinking there are also connections to concepts such as action, agency, and curriculum content, in the Anthropocene. Furthermore, connections can be found between GeoCapabilities and Klafki's *Bildung* as self-determination, co-determination, and solidarity. Capabilities connect educational aims to school subject teaching, and crucially they can be understood as subject-specific powerful knowings as they understand knowledge in a relational sense based on Carlgren (2015). We believe, therefore, ChemoCapabilities to be a construct close to ChemoKnowings, although the first mentioned construct not necessarily include embodied dimensions.

POWERFUL CHEMICAL KNOWLEDGE FOR SCHOOLING: ChemoKnowings AND "CHEMICAL AGENCY"

In order to embed chemistry education into environmental and sustainability education (ESE), Herranen et al. (2021) developed a new theoretical "didaktik model" (**Figure 2**) based on a previous model. Generally speaking, didaktik models are reflection tools (or frameworks) supporting teachers when deciding on one or several didaktik questions in relation to local "curriculum-making" and/or instruction design (e.g., Ingerman and Wickman, 2015; Sjöström et al., 2020; Wickman et al., 2020). Such models facilitate teacher didaktik decisions as they provide new perspectives in relation to why, what, and how questions. Furthermore, didaktik models provide a professional language for teachers for communication and documentation. They can be useful for teachers when having certain situations, questions, and student groups in mind. However, as local curriculum-making, didaktik analysis, didaktik decisions, and instruction design are complex processes, it can be argued that a specific didaktik model only facilitates certain aspects of this complexity (e.g., Wickman et al., 2020).

In their article Herranen et al. (2021) first proposed the term ChemoKnowings, which can be seen as an example of powerful subject-knowings. The term was coined within the fields of ESE and Curriculum Theory. It was also related to already mentioned systems thinking in chemical education (Mahaffy et al., 2018) and eco-reflexive *Bildung* (Sjöström et al., 2016). Herranen et al. (2021) described ChemoKnowings as including "[. . .] relevant theoretical and practical knowledge in and about chemistry as well as about the nature and culture of chemistry" (p. 17). The term encompasses action taking with socio-eco-critical awareness. Herranen et al. (2021) also argued that chemistry, as an example of one important knowledge area in relation to the challenges of the Anthropocene, shouldn't be understood in a fragmented way. In the didaktik model in **Figure 2** (from Herranen et al., 2021), ChemoKnowings are presented as encompassing four elements: critical views on chemistry's distinctiveness and methodological character; powerful chemical knowledge; critical views on chemistry in society; and eco-reflexivity through environmental and sustainability education.

However, we feel that student transformation of (and relation to) content for ChemoKnowings is not sufficiently explicit in the model of Herranen et al. (2021). Indeed, the model includes powerful chemical content knowledge in relation to so-called wicked problems, but it does not clearly take into consideration Carlgren's (2020) important powerful knowings-construct, including embodied and relational (or tacit) dimensions, in addition to the "knowns."

In an attempt to re-think a science curriculum oriented toward sociopolitical action, Hodson (2003, p. 658) formulated four elements of a science curriculum:

- *Learning science and technology* in relation to "conceptual and theoretical knowledge."
- *Doing science and technology* in relation to "scientific inquiry and problem-solving."
- *Learning about science and technology* in relation to learning the nature and the methods of science and technology together with their interaction. This element can be understood as including Science, Technology, Society, and Environment.
- *Engaging in sociopolitical action* in relation to responsible action.

Instead of the latter element, Aikenhead (2007) emphasised "knowing-in-action" and he was the first who suggested connecting it to a Vision III of scientific literacy. This idea, already mentioned in section "Towards Eco-Reflexive *Bildung*," has been broadened and developed further by Sjöström and Eilks (2018).

Based on Hodson's (2003) subdivision as well as on our own discussion above, we want to suggest that student's transformation of content for ChemoKnowings is related to the following four dimensions:

1. Learning chemistry (e.g., conceptual understanding)
2. Doing chemistry (e.g., chemical inquiry)
3. Learning *about* chemistry (philosophical, historical, socio-political, etc., perspectives)
4. Engaging in socio-political action (in a broad sense) related to chemistry (in a broad sense) (here called "chemical agency")

