RSC Sustainability

ROYAL SOCIETY OF CHEMISTRY

PERSPECTIVE

View Article Online
View Journal

Check for updates

Cite this: DOI: 10.1039/d5su00970g

Received 31st December 2025
Accepted 21st April 2026

DOI: 10.1039/d5su00970g

rsc.li/rscsus

Towards globally conscious chemistry: perspectives on educators' responsibilities, entrepreneurship and a framework for practice

Nikki Y. T. Man *

This perspective adds to growing work that sees chemistry classrooms as learning spaces where ideas about justice, power, and equity are learned alongside disciplinary content. When educators design and teach sustainable chemistry, they are not only inviting students to think about these issues; they are also already practicing particular ethical and political commitments through the examples they choose, the problems they centre, and the ways they frame entrepreneurship and innovation. Drawing together literature on systems thinking, socioscientific issues, decolonising and culturally-responsive teaching, as well as critical studies of entrepreneurship, this piece offers the perspective that green and sustainable chemistry education as a lived ethical practice rather than a neutral technical exercise. A reflexive curriculum checklist is proposed as a practical tool for chemistry educators, students, and community partners to make these commitments more explicit, bring hidden curricula to the surface, and orient curriculum design towards more globally concious and liveable chemical futures.

Sustainability spotlight

This perspective contributes to sustainability by framing chemistry education itself as an ethical practice that shapes who carries chemical risks and who benefits from innovation. It supports SDG 4 (Quality Education) by proposing a reflexive curriculum checklist that links green and sustainable chemistry, circular economy thinking, and justice-oriented pedagogy. By raising awareness for educators to make questions of power, equity, and entrepreneurship explicit in curriculum design, the work also contributes to SDG 10 (Reduced Inequalities) and SDG 16 (Peace, Justice and Strong Institutions), helping educators align teaching with more just and sustainable chemical futures.

1 Chemistry education as ethical practice

Without a doubt, chemistry sits at the heart of today's sustainability challenges and solutions, shaping how we produce energy, materials, food, and medicines across the 17 UN Sustainable Development Goals (SDGs).[1,2] From climate change and pollution to clean water, sustainable industry, and responsible consumption, chemical knowledge is always tied to questions of who carries environmental burdens and who benefits from innovation, including which communities are exposed to toxins and which gain from "green" products and infrastructures.[3,4] In this sense, learning and teaching "sustainable chemistry" is never just a technical exercise in efficiency or risk reduction; it is already a way of learning ethics, because every choice about reagents, processes, and products carries responsibilities toward particular communities, ecosystems, and futures.[2,5]

Over the past decade, efforts to link chemistry education with sustainability, and social and environmental justice have grown, from integrating green chemistry and SDG-aligned curricula to community-engaged projects on toxic exposures, environmental racism, and circular economy practices.[4,5] Related work on socioscientific issues (SSI),[6–8] decolonising chemistry curricula,[9–12] and culturally responsive chemistry teaching[13–16] likewise frames chemical knowledge as inseparable from questions of power, history, and whose futures matter. Together, these analyses present chemistry classrooms as places where students can learn to see chemical practices as both valuable and consequential, building disciplinary expertise alongside a sense of social responsibility, often in parallel with rising expectations that they develop "entrepreneurial mindsets" and innovation skills.[3,4,17,18] However, much of this activity is still organised as discrete formats, case studies, or stand-alone modules which—though important footholds in tightly constrained curricula—often leave unchallenged deeper assumptions about what counts as "real chemistry" (typically synthetic, laboratory-based, technical work). A more reflexive approach would be to aim for ongoing reflection on which problems are treated as urgent, how success is defined, and who is presumed as a genuine innovator.[19,20]

Humboldt-Universität zu Berlin, Institute of Chemistry, Chemistry Education Research, Brook-Taylor-Str. 2, 12489 Berlin, Germany. E-mail: nikki.man@hu-berlin.de

Building on Paulo Freire's view that education is never neutral—but either sustains the "logic of the present system" or becomes a practice of freedom aimed at transforming the world—chemistry education can be read as a political practice that helps shape which socio-technical futures seem conceivable and achievable.[21,22] Drawing on justice-oriented frameworks such as capabilities approaches,[23,24] human-rights-based perspectives,[25,26] and Indigenous notions of relational responsibility,[27,28] including Indigenous scholarship that understands sustainability as grounded in ongoing responsibilities to land, waters, and more-than-human communities,[29–31] this perspective treats sustainable chemistry as a lived ethical practice and asks how questions of justice, power, and equity can be made more explicit in curriculum design, pedagogy, and emerging emphases on entrepreneurship in chemistry education.[4,32] At the centre of this exploration is the idea that educators are themselves ethical and political actors who need to reflect on their social responsibilities, biases, and institutional constraints when they choose examples, frame sustainability problems, and create opportunities such as entrepreneurial projects. This work is better seen as a collective, ongoing practice shaped by diverse experiences, than as the application of a fixed expert model.[4,22,33] My hope is that this thought piece contributes to that conversation by offering a reflexive curriculum checklist for chemistry educators as one starting point for examining their own assumptions, constraints, and possibilities in teaching sustainable chemistry as ethical practice.

This perspective is written from my point of view as a scientist in chemistry education at a German university, working on integrating sustainable chemistry teaching materials at university and school levels, and on English language and academic communication for chemistry students—work that, by default, centres English as a colonial academic norm even as it seeks to expand students' access to scientific communities. My professional background spans synthetic chemistry research, chemistry education research, teaching in language, arts and science, and roles in green chemistry start-ups in both technical and founding positions; these experiences shape how I understand sustainability, entrepreneurship, and curricular change. I also recognise the limitations of my positionality within well-resourced Global North institutions, shaped by having grown up in Hong Kong under British administration and later as a Chinese immigrant on Aboriginal land in Boorloo/Perth, and by working in English-dominant academic spaces. These locations influence how I understand colonial legacies and decolonisation in chemistry education. I offer these reflections as one situated contribution that needs to be complemented, challenged, and re-worked in continuous dialogue with colleagues and communities whose histories, knowledges, and locations differ from my own.