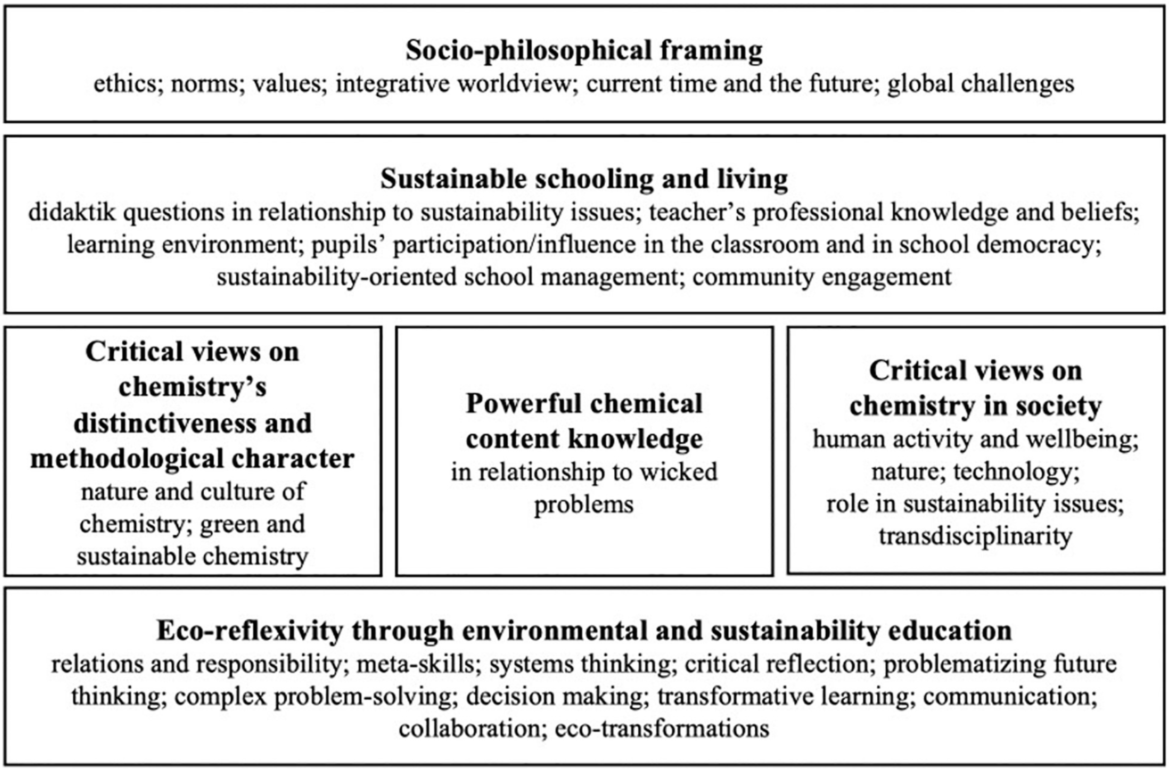

FIGURE 2 | Didaktik model for eco-reflexive chemistry education (Herranen et al., 2021, p. 5).

We believe that these four dimensions can be related to the four ChemoKnowings elements in **Figure 2**, opening to a linking of these elements to student's transformation of content (see **Figure 3**; the figures/numbers refer to the four dimensions just tabled).

From a *Bildung* perspective, three kinds of chemistry knowledge can be viewed as essential: (a) ontological knowledge meaning knowledge about chemical concepts and processes, (b) epistemological knowledge which is knowledge about chemistry, including the community of scientists ("nature of chemistry practice"), and (c) social or ethical knowledge, which takes chemistry into consideration together with society (Krageskov Eriksen, 2002; Sjöström, 2007a, 2013). These three kinds of chemistry knowledge can to some extent be related to the first three dimensions mentioned above (i.e., learning chemistry, doing chemistry, and meta-perspective on chemistry, especially in relation to society). As a corresponding kind of chemistry knowledge to the fourth dimension, one could add: (d) *embodied and relational chemistry knowledge*. Such knowledge is important for engaging in socio-political action (in a broad sense), although also the other kinds of chemistry knowledge (ontological; epistemological; social/ethical) are important for this (see the further discussion on this below). In this article, we use the term "chemical agency" for the capability and practice of socio-political action related to chemistry in a broad sense. This is a new way of using this term; in policy contexts, the term refers to an agency/bureaucracy governing chemicals used in society.

However, despite the pronounced link with *Bildung*, the embodied and relational (or tacit) dimensions that are crucial to Carlgren's distinction between powerful knowledge and powerful knowings and thus a fundamental link between ChemoKnowings and *Bildung*, remain predominantly unarticulated in **Figure 3**. Drawing from Rucker's description of *Bildung*-oriented teaching, and of the student's purposeful examination of a content's claim to validity, as well as the judgement of what value that content has for the student themselves, we suggest that a crucial embodied and relational dimension of ChemoKnowings is that they are experienced as meaningfully valuable. That is, they are knowings that matter meaningfully to the student and connect the student to themselves and the world (von Humboldt, 2000).

Interestingly, Biesta (2022) seems to touch on the embodiment of knowledge and its relationality in his recent description of a world-centered education, stating that it is about "[. . .] equipping and encouraging next generations [students] to exist 'in' and 'with' the world and do so in their own right" (p. 3). Significantly, a fundamental dimension that Rucker (2020) places on knowings that confer *Bildung* is that they lie always "under the claim of morality" (p. 51). Indeed, Klafki (2000b) also viewed the "ethical compass" as an essential dimension of *Bildung*. The ethical compass we suggest therefore is a fundamental tacit dimension of ChemoKnowings and a contemporaneous outcome of knowings mattering meaningfully to the student. Importantly, in their conferring of ethical compass, any actions ChemoKnowings may mobilise in the student ought themselves be ethically oriented.

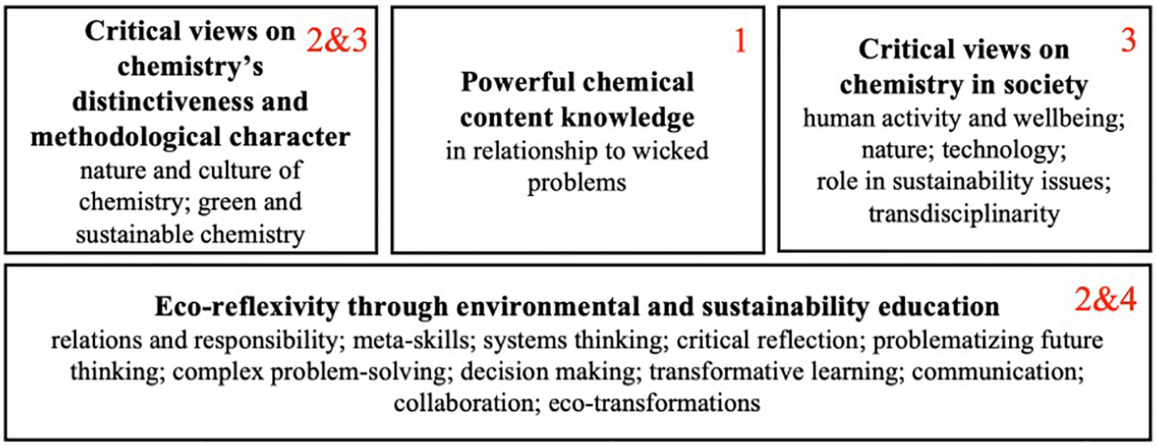

FIGURE 3 | Model linking student transformation of content for ChemoKnowings to four elements of Herranen et al.'s (2021) model viewed as important for ChemoKnowings. The context is ESE-framed chemistry education.