2 From technical sustainable chemistry to systems-orientated ethical learning

Sustainable chemistry education is often introduced through frameworks such as the principles of green chemistry, metrics like process mass intensity, tools for life-cycle assessment and safer substitution, and increasingly circular-economy thinking about material flows and end-of-life scenarios.[2,34] These approaches are absolutely important, because they allow students to see that choices about reagents, solvents, synthesis pathways, and product design have consequences for resource use, toxicity, and environmental persistence, and thus for the health and wellbeing of specific communities and places.[3,35] When students weigh trade-offs between yield and hazard, or compare the upstream and downstream impacts of alternative synthetic routes and circular options, they are already engaging with questions of harm, responsibility, and care, even if these are not named explicitly as "ethical".[2,34] This connects with work on SSI in chemistry that uses real-world contexts to help students critically examine risks, benefits, and value trade-offs.[7,36]

On the other hand, sustainable chemistry can easily be framed as a technical optimisation problem—making processes more efficient, less hazardous, more circular, or more compliant with regulations—without inviting learners to ask who defines sustainability, whose risks are deemed acceptable, and which social and economic structures remain unquestioned.[4] For example, a focus on greener solvents or better waste treatment may leave unexamined the global distribution of chemical production and disposal, the communities living near hazardous sites, or the labour conditions underpinning "green" supply chains.[37] In such cases, we learn to improve existing systems rather than to consider whether those systems themselves are just, or what alternative arrangements might look like.

In recent years, work on systems thinking in chemistry education has further reinforced this shift from isolated reactions toward seeing chemical practices as embedded in wider socio-technical, environmental, and economic systems.[38–41] Systems-thinking approaches invite learners to trace how substances, processes, and products connect across scales and contexts, and to consider not only molecular transformations but also where materials come from, how they move through supply chains, and whose environments and lives are affected over time.[38,42,43] In this sense, systems thinking aligns closely with the perspective developed here: it treats chemistry as part of interconnected systems, and asks whose risks are normalised, whose benefits are prioritised, and which futures become possible through the sustainable chemistry examples, problems, and design decisions we choose in teaching.[44–46]

Recognising sustainable chemistry as a form of ethical learning means making these implicit value questions more explicit in everyday teaching practice. For example, when designing teaching materials on life cycle assessment, one could align exercises on mapping material and energy flows or identifying leverage points in a process with prompts that ask which communities and environments sit at those leverage points and how risks and benefits are distributed across the system, so that ethical questions are treated as part of understanding the system rather than as a separate add-on. This can also involve pairing technical calculations with discussions about which stakeholders are affected by a given process, whose perspectives have been included in assessing benefits and harms, and how local and global inequalities shape exposure to chemical risks.[4,33,37] Work with SSI and justice-centred science teaching offers practical strategies here, such as structuring debates, position papers, or community-connected projects around controversial chemical issues.[7,33,36,47] It also means inviting students to see themselves not only as future problem-solvers working within established chemical industries, but as potential contributors to transforming those industries and the wider socio-technical systems in which chemistry operates, aligning their work with broader visions of social and environmental justice, and with precautionary approaches that emphasise preventing harm rather than managing it after the fact.[34,48]

3 Educators as ethical and political actors

If sustainable chemistry is already a way of learning ethics, then we as educators are never just providing neutral content; we are constantly making ethical and political choices about how sustainability is framed, whose experiences are acknowledged, and which futures are presented as desirable or possible.[21,22] Choosing a "green" synthesis that foregrounds cost savings for industry rather than reduced exposure for fence-line communities, or highlighting certain SDGs while ignoring others, subtly communicates whose interests matter and what kind of chemists students are expected to become.[4,37] These decisions are rarely made in isolation: they are shaped by institutional priorities, funding and policy structures, industry partnerships, accreditation requirements, and available resources, which means that educator responsibility also has to be understood in relation to these wider conditions, not just as a matter of individual moral willpower.[49,50] Work on decolonising chemistry curricula and equity-focused programme reforms[9,13,50,51] similarly shows how apparently technical choices about content, exemplars, and assessment can encode assumptions about whose knowledge and communities matter.

At the same time, research on justice-centred and sustainability-oriented science teaching shows that educators who engage in explicit reflection on their own positionality, values, and professional identities are better able to create learning environments where students critically examine the social dimensions of science rather than treating them as peripheral "add-ons".[32,33,50] Yet such reflexive work often sits uneasily within institutional and political climates that prioritise content coverage, competitiveness, and narrow performance metrics, and may not consistently reward or protect those who take it up. Culturally responsive and community-connected approaches to chemistry teaching likewise emphasise that this kind of reflexive work is relational and often carried out together with students and community partners, rather than by isolated individuals.[13,14,16] From this perspective, chemistry educators can be seen as ethical and political actors situated within larger systems, with responsibilities at multiple levels: to students, to colleagues, to the discipline, and to the communities and environments affected by chemical practices. The argument is not that individual lecturers must heroically overhaul entire programmes, but that small, situated decisions—about examples, assessments, partnerships, and how entrepreneurship is framed—can collectively shift chemistry education toward a more reflexive, socially responsible practice when supported by departmental cultures and professional communities that recognise and reward this work.[49,50] These same dynamics also shape how new emphasis on entrepreneurship and innovation are taken up in chemistry curricula.

4 Entrepreneurship, privilege, and neoliberal narratives

Entrepreneurship is becoming an increasingly prominent feature of chemistry and the wider STEM curricula, often framed as a way to transfer sustainable chemistry into tangible "impact" through innovation, start-ups, and spin-outs.[52] Within chemistry, entrepreneurial education is welcomed because it appears to widen students' options beyond a narrow choice between academic careers and positions in large industrial firms, offering possibilities to shape smaller, more agile organisations or mission-driven ventures.[52,53] Because entrepreneurship is now promoted as a key 21st century skill and is increasingly integrated into chemistry programmes, this section spends more time on how entrepreneurial narratives intersect with privilege, power, and responsibility in sustainable chemistry education. A growing body of work on social and sustainability-oriented entrepreneurship in STEM likewise presents entrepreneurial learning as a route to tackling environmental and social challenges, not only to enhancing competitiveness.[18,20,54] This thought piece does not reject that promise; rather, it asks how such expanded options can be made genuinely accessible and socially responsible, instead of remaining primarily available to those already well positioned—socially, financially, and institutionally—to take on entrepreneurial risk.[54,55]

Studies of chemistry and science education suggest that particular educational approaches can foster entrepreneurial characteristics such as self-confidence, risk-taking, leadership, creativity, and foresight, reinforcing the idea that "entrepreneurial thinking" is a desirable and teachable graduate attribute in chemistry.[52,56] At the same time, thematic reviews of entrepreneurship in science education have largely celebrated integrating entrepreneurship into science and chemistry curricula, while paying much less attention to how privilege, social capital, and unequal opportunities shape who is recognised as having "potential" and who can realistically pursue venture creation.[55,57] Critical perspectives on entrepreneurship education further suggest that such programmes can, unless questions of power and inequality are addressed explicitly, unintentionally reproduce neoliberal assumptions about individual responsibility and merit.[58–60] Against this backdrop, the following subsections look at how entrepreneurial opportunities in chemistry education are patterned by inequality, how startup-centred narratives can reflect and reproduce neoliberal logics, and how educators might design entrepreneurial learning formats that remain attentive to justice and responsibility rather than only to competitiveness and growth.[20,55,61]

4.1 Inequality and access in innovation

Although entrepreneurship is often promoted as an open opportunity for any motivated student, access to entrepreneurial pathways in chemistry is structured by persistent inequalities of gender, class, race, citizenship status, and caring responsibilities.[52,62,63] Akrami's study shows that STEM-based chemistry teaching can support entrepreneurial characteristics such as self-confidence, risk-taking, and leadership, but also reports significant gender differences in the development of these traits, echoing wider evidence that men and women experience entrepreneurial education and intention differently.[52] Other work on entrepreneurship education similarly documents how cultural norms, financial security, and access to supportive networks shape who feels entitled and able to see themselves as potential founders, even when programmes are formally open to all.[54,55,62]

For many chemistry students, particularly those who are first-generation, from lower-income backgrounds, on visas, or with substantial caring responsibilities, the idea of taking on the risks and unpaid time associated with a start-up is far less feasible than for peers with financial buffers, flexible time, and family support.[64–67] When curricula celebrate the entrepreneurial chemist without acknowledging these asymmetries, they can inadvertently recast structural advantages as individual “entrepreneurial spirit”, and position students who cannot or do not wish to pursue start-ups as less impactful or less ambitious, even when they may be deeply committed to sustainability and social responsibility in other arenas.[55] Recognising the unequal terrain of innovation is therefore a necessary starting point for designing entrepreneurial learning in chemistry that widens, rather than narrows, who can participate meaningfully in shaping more sustainable chemical futures.[54–57]

4.2 Ethics of the startup narrative: neoliberalism and individualised responsibility

The growing emphasis on entrepreneurial mindsets and start-up creation in higher education is closely intertwined with broader neoliberal logics that frame universities as engines of competitiveness and students as “entrepreneurial selves” responsible for maximising their own human capital.[58,59,61] In this discourse, innovation and impact are often understood in market-centred terms: sustainability problems become opportunities for new products and services, and responsibility for addressing environmental and social harms is shifted onto individual entrepreneurs and consumers rather than onto states, regulators, or collective forms of democratic action.[20,55] Entrepreneurial education can, under these conditions, risk reinforcing the idea that those who succeed in creating ventures are more deserving or more ethical actors, while those who do not or cannot participate are implicitly responsible for their own limited impact.[55,63] In this sense, the concern is less with judging individual founders and more with how chemistry programmes may frame entrepreneurship in ways that either normalise these logics or enable students to critically examine and re-imagine them.

Drawing again on Freire's distinction between education that maintains existing arrangements, and education that helps people collectively transform them,[21] this raises a pointed question about whether sustainable entrepreneurship teaching in chemistry primarily socialises students into dominant market logics or supports them in critically examining and reshaping those logics.[21,68] When curricula focus on pitching, business plans, and market fit without questioning who sets the rules of the game, who is excluded from markets, or how profit motives can collide with long-term ecological and social well-being, education risks becoming a sophisticated form of adaptation to existing power structures rather than a practice of freedom. By contrast, framing sustainable entrepreneurship as one possible strategy within a broader landscape of social innovation—where market, state, and community logics are held in tension, and where students are invited to question which problems should be commercialised at all—can align entrepreneurial learning more closely with Freire's vision of education that fosters critical consciousness and collective responsibility rather than simply producing more competitive individuals.[20,55]

4.3 Complementary innovation pathways beyond start ups

If sustainable chemistry is understood as ethical practice, then innovation and entrepreneurship cannot be reduced to founding start-ups; it also includes changing how existing institutions, infrastructures, industries, and communities organise chemical knowledge and technology.[34,69] Public-sector laboratories, regulatory agencies, established chemical companies, municipal services, and civil-society organisations all play crucial roles in shaping how chemicals are produced, monitored, and governed, yet these sites of innovation are often marginal in entrepreneurial narratives compared with the figure of the venture-backed founder.[70,71]

Similarly, community-based projects around air and water quality, waste management, or circular repair and reuse can involve highly creative chemical problem-solving oriented first toward collective wellbeing rather than market share.[72,73] For many students, their initial attraction to green and sustainable chemistry already comes from a wish to contribute to social and environmental good rather than to maximise profit, and an ethics-focused framing can affirm and help develop these motivations instead of displacing them with purely market-centred logics.