This is also consistent with ideas of *Bildung* (e.g., Klafki, 2000b; Rucker, 2020).

As was mentioned before, students' need to acknowledge nature, the world and social limits in the context of guiding their action "in their own right" means that they cannot do whatever they want with the world. According to Biesta (2022), it is a matter of democracy and ecology, which we believe, points toward ethically motivated action. In the context of ChemoKnowings, we believe the direction of such action can be informed by the teacher making salient a vision for chemistry teaching as a part of schooling as a whole, with the vision of schooling as a whole being a world-centered vision for schooling in the Anthropocene. In such a context ChemoKnowings would be viewed as having the power to mobilise ethically oriented socio-political actions as world-centered actions in the Anthropocene.

However, crucially and in line with what van Poeck and Östman (2020) have described as a "double responsibility of the teacher," we believe content brought into the classroom needs, explicitly by the teacher, to be "put on the table." To emphasise world-related problems in the classroom, the teacher takes responsibility for answering questions "*what* to put on the table and *how* to make it free" (van Poeck and Östman, 2020, p. 1010) and makes didaktik choices accordingly. By putting it on the table and "making it free," the teacher opens up possibilities for students to engage and study what is put on the table and make it meaningful for them. In other words, students' engagement in content that has been "put on the table" engenders open-ended inquiries which facilitate critical and plural points of view on the issue at hand (Öhman and Sund, 2021). Such an idea we believe is consistent with what Rucker (2020) means by teaching being only *Bildung*-supportive when it leaves the room "for the self-relationship of the learner with what is being learned and taught" (p. 59).

Figure 4 presents the four ChemoKnowings elements of Herranen et al.'s (2021) model (shown in **Figure 3**) situated within (1) an ethically oriented vision for chemistry teaching as a part of an ethically oriented world-centered vision for schooling in the Anthropocene, and (2) the student's ChemoKnowings as embodied and relational knowings that matter meaningfully to the student, conferring ethical compass, and having the power to mobilise ethico-socio-political action. Knowings that come to matter meaningfully for the student, conferring ethical compass and engendering a power that can mobilise ethico-socio-political action, can be viewed as ChemoKnowings (for the individual student or world citizen). Therefore, we view each of the selected elements of Herranen et al.'s (2021) model as potentially giving rise to students engaging in socio-political action related to chemistry in a broad sense, that is, what we here call the chemical agency. When the selected elements (**Figure 3**) are put in the context of an ethically oriented world-centered vision for schooling in the Anthropocene, embodiment, relationality, and chemical agency are visible in every element of the model. That is why the 4th dimension of students' transformation of content for ChemoKnowings (marked with "4") is shown in all four boxes in **Figure 4**. Significantly, we also include in the model in **Figure 4** van Poeck and Östman's (2020) idea of putting content "on the table" and "make it free."

By *chemical agency* we mean engaging in socio-political action related to chemistry in relation to the different elements/boxes within the circle in **Figure 4**, that is, "critical views on chemistry's distinctiveness and methodological character," "powerful chemical content knowledge," "critical views on chemistry in society," and "eco-reflexibility through sustainability and environmental education."

AUTHORS' REFLECTIONS ON PERSONAL EXAMPLES OF ChemoKnowings

This article seeks to explore what ChemoKnowings might mean for us, the students or world citizens in the Anthropocene and, based on that, to outline didaktik models for promoting