Bringing these complementary pathways into chemistry curricula can broaden students' sense of what it means to innovate responsibly.[69,74] Examples might include cooperative enterprises managing local recycling or materials recovery,[75,76] intrapreneurial initiatives inside established companies that push for greener processes,[77] or public-sector programmes redesigning regulatory frameworks to better protect vulnerable populations.[20,69,78] Treating such cases as equally legitimate and inspiring “innovation stories” alongside start-up successes helps to decentre a purely market-driven imagination of impact and highlights that socially responsible chemistry often depends on long-term, collective work in institutions that are not easily captured by pitch decks or venture metrics.[70,71] In this way, entrepreneurial learning can be reframed as exploring multiple, sometimes overlapping roles—founder, intrapreneur, public servant, cooperative member, community partner—through which chemists might participate in reshaping socio-technical systems toward greater justice and sustainability.[74,79]

4.4 Designing fair and accessible entrepreneurial learning in chemistry

Designing entrepreneurial learning in chemistry through a fairer lens therefore means both paying attention to what kinds of innovation are encouraged and to who can realistically participate.[52,55] Evidence from entrepreneurship education more broadly suggests that students' skills and dispositions are shaped by course design rather than being fixed traits, which increases educators' responsibility to design opportunities that do not rely on pre-existing privilege in time, money, or social capital.[52,56,63]

One way that fairer entrepreneurial learning can be advanced is by embedding low-risk, team-based projects within required chemistry courses so that students do not need to take on unpaid extra workloads to "opt in" to innovation.[52,80] Programmes can provide targeted mentoring, stipends, and access to networks for students from under-represented and financially constrained backgrounds, and assess projects not only on technical feasibility or market potential but also on their attention to social and environmental justice, stakeholder participation, and long-term public value.[20,81] Framed this way, entrepreneurial components in sustainable chemistry curricula become one structured space among many where students can practice collective, reflective decision-making about how to use chemical knowledge in fair and responsible ways, rather than a sorting mechanism that rewards those already best positioned to play the start-up game.[55]

5 Emotional and relational dimensions of responsible teaching

Working with sustainability, social responsibility, and justice in chemistry classrooms is not only an intellectual task; it is also a deeply emotional and relational one. Studies of justice-centred science pedagogy describe how educators and students navigate feelings of anger, grief, guilt, defensiveness, and hope when confronting issues such as environmental racism, unequal exposure to toxins, or histories of exclusion in science.[82,83] Faculty who move toward justice-centred teaching in STEM report "switch moments" shaped by personal experiences and relationships, and emphasise that sustaining this work requires communities of care and support rather than isolated individual effort.[50] These accounts highlight that teaching sustainable chemistry as ethical practice involves emotional labour—particularly for educators from marginalised groups who may already carry disproportionate burdens in diversity and inclusion work—which institutions have a responsibility to recognise, resource, and not simply absorb as invisible extra work.[48,82] This falls in line with wider analyses of academic labour under late neoliberalism, which show how care, mentoring, and inclusion work are often undervalued even as institutions publicly commit to equity and sustainability.[59,60]

A growing body of scholarship on care in justice-centred science teaching argues that classrooms oriented toward sustainability and social responsibility must intentionally cultivate relational practices: building trust, respecting students' lived experiences, creating safe spaces for difficult dialogue, and making space for uncertainty and disagreement.[82,84] Emerging work in chemistry education on culturally responsive and community-connected teaching similarly centres relationality, reciprocity, and attentiveness to students' and communities' wellbeing as central to responsible practice.[13,32,47] In this context, this might mean framing discussions of "greener" processes, circular economies, and precautionary regulation in ways that validate students' emotional responses to injustice, inviting them to connect chemical concepts to their own communities, and modelling vulnerability by acknowledging the limits of one's knowledge and the constraints of one's institutional context.[50,85] Approached in this way, responsible teaching in sustainable chemistry is not only about adding new topics or tools, but about reshaping relationships—between educators and students, among students, and between the classroom and affected communities—so that ethical reflection, precaution, and collective care become ordinary parts of learning to do chemistry.

6 Implementation, challenges, and unintended consequences

Translating these ideas into day-to-day sustainable chemistry teaching is constrained by very real structural conditions: tightly packed curricula, assessment rules focused on content coverage, precarious contracts, limited time for redesign, and uneven institutional recognition of justice-oriented work.[49,50,86,87] Recent work on green and sustainable chemistry education shows that many chemistry teachers and instructors regard sustainability, ethics, and core values as important, but feel underprepared to facilitate values-based discussions, unsure how far they can depart from established content norms, and uncertain about how to connect sustainability and entrepreneurship meaningfully to their existing courses.[88–91] Studies of chemistry educators' belief systems likewise indicate that their views about what counts as "proper" chemistry, about students' capacities, and about the purposes of education shape whether they interpret sustainable chemistry, environmental justice, and entrepreneurship as integral to the discipline or as optional extras, and in turn how willing or able they feel to change their teaching.[91–94]

At the same time, road-map and professional-development work in green and sustainable chemistry education highlights the role of structured support, communities of practice, and shared curricular resources in helping educators build confidence and competence, navigate institutional constraints, and sustain changes to their practice over time.[86,87,95] Educators describe tensions between wanting to centre social responsibility and feeling pressure to "get through" required material or

Table 1 Reflexive curriculum design checklist for awareness in socially responsible chemistry teaching and curriculum innovation

Dimension	Critical reflection questions	Background reading or exemplary works	Possible actions or examples
Power and positionality	How do social, cultural, and institutional positions shape what is considered important in sustainable chemistry and circularity? Whose interests end up being served through the examples and problems presented in class?	9, 32 and 33	Host peer reflection sessions; include brief positionality statements in course materials; invite diverse guest speakers (including community partners)
Representation and voice	Whose knowledge, histories, and contributions are visible? Who is omitted or stereotyped (*e.g.* Global South communities, informal recyclers, Indigenous scientists)?	9, 10, 13 and 14	Diversify examples of chemists and case studies; integrate Indigenous and local knowledge; use inclusive visuals and language
Ethical framing and precaution	What assumptions underpin the "problems" and "solutions" we study? Is precaution (anticipating and preventing harm) made explicit, or is chemistry presented as value-neutral?	7, 36 and 48	Use historical examples (*e.g.* TEL, thalidomide) to discuss precaution; pair technical design tasks with analysis of worst-case scenarios and regulatory responses
Hidden curriculum and norms	What unspoken messages about success, failure, "real chemistry," or "good innovation" do labs, assessments, or discussions convey?	33, 100 and 101	Include reflection on professional responsibility; make visible and value forms of achievement such as care work, collaboration, community engagement, or regulatory innovation
Access and inclusion	Who faces barriers to participating fully- financial, linguistic, cultural, or structural?	6, 98 and 99	Offer flexible assessment formats; use open-access resources; acknowledge constraints like work and caregiving; scaffold participation in group work
Politics of knowledge and systems	What economic and institutional logics (*e.g.* fossil-based industry, growth, IP models) shape the examples and partnerships that are being choosen? Do students learn to critique these systems?	4, 20 and 103	Make funding and regulatory contexts visible; analyse policy trade-offs and socio-technical systems, not only individual technologies
Entrepreneurship and equity	Who can realistically benefit from entrepreneurial opportunities that are offered—for example in terms of time, capital, and networks? How are risk and reward distributed?	17, 18 and 52	Design team-based, course-embedded projects; bring in founders with diverse backgrounds; discuss structural barriers and complementary innovation pathways (coops, public sector, community labs)
Circularity and labour	How are circular economy examples framed? Do they obscure or highlight the labour and risks involved in recycling, repair, and waste management?	104–106	Include cases on informal recycling, e-waste, and repair economies; invite students to map who does what work in a given circular system
Emotional and relational dimensions	How can trust and care be fostered when discussing injustice, harm, and privilege? Whose emotional labour is being relied on?	33, 82 and 97	Co-create discussion norms; use reflective journals; share facilitation roles thoughtfully; avoid over-burdening minoritised students as spokespeople
Co-creation and accountability	Are students and community voices involved in shaping the curriculum? How is ethical intent evaluated over time?	107–110	Use participatory design workshops; collect and act on mid-course feedback; invite external review of cases; revisit the checklist periodically as a group