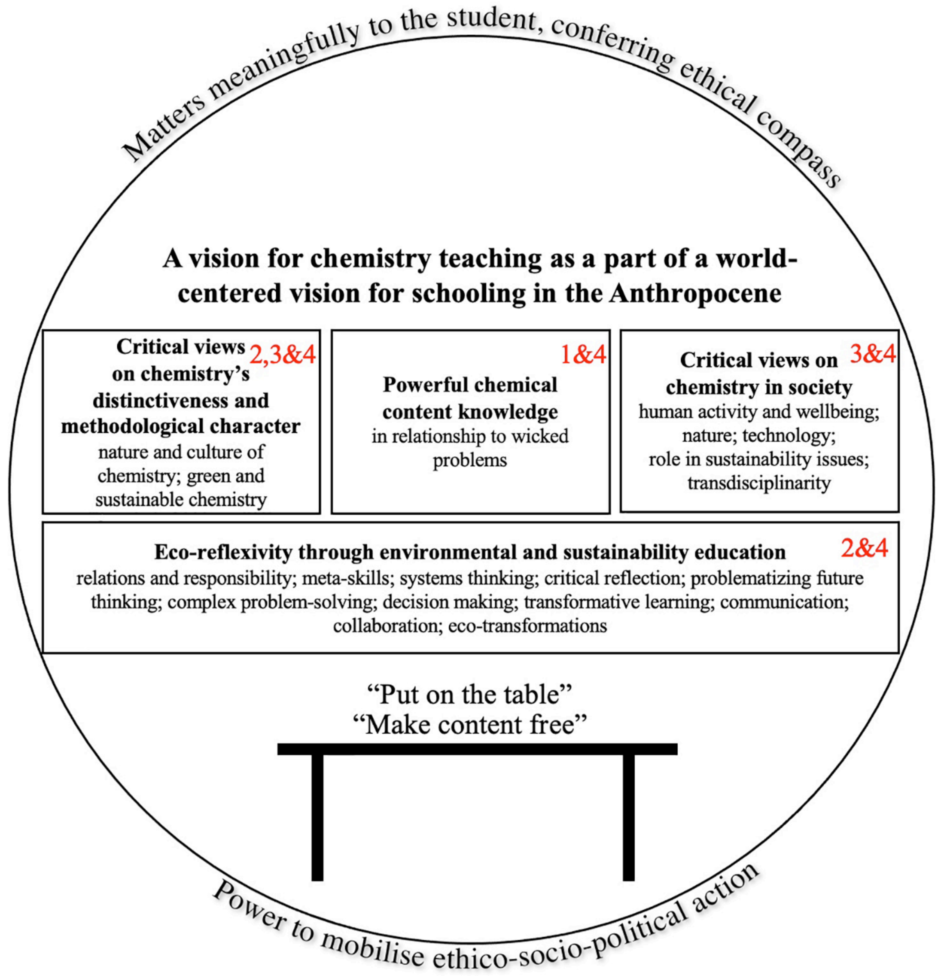

FIGURE 4 | A vision-oriented didaktik model for promoting ChemoKnowings and "chemical agency" in chemistry teaching. It includes the teacher's consideration of student transformation of content. Note that the numbers in red indicate connection to Hodson's (2003) four elements of the science curriculum: (1) learning relevant chemistry concepts; (2) doing chemistry (in a broad sense); (3) critical contextualisation of chemistry; and (4) chemical agency, including relational and embodied elements.

ChemoKnowings that include teachers' consideration of student transformation of content for ChemoKnowings and chemical agency. Although we believe the vision-oriented didaktik model presented in **Figure 4** can be valuable in itself in helping teachers orient themselves to the goal of promoting ChemoKnowings in chemistry teaching in the Anthropocene, we feel our aim can be further strengthened by reflecting (guided by for instance the model in **Figure 4**) over what ChemoKnowings have been for us individually in our own schooling, careers and everyday lives, as well as in relation to our didaktik thinking and choices as teachers. In the reflections, we give different examples on how chemistry knowing has mattered to each of us individually in a meaningful way (driven by an ethical compass), including being a basis for chemical agency.

P. Clucas. As an undergraduate and graduate student in organic chemistry, I was always fascinated by reactions and reaction mechanisms. It created a sense of awe in me to draw these mechanisms, to experience the movement of electrons both within and across different structures. Engaging myself in this elegant art opened my imagination to another world, "the molecular world": An engaging world of molecular interactions and creative human invention. As a Ph.D. student in polymer technology during the 1990s, I spent many hours connected with this world, fueling my wonder and exploration of mechanisms that might be with the results of my experimental work. As a teacher, later, I wanted to share this world with my students. I wanted them to experience the art and wonder of "the molecular world" by our becoming a part of it. I will always remember the very first "performance": Climbing out through the classroom window onto a flat inner roof, together we stepped into this world and became connected as we acted and danced Kekulé's electrons chasing each other in a benzene ring.

The elegance, wonder and creativity of "the molecular world" stands in stark contrast, however, to the messiness, difficulty, and moral ambiguity of human utilisation of chemistry knowing in the real world. Indeed, coming to know this ambiguity, as well as the multiplicity of motives that drive our utilisation of chemistry knowing, is for me a crucial knowledge outcome in our education of future scientists, teachers, and citizens. Inspired by Sjöström and Eilks (2018) critical-reflexive *Bildung*, I have sought to generate a dialogue amongst chemistry students that situates them in a critical examination of the ethics of our use of chemistry knowledge, of how it improves and even saves lives, but also creates risk and leverages potentially catastrophic costs. To achieve this goal, I have provided students with a detailed summary of the industrial production, use, and environmental impact of two common chemical products; namely, acetylsalicylic acid and polyvinyl acetate. I have also presented green chemistry's 12 principles (Anastas and Warner, 1998) and a model for ethical leadership that draws from Starratt (2004). Putting the information "on the table," I have asked students, in groups, to make an analysis and come to their own conclusions regarding the ethics of our using chemistry knowledge, as a society and in our everyday lives. In this course, which I have given in high school chemistry as well as in science teacher training settings, I have witnessed and participated in dialogues that have awoken in students an awareness for complexity in relation to the question in hand. Also, I have experienced the dialogues connect us to a shared sense of moral purpose in connection with human use of chemistry knowledge in our world.

Both examples describe ChemoKnowings for me because they matter to me in a meaningful way that connects me to something greater than myself. In the case of "the molecular world," I am connected through awe, an appreciation of beauty, and creativity. By opening the door to this world for my students we become connected as we experience it together. In the case of critically examining the morality of human use of chemistry knowing, I am again connected with the students, but this time it is within the context of a dialogue that is much greater than any of us, a dialogue that is purposeful and which connects all of us to the complexity of the issue at hand, and to our world whose health is benefited and threatened at the same time.

J. Sjöström – life as a chemist 25 years ago. Just like Clucas, I was very fascinated by "the molecular world." Therefore, I chose chemistry as my major at university level and in 1998 I started as a doctoral student in surface and colloid chemistry. However, early on, I became skeptical of the lack of a good working environment at the large chemistry research center at Lund University, Sweden (approximately 600 researchers, including doctoral students, around year 2000) (Sjöström, 2007b). During my first 2 months as a doctoral student, a number of events occurred that was an alarm clock for me personally. One example was a mercury thermometer that evaporated in the lab in which I worked. Through such events, I realised that risk awareness was actually not that great at the Chemistry Center (CC). As an embodied reaction, I wrote an e-mail to the professors in my research department. I thought it felt like they were prioritising research results ahead of safety and a good working environment (ibid., p. 224). During the following years, my frustration grew over CC's lack of good physical working environment, and I considered quitting as a doctoral student. However, the incidents also became seeds to my increasing interest in the philosophy and culture of chemistry (Sjöström, 2007a), with important implications for my thinking about chemistry education (e.g., Sjöström, 2013).