to align with accreditation expectations, which can make such changes feel risky, exhausting, or only possible at the margins of courses.[96,97] Without explicit departmental and institutional support—such as workload allocation, professional development, and inclusion of this work in promotion criteria—responsible teaching risks becoming dependent on the goodwill of a few individuals rather than a shared commitment, effectively reinstating a value-neutral curriculum by default.[22,50,98] Similar dynamics are documented in work on inclusive and green chemistry initiatives, where isolated champions struggle to sustain change without programme-level structures and recognition.[2,5,99]

There are also unintended consequences to anticipate. Adding sustainability, ethics, or entrepreneurship modules without changing assessment or institutional incentives can lead to tokenism, where students perceive these topics as "extra" or symbolic rather than integral to chemistry.[34,49] Justice-centred efforts may inadvertently place additional emotional and representational burdens on students and staff from marginalised groups, who are often expected to speak for their communities or to lead difficult conversations.[50,82] On top of that, if entrepreneurial components are introduced without attending to privilege and risk, they can further deepen inequities by rewarding those already best positioned to take advantage of them.[52,63] Attempts to rapidly 'green' or 'decolonise' curricula without meaningful conversations can also generate resistance or change fatigue among staff, underscoring the need for paced dialogues and processes, rather than top-down mandates.[9,10,51] Making these challenges explicit—and treating implementation as iterative, collectively evaluated work guided by precaution and care—can help chemistry educators and institutions move toward more sustainable, socially responsible practices without assuming that any single intervention will be a simple or universally beneficial solution.[48,50] Across these implementation challenges, much depends on the often-invisible norms and assumptions embedded in existing programmes.

7 Ethics, bias, and the hidden curriculum

When sustainable chemistry and circular economy concepts are presented primarily as technical optimisation—designing more efficient syntheses, improving atom economy, or closing material loops—the value judgements behind what counts as a "good" decision often remain invisible, forming part of the hidden curriculum: the unspoken norms about whose knowledge counts, whose harms matter, and what kinds of futures are valued.[4,100,101] Case studies that focus on circular business models in high-income contexts, for example, can implicitly suggest that circularity is driven by well-capitalised firms and technologically intensive solutions, while saying little about informal recycling labour, hazardous e-waste processing, or communities whose lands and waters are used as sites for extraction and disposal.[35,42] Similarly, when curricula connect chemistry mainly to SDGs around industry, innovation, and economic growth, and pay less attention to goals on reduced inequalities or peace and justice, students can receive the message that some dimensions of sustainability are central to "real chemistry" while others are peripheral, reinforcing the impression that chemistry has a value-neutral core, with "ethical" issues pushed to the margins.[4,34,48] This pattern echoes broader analyses of how hidden curricula in STEM shape belonging, career trajectories, and whose concerns are treated as legitimate.[100–102]

Recognising that there is no neutral view of sustainability means acknowledging that educators' own histories, identities, and institutional locations influence how they frame green chemistry, circular economy, and "responsible" innovation—whose perspectives they highlight, which trade-offs they centre, and which ethical questions they consider relevant.[22,98] To support more reflexive practice, this perspective proposes a Reflexive Curriculum Design Checklist (Table 1) not as an expert prescription, but as a living tool that educators, students, and community partners can adapt and contest together, selecting those questions that fit their course and institutional constraints at a given moment. This checklist grew out of close readings of literature on sustainable and green chemistry education, justice-centred and decolonising approaches in STEM, alongside work in sociology, philosophy, and critical theory on power, inequality, and ethics, and was iteratively refined through teaching practice and informal conversations with colleagues and students.

This invites questions across dimensions such as power and positionality, representation and voice, ethical framing of content, access and inclusion, politics of knowledge, entrepreneurship and equity, and emotional–relational dynamics—for instance: Whose sustainability and circularity problems are centred? Who is imagined as the decision-maker, the worker, the community at risk, or the beneficiary? Whose risks are normalised or exported, geographically or socially?.[4,37,81] In this way, the checklist adapts ideas from equity-minded curriculum review and participatory course-design frameworks to the particular context of sustainable chemistry.[111–113] When it is used in this way, the chemistry classroom could become a space where ethical assumptions are made discussable and open to change, rather than silently transmitted as the natural order of things.

8 Conclusions and open thoughts: teaching chemistry as collective ethical action

Chemistry education, particularly when it engages with green chemistry, circular economy, and sustainability, already teaches ethics because it requires learners to wrestle with questions of harm, responsibility, and whose futures are being designed or excluded through chemical decisions. This perspective has hopefully shown that such teaching is never neutral: it either quietly reproduces existing socio-technical arrangements—about whose labour, land, and health are expendable—or becomes a practice of freedom in Freire's sense, where educators and students work together to critically read and transform the chemical worlds they take space in, moving beyond the older ideal of value-neutral science toward precautionary responsibility. This view sits alongside other justice-oriented approaches in sustainability and chemistry education, including capabilities, human rights, and Indigenous relational frameworks that similarly foreground responsibility for shared futures.