During my years at CC, I observed a number of serious errors in the handling of chemicals. It was common for toxic chemicals and solvents to be handled outside fume cupboards. The worst example was a distinct odor of mercaptoethanol in the laboratory where I worked. The guest researcher who handled the toxic chemical blamed bad fume cupboards and wondered what he could do about it. Refraining from experiments, while waiting for better fume cupboards, never seemed to be relevant for him, which shows the risk tendency of some chemists in the pursuit of new results and careers (Sjöström, 2007b, p. 225). Also, during my undergraduate education, I had experienced a lot of remarkable things from a safety point of view. One example is how one of my teachers handled residues of a very toxic and carcinogenic chemical (divinyl sulfone) without protective gloves – outside the fume cupboard – and how I imitated his behaviour, although my body said that this is wrong (ibid., p. 224). In addition to intellectual (the head) and practical (the hand) knowledge in chemistry, ChemoKnowings also include embodied chemical knowledge (the body, including the heart).

When it comes to the working environment at CC, I was frustrated by the often poor air quality and the strange smells in corridors and in the lab. It was very common with a nauseating and pungent smell in corridors and labs. I very often felt irritation in the airways when I was staying at CC. Almost daily, there were various chemical odors in stairwells and corridors. Such chemical fumes irritated my eyes and caused me a headache. I addressed these major shortcomings in the physical work environment at CC in a sharply worded letter to CC's board in December 1999. As a doctoral student member of the board, I demanded that the handling of volatile and reactive chemicals at CC be stopped while waiting for rebuilt premises. However, one male board member and chemistry professor was very clear that he believed that as a chemistry researcher you must be prepared to sacrifice yourself for the research! (ibid., p. 226). My opinion is that the local culture at CC at least until 25 years ago was characterised by a "macho culture" that denied the severity of chemical risks, both for the practitioners' own health and the environment. I now move in time to the present.

J. Sjöström – everyday life. That it is very difficult to be a conscious consumer, I realised (again) at the time of working with this article. I decided – based on my ChemoKnowings – more than 10 years ago that I don't want to buy and eat food with artificial sweeteners. Nevertheless, I by mistake bought and drank a sweetened Fanta Orange during the New Year's Eve 2021. The bottle wasn't marked in an informative way, at least not from my point of view. Its label said, "New fantastic taste" (translated from Swedish), but otherwise it looked like "normal" orange Fanta without artificial sweeteners. However, I didn't think it tasted the way it should, so I looked at the ingredient list and then saw that it contained three artificial sweeteners, in addition to everyday sugar (sucrose): acesulfame K, aspartame, and sucralose. For most artificial sweeteners there are concerns about their safety. Some critics say, for instance, that they may be carcinogenic, but food safety authorities claim that they make overall assessment mainly focusing on consumption patterns and health aspects. All the three artificial sweeteners in the above-mentioned Fanta Orange are approved by the Swedish Food Agency, so legally there is no problem at all. However, based on a precautionary principle I am skeptical to eating/drinking food containing sucralose, which is chlorinated sucrose. Thus, sucralose belongs to the chemicals group chlorocarbons. Examples of other more well-known chlorocarbons are DDT, PCB:s, and dioxins. Common for many chemicals of this kind is that there were early warnings, most often before mass production and large-scale use. For example chloracne from PCB:s were identified among workers already 30 years before commercial use (Koppe and Keys, 2001).

Especially when heated, sucralose may dechlorinate and decompose into compounds like carcinogenic chloropropanols and polychlorinated dibenzodioxins. Another probably bigger problem with artificial sweeteners are uncertainties about their impact on the environment. Some artificial sweeteners are not easily decomposed in the environment. For instance, the environmental fate and effects of acesulfame K (another sweetener in the above-mentioned Fanta) have recently been reviewed by Belton et al. (2020). Also sucralose is problematic in a similar way. The Swedish Environmental Research Institute have shown that wastewater treatment has little effect on sucralose. Because sucralose is only slowly degraded in nature, there is a risk of continuously increasing levels in rivers and lakes.

For the case of sucralose there has been some reporting in Swedish mass media, for instance a news article in *Svenska Dagbladet*, January 30, 2008, with the heading "Sweeteners threat against environment" (translated from Swedish), but it is mainly other sweeteners – for instance aspartame (also in the above-mentioned Fanta) – that a decade ago was highlighted in the public debate, mainly connected to their potential health effects. A more general public discussion on food additives in Sweden started with the publication of the book "The Secret Cook" (translated from Swedish), criticising the use of food additives (Nilsson, 2007).

Around 2006 a sucralose-sweetened version of the much consumed Swedish tomato ketchup, Felix Tomato Ketchup, was introduced on the Swedish market. Driven by "chemical agency," I sent a mail to the producer. They answered and motivated with "that the approval of sucralose is based on EU's scientific committee's review of all scientific reports on sucralose and food safety. [. . .] It is Europe's leading scientists who review research studies and based on these have approved sucralose" (translated from Swedish). Three years later, after a boost in the debate about food additives, the producers' rhetoric had changed a lot. The sucralose-sweetened version of Felix Tomato Ketchup had by then been taken away from the market again. The producer now wrote: "Swedish authorities have approved sucralose and there is no decision to ban sucralose, but there is uncertainty about the impact of sucralose on the environment. Several studies are ongoing around this. We have received many consumer reactions due to our use of sucralose" (translated from Swedish). It is now more than a decade ago since there was a focus on food additives and among them artificial sweeteners in the public Swedish debate, and apparently sucralose (and other artificial sweeteners) are now back in some food products. However, it is now much more hidden than before! It can therefore be regarded as a contemporary example of "chemicalisation" of our society, our bodies and nature (Hodges, 2015). One could, as suggested by Belova et al. (2017, pp. 298–299), even talk about a "chemical oppression," where people are exposed to different risk-related chemicals, such as additives and contaminants, generally without being aware of the fact. Therefore, teachers should put examples of chemical oppression on the table for their students, as a potential basis for the students' development of ChemoKnowings and chemical agency.

M. Yavuzkaya. As a young student teacher (in the field of chemistry), I was trying to make sense of and contextualise the chemistry knowledge I had built so far. Therefore in 2013 and 2014, I enrolled in two senior undergraduate courses in the chemistry department, "Environmental Chemistry" and "Chemistry in Everyday Life," which changed my perspective on chemistry, teacher education, and research in chemistry education. The Environmental Chemistry course I took was taught by a professor who had gotten sick due to chemical exposure in his early years as a researcher and who later dedicated his teaching time to Environmental Chemistry. The course, taken in 2013, opened with the statement: "According to OECD, more than 500 million tons of man-made chemicals are manufactured per year and there are approximately 100,000 synthetic chemicals in everyday use." Later, so as to introduce what having 100,000 synthetic chemicals in one's everyday life means, the course moved on with the documentary "Underkastelsen" (title in Swedish; English translation: "the Submission"), that engaged me by presenting a blood analysis to determine which chemicals are present in human blood. It made me think what kind of man-made chemicals there are in my own blood and what the "cocktail effect" might potentially lead to. I realised, then, the molecules in my textbooks and notepads are indeed in my blood and are doing "something," which was a frightening thought. However, when I took the course "Chemistry in Everyday Life," I started to find this reality intriguing too. This is because my professor encouraged us "enjoy creating [on paper] the molecules" and experimentally thinking about their interactions. What I did in this course was to be creative with chemistry ideas, such as thinking about the following example: Liquid soaps include water and many organic substances which creates a nutrient media for bacteria. Therefore, commercial liquid soaps already have to include anti-bacterial agents to prevent bacterial growth. So, the difference between regular liquid soaps and the soaps that are labelled "anti-bacterial" is the addition of extra anti-bacterial substances. Is it necessary to purchase them? What are the consequences for health? Overall, my gains from these courses connected with my chemical knowledge like puzzle pieces and created a "way of thinking." I have been, as a consumer, problematising the foodstuffs I buy, as well as the ingredients of the products of everyday use (such as medicines, toothpaste, cosmetics, and clothing). It was not something that I forced myself into; it was my new way of thinking about the world, after taking the mentioned courses. Almost 10 years later, as an academic and doctoral student, I realised the courses indeed had put "something" on the table (van Poeck and Östman, 2020) that helped me realise that chemistry is not only about how we act on the material world, but also what the material world does to us, living and non-living. What my professors put on the table, be it with facts, dilemmas, or a documentary, got me (re)thinking, as I was learning about photochemical smog or phthalates in plastics, what chemistry means, for example, in our bodies, in our environment, in the bodies of other beings.

Such chemistry education has a potential to address powerful chemical knowledge in relation to wicked problems, such as ozone hole, ozone depletion, hazardous waste (plastics, toxic heavy metals, toxic organic waste, etc.), and hormonal pollution. Both courses I mentioned above addressed critical views on chemistry's distinctiveness and methodological character, by including green chemistry, regulations, and organisations to control chemical hazards and pollution, and how for example chemical industry works in the particular context. This also is related to critical views on chemistry in society. A transdisciplinary perspective was integrated in especially the Environmental Chemistry course, by mentioning major industrial chemical accidents that also includes the thalidomide scandal with a historical and futures perspective, which also is related to eco-reflexivity through environmental and sustainability education. I, back then, was feeling both amazed and frustrated because these courses helped me to make sense of the chemistry knowledge I had learned, but at the same time enabled me to problematise my own chemistry education and why we did not have the chance to problematise and contextualise chemistry in the mainstream courses. This – almost – existential questioning gave me insight into what chemistry is about for me and what it means in relation to health and environment. This, in turn, helped me develop my agency at several levels, such as my everyday choices and my consuming habits. Also as a consequence, I changed my interest of research from conceptual understanding to problematising the vision of chemistry with the help of an article by Sjöström and Talanquer (2014). As a result, my ChemoKnowings shape what kind of consumer, citizen, teacher, and researcher I am and allow me to keep an inner discussion alive: How do we relate to the world; what is our place in the world; and our responsibility?

TEACHING CONTRIBUTING TO STUDENTS' ChemoKnowings

We start this section by listing some of the major aspects of ChemoKnowings highlighted in the personal reflections in the previous section, although the list is not at all absolute in the sense that it is including all possible ChemoKnowings. The list gives some major examples of ChemoKnowings, but other ChemoKnowings and variants of ours are of course also possible.

Crucially, we are chemistry teachers (in addition to being researchers), and as such we are mindful of the fact that we view our own ChemoKnowings as being knowings that can have important value for our chemistry students. However, we are equally mindful that in our own chemistry didaktik praxis we need to consider the volition of our students in transforming the content we bring into the classroom (put on the table) for ChemoKnowings. That is, what ChemoKnowings are for us as teachers might not necessarily become ChemoKnowings for our students in their transformation of content, and if it does their ChemoKnowings probably differ from the teacher's ChemoKnowings, at least to some extent. It is important that the teacher is aware of this fact. Keeping this in mind, we want now to list some of the major aspects of ChemoKnowings highlighted in our personal reflections, and thereafter present some ideas and models that we believe can also be of value to teachers in their didaktik work in selecting content important for ChemoKnowings, and thus what they view as important for the student to learn for *Bildung*, and how to work with it in practice.