Taking this seriously shifts attention from "adding ethics" to chemistry teaching toward recognising educators as ethical and political actors who make consequential choices about how sustainability, social responsibility, and entrepreneurship are framed, whose voices and experiences are centred, and which innovation pathways are legitimised. In parallel, a systems-oriented view of chemistry education underscores that these choices are always made within wider socio-technical and ecological systems, and that responsible teaching involves helping students see how chemical decisions shape and are shaped by those systems over time. It invites ongoing reflexive work—supported by tools such as the curriculum checklist, by communities of practice, and by institutional recognition—that brings hidden curricula to light, questions privilege in entrepreneurial opportunities, and treats emotional and relational labour as integral rather than incidental to responsible teaching. For chemistry education communities, this also means attending to programme- and institutional-level conditions—assessment rules, accreditation, funding, and recognition structures—so that justice-oriented practices are sustainable and shared rather than reliant on a few individual champions. A final thought: if chemistry education is already helping to shape the conditions under which chemical knowledge is used, then to "wash one's hands" of the conflicts and inequities intertwined with that knowledge is, as Freire warns, to side with the status quo; choosing sustainable chemistry as ethical practice means consciously orienting teaching toward more just and liveable chemical futures instead.

Author contributions

This manuscript was conceived and developed by NYM.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included, and no new data were generated or analysed as part of this review.

Acknowledgements

A million thanks to Siobhán S. Wills and Christene A. Smith for their thoughtful readings of and generous feedback on this article. Acknowledgements also to the people who helped shape my perspectives on this topic through insightful conversations. The literature review and reference mapping were supported by the Research Rabbit AI tool.

Notes and references

1 ACS Green Chemistry Institute, Chemistry & the UN Sustainable Development Goals, American Chemical Society, https://www.acs.org/green-chemistry-sustainability/education/chemistry-sustainable-development-goals.html, accessed 29 December 2025.
2 V. G. Zuin, I. Eilks, M. Elschami and K. Kümmerer, *Green Chem.*, 2021, **23**, 1594–1608.
3 A. Murti and H. Hernani, *J. Chem. Educ.*, 2023, **15**, 1–9.
4 G. A. Lasker, K. E. Mellor, M. L. Mullins, S. M. Nesmith and N. J. Simcox, *J. Chem. Educ.*, 2017, **94**, 983–987.
5 K. B. Aubrecht, M. Bourgeois, E. J. Brush, J. MacKellar and J. E. Wissinger, *J. Chem. Educ.*, 2019, **96**, 2872–2880.
6 A. Wiyarsi, A. K. Prodjosantoso and A. R. E. Nugraheni, *Front. Educ.*, 2021, **6**, DOI: 10.3389/feduc.2021.660495.
7 M. d. M. López-Fernández, F. González-García and A. J. Franco-Mariscal, *J. Chem. Educ.*, 2022, **99**, 3435–3442.
8 Z. Kong, S. Zhang, F. Zhu and J. Zhang, *Front. Psychol.*, 2022, **13**, 877311.
9 C. E. H. Dessent, R. A. Dawood, L. C. Jones, A. S. Matharu, D. K. Smith and K. O. Uleanya, *J. Chem. Educ.*, 2022, **99**, 5–9.
10 K. O. Uleanya, S. K. Furfari, L. C. Jones, K. P. Selwe, A. B. Milner and C. E. H. Dessent, *J. Chem. Educ.*, 2023, **100**, 2583–2590.
11 University of York, Decolonising Chemistry, https://www.york.ac.uk/chemistry/about/news/news-2021/decolonising-chemistry/, accessed 30 December 2025.
12 N. Notman, A journey towards decolonisation in undergraduate chemistry curriculums, https://edu.rsc.org/feature/a-journey-towards-decolonisation-in-undergraduate-chemistry-curriculums/4015683.article, accessed 30 December 2025.
13 Y. Rahmawati, A. Mardiah, E. Taylor, P. C. Taylor and A. Ridwan, *Sustainability*, 2023, **15**, 6925.
14 Y. Rahmawati, A. Ridwan, U. Cahyana and D. Febriana, *Univers. J. Educ. Res.*, 2020, **8**, 468–476.
15 B. Chibuye and I. S. Singh, *Heliyon*, 2024, **10**, e29174.
16 A. Ridwan, Y. Rahmawati and A. Mardiah, *Multidiscip. Sci. J.*, 2025, **7**, 2025530.
17 B. K. Ghatora and R. Strutt, *New Dir. Teach. Nat. Sci.*, 2017, **12**, DOI: 10.29311/ndtps.v0i12.2335.
18 P. Torres-Sánchez, A. M. Juárez and J. Miranda, *Front. Educ.*, 2024, **9**, 1392131.
19 Z. M. Ali, V. H. Harris and R. L. LaLonde, *J. Chem. Educ.*, 2020, **97**, 3984–3991.
20 Y. J. Wu, M. Goh and Y. Mai, *Hum. Soc. Sci. Commun.*, 2023, **10**, 283.
21 P. Freire, *Pedagogy of the Oppressed (Trans. MB Ramos)*, Continuum, New York, 1970, vol. 2005.
22 J. Garcia-Martinez, Responsible chemistry in a time of mistrust, https://council.science/blog/responsible-chemistry-in-a-time-of-mistrust/, accessed 29 December 2025.
23 C. S. Hart, *Camb. J. Educ.*, 2012, **42**, 275–282.