- ChemoKnowings often include *embodied chemical knowledge* (the body, including the heart), *intellectual chemical knowledge* (the head), and *practical chemical knowledge* (the hand).
- *Benefit-risk-perspectives and corresponding moral aspects* in relation to usefulness and risks of "the chemical life" (Hodges, 2015), especially related to environmental and health issues – awareness of "chemical oppression" (Belova et al., 2017), cocktail effect in the body by mixing of many synthetic chemicals, artificial sweeteners and other food additives, phthalates in plastics, etc.
- *Traditional culture of chemistry* – previously a "macho culture" at chemical research departments. Embodied chemical knowledge and risks – irritated eyes, precautionary principles, chemicals in human blood, etc.
- *Chemical agency framed by ethico-socio-political action* – alarming, protesting, highlighting, avoiding, etc.
- *Meaningful connection with the molecular world* and the possibility of "analysing, synthesising, and transforming matter for practical purposes" (Sevian and Talanquer, 2014, p. 11). "Molecular dancing" in teaching – e.g., the electrons in a benzene ring.
- *Eco-reflexivity through* understanding the role of chemistry in environmental systems thinking.

A chemistry teaching aiming at contributing to students' development of ChemoKnowings (with an ethical–political compass) needs to be varied. Generally, one can say that different types of *(post)humanisation* are needed in the choice of questions/content (Sjöström and Talanquer, 2014) – or what is put on the table – as well as in the choice of teaching methods (in a broad sense). In addition to intellectual reasoning, there is also a need for the experience of the fascinating molecular world (e.g., through playing and virtual reality simulations) as well as different types of chemical praxis (in a broad sense), as a way of understanding and developing embodied and practical chemical knowledge. Another related idea is to meet different kinds of chemists (in academia, industry, etc.), preferably in their own working environments, as a way to get a more multifaceted idea of the culture and nature of chemistry. However, such meetings need to be followed up by critical discourse analysis.

Also important is to better understand the role of chemistry in society, especially in relation to environmental systems and the planetary boundaries. Here well-selected current and historical cases can be put on the table and elaborated on from complex systems thinking perspectives (e.g., Mahaffy et al., 2019a,b; Talanquer et al., 2020), as a way for the students to develop benefit-risk-reasoning (including moral aspects) as well as eco-reflexivity.

The interdisciplinary area of Environmental Citizenship in the 21st Century Education (Hadjichambis et al., 2020) has ideas and models that can be used and transformed into chemistry teaching. Some examples are ideas regarding youth activism (Reis, 2020) and different approaches and teaching models in "the pedagogical landscape of Education for Environmental Citizenship" (Hadjichambis et al., 2020). One of these is socio-scientific inquiry-based learning (SSIBL) (Levinson and PARRISE Consortium, 2017; Ariza et al., 2021). Generally, it is important to work with what can be called controversial socio-chemical issues (type of socio-scientific issues, SSI) (for references about SSI in a broad sense see, e.g., Sadler, 2009; Hand and Levinson, 2012; Bencze et al., 2020) in chemistry teaching. This is a way of contributing to students' development of ChemoKnowings. This is connected to the development of reflective judgment (Zeidler et al., 2009) and a risk understanding (e.g., Christensen, 2009; Schenk et al., 2019) based on critical realism as an ethico-onto-epistemology (e.g., Zembylas, 2006; Levinson, 2018). It can also be connected to a critical and *Bildung*-oriented vision (Vision III) of scientific/chemical literacy (e.g., Sjöström and Eilks, 2018), emphasising "engagement with social participation and emancipation" (Valladares, 2021, p. 557). In relation to chemistry, it is about being aware of the already mentioned "chemical life" surrounding us (Hodges, 2015) as well as about chemical risks, society, and discourses (Sjöström and Stenborg, 2014) as a basis for *Bildung*-oriented action competence (e.g., Sass et al., 2020), i.e., chemical agency. Some examples of socio-chemical issues in relation to teaching are nanotechnology (Jones et al., 2013), use of different types of pesticides (Zowada et al., 2020), phosphate use and recovery (Zowada et al., 2019a,b), hydraulic fracturing ("fracking") (Dunlop et al., 2021), and fuels choice (Banks et al., 2015). Cullipher et al. (2015) have discussed different levels of sophistication of reasoning about the benefits, costs, and risks of chemical substances. This would have been interesting to relate to individual ChemoKnowings, which is, however, beyond the scope of this article.

In their *Bildung*-oriented didaktik model for sociocritical and problem-oriented chemistry teaching, Marks and Eilks (2009) emphasised a mixture of teaching methods/approaches, such as authentic media, learner-centered instruction, and controversial issues debating, and chemistry lab work. Their suggested chemistry teaching is clearly *(post)humanised* but at the same time close to chemistry content and practice. Dudas et al. (2022) have developed and mangled another didaktik model with the purpose of supporting chemistry teachers when designing activities aiming to support students' exploratory considerations of complex issues. They recommend "real-life issues to invite the unpredictability needed for experiencing complexity and the exploratory nature of chemistry" (p. 1 a.o.p.). Such issues enable students to increase their understanding of the nature of chemistry by experiencing aspects of tentativeness in chemistry.

FINALISING WITH FOUR POWERFUL KNOWINGS-ORIENTED DIDAKTIK QUESTION AREAS

In this article, we have sought to develop ChemoKnowings as a subject-specific form of powerful knowledge for (becoming) world citizens. Chemistry education (in a broad sense) has a central role in catalysing the individual learning processes which include knowledge transformation for *Bildung*. In this context, we have come to view ChemoKnowings as including embodied and relational dimensions as tacit dimensions (Carlgren, 2020). Crucially, we have come to view the teacher's consideration of students' volition in transforming content for ChemoKnowings as an important dimension of chemistry didaktik, something which is achieved in part through the teacher's own knowledge transformations. More generally, we would claim that teachers' consideration of student transformation of content for powerful subject-knowings is an important part of 21st century general subject didaktik (Vollmer, 2021).