24 J. M. Alexander, *Capabilities and Social Justice: the Political Philosophy of Amartya Sen and Martha Nussbaum*, Routledge, 2016.
25 T. Tajmel, K. Starl and S. Spintig, *The Human Rights-Based Approach to STEM Education*, Zentralinstitut Professional School of Education, 2021.
26 F. Tibbitts, *Prospects*, 2024, **54**, 401–409.
27 R. K. Gould, D. E. Martinez and K. R. Hoelting, *Ecosyst. People*, 2023, **19**, 2229452.
28 P. M. Wehi, K. L. Kamelamela, K. Whyte, K. Watene and N. Reo, *People Nat.*, 2023, **5**, 1403–1414.
29 J. K. Weir, C. Stacey and K. Youngetob, *The Benefits Associated with Caring for Country: Literature Review*, AIATSIS, 2011.
30 D. Throsby and E. Petetskaya, *Int. J. Cult. Property*, 2016, **23**, 119–140.
31 M. N. Tom, E. S. Huaman and T. L. McCarty, *Int. Rev. Educ.*, 2019, **65**, 1–18.
32 K. Ribay, *Considering Chemistry Education for Social Justice: Examining Teachers' Conceptions and Applications*, Stanford University, 2022.
33 D. Morales-Doyle, *Sci. Educ.*, 2017, **101**, 1034–1060.
34 J. E. Wissinger, A. Visa, B. B. Saha, S. A. Matlin, P. G. Mahaffy, K. Kümmerer and S. Cornell, *J. Chem. Educ.*, 2021, **98**, 1061–1063.
35 M. Mitarlis, U. Azizah and B. Yonata, *J. Technol. Sci. Educ.*, 2023, **13**, 233–254.
36 R. Mamlok-Naaman, D. Katchevich, M. Yayon, M. Burmeister, T. Feierabend, and I. Eilks, in *Worldwide Trends in Green Chemistry Education*, ed. V. Zuin and L. Mammino, The Royal Society of Chemistry, 2015, pp. 45–60.
37 H. E. Gandolfi, *Sci. Educ.*, 2025, **109**, 1652–1668.
38 M. Orgill, S. York and J. MacKellar, *J. Chem. Educ.*, 2019, **96**, 2720–2729.
39 H. Tümay, *J. Chem. Educ.*, 2023, **100**(10), 3925–3933.
40 P. G. Mahaffy, A. Krief, H. Hopf, G. Mehta and S. A. Matlin, *Nat. Rev. Chem.*, 2018, **2**, 0126.
41 S. A. Matlin, Systems thinking in chemistry: A key competency for a sustainable future, https://www.iocd.org/perspectives/Perspective2020-IOCD-02-STIC.pdf.
42 S. Pazicni and A. B. Flynn, *J. Chem. Educ.*, 2019, **96**, 2752–2763.
43 L. E. Krab-Hüsken, L. Pei, P. G. de Vries, S. Lindhoud, J. M. Paulusse, P. Jonkheijm and A. S. Wong, *J. Chem. Educ.*, 2023, **100**, 4577–4584.
44 G. A. Hurst, *Curr. Opin. Green Sustainable Chem.*, 2020, **21**, 93–97.
45 D. J. C. Constable, C. Jiménez-González and S. A. Matlin, *J. Chem. Educ.*, 2019, **96**, 2689–2699.
46 A. B. Flynn, M. Orgill, F. M. Ho, S. York, S. A. Matlin, D. J. Constable and P. G. Mahaffy, *J. Chem. Educ.*, 2019, **96**, 3000–3005.
47 K. Ribay, *Sci. Educ.*, 2024, **108**, 734–761.
48 J. D. Rivera-Ramírez, *Open J. Philos.*, 2020, **10**, 374–387.
49 R. Lozano and M. Katherine Watson, *Educ. Quim.*, 2013, **24**, 184–192.
50 D. Forsythe, B. Dewsbury and J. L. Hsu, *CBE-Life Sci. Educ.*, 2024, **23**, ar60.
51 University of York, University of York 'Decolonising the Chemistry Curriculum' Group, https://www.rsc.org/standards-and-recognition/prizes/winners/curriculum-decolonisation, accessed 30 December 2025.
52 Z. Akrami, *Chem. Educ. Res. Pract.*, 2022, **23**, 475–485.
53 A. G. Jennifer, J. C. Jenny, V. P. Balaji and R. Yadav, *J. Chem. Educ.*, 2022, **99**, 1556–1562.
54 V. Ratten and P. Usmanij, *Int. J. Manag. Educ.*, 2021, **19**, 100367.
55 K. Jensen, *The Ethics of Entrepreneurship Education*, The MIT Press, 2024.
56 N. Dyantyi and N. Faleni, *Int. J. Acad. Res. Bus. Soc. Sci.*, 2023, **12**, 209–216.
57 İ. Deveci and S. Çepni, *J. Turk. Sci. Educ.*, 2017, **14**, 126–143.
58 M. Lackéus, *Educ. + Train.*, 2017, **59**, 635–650.
59 T. Delahunty, *Educ. Rev.*, 2025, **77**, 2327–2349.
60 J. DeSaxe, in *Conceptualizing the Purpose of School*, 2015, vol. 5, p. 7.
61 M. Peters, *J. Educ. Enq.*, 2001, **2**(2), 58–71.
62 A. S. Adikaram and R. Razik, *J. Entrep. Emerg. Econ.*, 2022, **15**, 1113–1138.
63 C. G. Brush, A. de Bruin and F. Welter, *Int. J. Gend. Entrep.*, 2009, **1**, 8–24.
64 J. Bruder, D. Neuberger and S. Räthke-Döppner, *Int. J. Entrep. Behav. Res.*, 2011, **17**, 296–313.
65 J. Ferreira, A. Paço, M. Raposo, C. Hadjichristodoulou and D. Marouchou, *J. Int. Enterpren.*, 2021, **19**, 130–147.
66 A. David and J. Terstriep, *J. Enterprising Communities People Places Glob. Econ.*, 2024, **19**, 248–275.
67 T. Shen, A. E. Osorio and A. M. Settles, *Acad. Enterpren. J.*, 2017, **23**(1), 24–43.
68 H. A. Giroux, P. L. McLaren, P. McLaren and M. Peter, *Critical Pedagogy, the State, and Cultural Struggle*, Suny Press, 1989.
69 R. Von Schomberg, *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society*, 2013, pp. 51–74.
70 R. R. Ernst, *Angew. Chem., Int. Ed.*, 2003, **42**, 4434–4439.
71 P. Mahaffy, J. Zondervan, A. Hay, D. Feakes and J. Forman, *Chem. Int.*, 2014, **36**, 9–13.
72 M. A. Yevenes, H. Pereira and R. Bermudez, *Front. Environ. Sci.*, 2022, **10**, 940778.
73 L. Mersico, S. Aureli and E. Foschi, *Sustainability Account. Manag. Policy J.*, 2026, **17**(1), 233–266.
74 L. Mammino, *Chem. Teach. Int.*, 2024, **6**, 419–429.
75 The DEAL team, SWaCH, https://doughnuteconomics.org/stories/swach-doughnut-design-case-study, accessed 31 December 2025.
76 International Finance Corporation, *Supporting Cooperatives: How ABIHPEC Strengthens Recycling, Supply Chains, and Livelihoods for Waste Pickers in Brazil*, World Bank, Washington, DC, 2023.
77 E. Bennett, *To Chem. J.*, 2024, **11**, 1–2.
78 M. P. Wilson and M. R. Schwarzman, *Environ. Health Perspect.*, 2009, **117**, 1202–1209.

79 S. Kaya, S. Erduran, N. Birdthistle and O. McCormack, *Sci. Educ.*, 2018, **27**, 457–478.

80 R. Pearce, I. Zitha, G. Mokganya, V. Molaudzi, V. Nekhubvi and O. Matsilele, *Int. J. Res. Bus. Soc. Sci.*, 2025, **14**, 151–159.

81 K. N. White, A Discipline Brief for Equity in Chemistry, [Research Review], https://www.everylearnereverywhere.org/resources/a-discipline-brief-for-equity-in-chemistry/, accessed 30 December 2025.

82 K. Billings, C. McGhee-Esquivel and M. C. Linn, *Sci. Teach.*, 2025, **92**, 46–55.

83 K. Cairns, *Curric. Inq.*, 2022, **51**, 522–541.

84 M. Varelas, *Sci. Educ.*, 2026, **110**, 53–58.

85 D. Upegui, J. Coiro, S. Battle, R. Kraus and D. Fastovsky, *Sci. Educ.*, 2022, **31**, 923–941.

86 J. W. Moir, N. K. Obhi, J. MacKellar, D. A. Laviska and A. S. Cannon, *J. Chem. Educ.*, 2025, **102**, 3387–3398.

87 J. J. MacKellar, D. J. C. Constable, M. M. Kirchhoff, J. E. Hutchison and E. Beckman, *J. Chem. Educ.*, 2020, **97**, 2104–2113.

88 M. Stojanovska, *Chem. Teach. Int.*, 2024, **6**, 373–383.

89 J. Apotheker, *Chem. Teach. Int.*, 2024, **6**, 337–339.

90 D. Quiroz-Martinez, *Environ. Educ. Res.*, 2024, **30**, 432–449.

91 P. Duangpummet, P. Yasri and P. Chenprakhon, *J. Chem. Educ.*, 2026, **103**, 1159–1169.

92 A. Parker, E. Noronha and A. Bongers, *J. Chem. Educ.*, 2023, **100**, 1728–1738.

93 K. Kotul'áková, *Chem. Educ. Res. Pract.*, 2020, **21**, 730–748.

94 K. Grieger, B. Hill and A. Leontyev, *Green Chem.*, 2022, **24**, 8770–8782.

95 A. S. Cannon, K. R. Anderson, M. C. Enright, D. G. Kleinsasser, A. R. Klotz, N. J. O'Neil and L. J. Tucker, *J. Chem. Educ.*, 2023, **100**, 2224–2232.

96 F. M. Mensah and K. Larson, *A summary of inclusive pedagogies for science education*, The National Academies of Sciences, Engineering, Medicine, 2017.

97 H. Cooke, T. Campbell, A. Luehmann, Y. Zhang and D. Scipio, *J. Res. Sci. Teach.*, 2025, **62**, 1040–1072.

98 K. T. Xia, F. Dean Toste, M. B. Francis and A. M. Baranger, *Chem. Sci.*, 2025, **16**, 4412–4429.

99 N. K. Obhi, J. Moir, A. Oseolorun and A. S. Cannon, *Sustainable Chem. Pharm.*, 2025, **44**, 101944.

100 M. J. Hopkins, B. N. Moore, J. L. Jeffery and A. S. Young, *eLife*, 2024, **13**, e94422.

101 H. Tan and G. Kidman, in *Knowledge Generation in STEM and STEAM Education: Integrative Thinking and Agency*, ed. G. Kidman, H. Tan, R. Gesthuizen and D. D. Mangao, Springer Nature Switzerland, Cham, 2025, pp. 205–256.

102 V. R. Ralph, L. J. Scharlott, A. G. L. Schafer, M. Y. Deshaye, N. M. Becker and R. L. Stowe, *JACS Au*, 2022, **2**, 1869–1880.

103 A. J. Winstead, P. C. McCarthy, D. S. Rice and G. W. Nyambura, *J. Chem. Educ.*, 2022, **99**, 402–408.

104 C. Garcia-Saravia Ortiz-de-Montellano, A. Ghannadzadeh and Y. van der Meer, *Front. Sustainability*, 2023, **4**, 1197659.

105 B. M. Finn, P. B. Cobbinah and D. Gounaridis, *npj Urban Sustainability*, 2025, **5**, 101.

106 A. L. Srivastav, Markandeya, N. Patel, M. Pandey, A. K. Pandey, A. K. Dubey, A. Kumar, A. K. Bhardwaj and V. K. Chaudhary, *Environ. Sci. Pollut. Res. Int.*, 2023, **30**, 48654–48675.

107 D. Morales-Doyle, *J. Res. Sci. Teach.*, 2018, **55**, 749–773.

108 V. Millar, W. Park and J. Dillon, *Int. J. Sci. Educ,*, 2025, **47**, 1965–1971.

109 A. Arcia, S. Stonbraker, S. Mangal and M. Lor, *J. Particip. Med.*, 2024, **16**, e64508.

110 M. Perez, in *Proceedings of the 20th Annual ACM Interaction Design and Children Conference*, Association for Computing Machinery, New York, NY, USA, 2021, pp. 631–632.

111 G. Chahni, J. Griffiths, H. Leach, E. Medcalf, L. Medlock, A. Nicum, A. C. Cruchley, M. J. Jenkins and S. Cruchley, *J. Chem. Educ.*, 2025, **102**, 4847–4854.

112 N. Notman, Striving for an inclusive curriculum, https://edu.rsc.org/feature/striving-for-an-inclusive-curriculum/4015981.article, accessed 30 December 2025.

113 A. L. Curtin and J. P. Sarju, in *Advances in Online Chemistry Education*, ACS Publications, 2021, pp. 135–163.