In order to begin understanding what ChemoKnowings might be for the student in the Anthropocene, we have suggested and argued that critical chemical literacy, eco-reflexive chemical thinking, and ChemoCapabilities are related constructs. We have thus also begun to consider several potentially important dimensions, for example, "the role of chemistry in everyday life," "meta-cognitive dimensions," "affective dimensions," "concentration and transportation aspects in relation to environmental issues," "technological aspects related to chemistry" and "humanistic perspectives toward multifaceted problematisation." In addition to considering these relations, we further developed our ChemoKnowings construct by linking student transformation of content for ChemoKnowings to selected elements of a theoretical didaktik model proposed by Herranen et al. (2021) describing ChemoKnowings as consisting of: "critical views on chemistry's distinctiveness and methodological character," "powerful chemical knowledge," "critical views on chemistry in society," and "eco-reflexivity through environmental and sustainability education."

In our view, however, neither relating of ChemoKnowings to the other three constructs nor linking student transformation of content for ChemoKnowings to elements of Herranen et al.'s (2021) theoretical didaktik model, has enabled us to sufficiently articulate the constructs' embodied and relational dimensions. Drawing from Rucker (2020), as well as the classical writings of Klafki (2000b) and von Humboldt (2000), we have here suggested that ChemoKnowings are such knowings that matter meaningfully to the student and connect the student to themselves and to the world, and as a consequence confer ethical compass and promote an ethics-oriented agency. We have also suggested that when a vision for chemistry teaching (all educational levels) as a part of a world-centered vision for schooling in the Anthropocene is made salient in the classroom, such agency will become a chemical agency, that is, eco-reflexive and embodied ethico-socio-political action competence. Further, and in view of these ideas, we have suggested that each of the four selected ChemoKnowings elements of Herranen et al.'s (2021) model potentially give rise to world citizens' chemical agency. This is something which we believe should be cultivated by the teacher by bringing content into the classroom (put on the table) that has the potential to become ChemoKnowings through student transformation (make content free).

By including the above mentioned aspects, we have opened to accounting for the embodied and relational dimensions of the ChemoKnowings construct. A crucial consequence of this, we believe, is that these aspects have shifted the construct to embody ideas of personalness and plurality. Indeed, this is something powerfully brought out through our personal reflections with examples of what ChemoKnowings are for each of us. Clear in each account are chemistry-related knowings that matter meaningfully to us, and which have mobilised in each of us an embodied ethico-socio-political action. Significantly, in all the accounts, the idea of content brought into the classroom being "put on the table" and "made free" has been seen as crucially important.

We believe that the ChemoKnowing construct we have elaborated on in this article, embodying ideas of personalness and plurality, opens toward a more extensive empirical exploration of what ChemoKnowings might be for students (and teachers) in the Anthropocene. Based on such an exploration, it would be possible to construct an empirically based didaktik model (e.g., Sjöström et al., 2020; Wickman et al., 2020) on ChemoKnowings. It can guide the teacher when designing teaching that can promote ChemoKnowings and chemical agency. However, such a model is never fully ready-made in the meaning that it has to be tested in different settings, mangled, specified, and revised in an iterating process.

In this mainly theoretical article, we have, for instance, presented a visionary didaktik model (**Figure 4**), aiming to broadly orient teachers toward the idea of promoting ChemoKnowings and chemical agency in their teaching and broadening their chemistry didaktik praxis by taking into consideration student's transformation of the content the teacher brings into the classroom. We wish to conclude the article by presenting also another complementary "didaktik model" that more specifically can promote teachers' own critical reflection on, as well as preparation and transformation of, content for the classroom with a view to promoting students' ChemoKnowings. Crucial we believe in this regard, is the idea that for the teacher to come into a position of being able to consider the volition of students in transforming content for ChemoKnowings, they must first connect to their own personal transformations of content for ChemoKnowings. That is, they must consider their own experiences as learners. Inspired by Klafki's didaktik analysis questions (section "Powerful Knowledge and Knowings"), and drawing from the visionary model in **Figure 4**, as well as insights gained when writing about what ChemoKnowings are for us personally, we propose the following four areas of questions for subject teachers to consider (when concerning another subject area than chemistry, one should of course exchange "chemistry" or "chemical" with the other subject area and ChemoKnowings with another [subject]Knowings):

Discovering One's Own View of ChemoKnowings

Can you think of specific knowledge (or knowing) that has enabled you to come into a relationship with chemistry and therefore has mobilised for ethico-socio-political action? (For example, protecting and/or nurturing your own health, or the health of others, including other species, a particular ecological environment, or a non-living thing.) Can you imagine what ChemoKnowings could be for you also in a broader sense?

Getting Awareness of One's Own Worldview and Educational Vision

What is your own worldview and how does it affect your view on *Bildung* and education in the Anthropocene era? How might your reflections in relation to this question as well as the ChemoKnowings that are salient for you (e.g., your own ChemoKnowings) guide you in conceiving a vision for chemistry teaching as a part of a world-centered vision for schooling in the Anthropocene?

Discovering the Content

What is your view on content for teaching – powerful knowledge in and about chemistry – that is potentially relevant to your students and potentially contributes to their ChemoKnowings, eco-reflexive *Bildung*, and chemical agency?

Putting the Content on the Table and Make It Free

In what ways can you put this content on the table so that you engender open-ended inquiries which facilitate critical and plural points of view on the issues at hand? Try to think in terms of complex challenges and creative practical–theoretical–aesthetical representations.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

MY, PC, and JS have together developed the conceptualisation and the models and have written the manuscript. All authors have read and approved the submitted manuscript.

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