

Rethinking Instructional Materials: A Sustainability Framework for Science Education

Jui-Lien Tseng¹, Chih-Cheng Lin^{2*}

¹Technology Education Division, National Science and Technology Museum, Kaohsiung, Taiwan, ²Department of Fisheries Technology and Management, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan

*Corresponding Author: cclin108@n kust.edu.tw

ABSTRACT

While museums are increasingly recognized as key sites for Education for Sustainable Development, a significant gap persists between their environmental messaging and material practices. This paper addresses an overlooked dimension of museum pedagogy: The design of physical instructional materials. We argue that the prevalent use of single-use, resource-intensive science kits represents a missed opportunity to model sustainable science. This paper introduces ECO-INSTRUCT, a conceptual framework to guide the development of sustainable instructional materials. Derived from reflective practice at the National Science and Technology Museum, the framework is built on five core principles: Material Circularity and Regeneration, Low-Carbon and Localized Production, Design for Multi-functionality and Reusability, Design for Durability and Repairability, and Digital Integration for Dematerialization. We posit that instructional materials are not neutral but are value-laden artifacts that shape learners' understanding of the nature of science. By embedding sustainability into the design process, educators can create tools that reduce their ecological footprint and enhance pedagogical practice by fostering key sustainability competencies such as systems thinking, creativity, and resourcefulness. This framework guides museums to pioneer a more responsible and philosophically coherent approach to science education.

KEY WORDS: Circular economy, instructional design, museum education, science materials, sustainable education

INTRODUCTION

The global community confronts profound and interconnected challenges, from climate change to social inequality, which have established sustainable development as an urgent and collective imperative. The United Nations' 2030 Agenda for Sustainable Development, with its 17 Sustainable Development Goals, provides a comprehensive blueprint for global action, calling for a fundamental transformation in how societies and economies function (United Nations, 2015). Education for Sustainable Development (ESD) is central to this agenda, envisioned as a foundational mechanism for equipping learners with the knowledge, dispositions, and agency needed to foster sustainable futures and act as agents of change (UNESCO, 2020).

While much of the discourse on ESD has centered on formal schooling, museums, especially science museums, occupy an equally important position within the broader ecology of education. As dynamic, non-formal institutions, museums possess distinctive affordances: interdisciplinary, public-facing, and materially rich. These characteristics uniquely position them to cultivate sustainability literacy through immersive, hands-on experiences (Hansson and Öhman, 2021). The International Council of Museums (ICOM, 2022) has articulated this evolving role by urging museums to embed sustainability across all dimensions of practice, including exhibitions, operations, and educational engagement.

In response, many science museums have taken proactive steps, addressing themes such as climate change, biodiversity, and the circular economy through interactive programming. These efforts help translate complex global systems into accessible and affectively resonant learning experiences (Hansson and Öhman, 2021). However, an important gap remains unaddressed regarding the sustainability of the physical instructional materials that museum educators design and use, such as manipulatives, take-home kits, and workshop tools.

Although these materials are integral to tactile science learning, their life cycle, including design, sourcing, use, and disposal, has received limited scrutiny. Historically, the professional practice of museum educators has emphasized pedagogical alignment with curricular goals and audience engagement (Brett, 2014; Duran et al., 2010). Moreover, drawing on our extensive field research and practitioner experience, we have observed that contemporary educators face significant storage constraints for instructional materials. This limitation, coupled with the practical burden of maintaining reusable resources, has contributed to a growing preference for single-use instructional kits. A pertinent example occurs in the teaching of electrical circuits, where the reliance on batteries, which are often disposed of immediately after use, is environmentally unsustainable. As a result, the ecological consequences of material choices have often been treated as secondary concerns, if acknowledged at all. This creates a troubling paradox: a museum may host a climate change exhibition

while distributing educational kits made from unsustainable, single-use materials. Such misalignments represent not only operational contradictions but also missed pedagogical opportunities. If instructional materials are indeed value-laden artifacts, as much cultural as functional (Filippini-Fantoni and Bowen, 2007), then sustainability should be treated as a core design criterion rather than an afterthought.

This paper, therefore, advocates for a new approach by proposing a conceptual framework of five design principles. The framework emerges from reflective practice at the National Science and Technology Museum (NSTM) in Taiwan and is grounded in the view that sustainable instructional design must attend simultaneously to material practice, pedagogical strategy, and epistemic values. NSTM has been a national leader in promoting green museum initiatives (Chen and Chang, 2010), and this framework draws from its ongoing efforts to align educational materials with broader ecological values. Although developed within a museum context, these principles serve as generative tools for a broad range of science educators, including school teachers, curriculum designers, and informal education practitioners, who seek to embed sustainability meaningfully into their pedagogical materials.

WHY SUSTAINABILITY MATTERS IN SCIENCE INSTRUCTIONAL MATERIALS?

Environmental Impacts of Science Kits

The material culture of science education is integral to hands-on inquiry but also carries substantial ecological costs. The widespread use of single-use laboratory equipment and consumable components in both formal and informal science learning mirrors broader patterns of disposability within scientific practice. For example, global scientific research generates over 5.5 million tonnes of plastic waste annually, an amount equivalent to 67 cruise ships (Freese et al., 2024). This entrenched a “take-make-dispose” pattern of resource consumption starkly contrasts with the values of sustainability that many institutions aim to promote.

A significant proportion of hands-on science education is delivered through pre-packaged instructional kits. These kits, often favored for convenience and standardization, are typically designed for single-use deployment with limited regard for ecological durability (Ling et al., 2022; Oliveira et al., 2021). Museum-produced kits are no exception. They frequently incorporate plastic-based components, disposable parts, and imported materials, which represent practices that contribute to heightened greenhouse gas emissions, resource depletion, and long-term waste (Vozzola et al., 2018).

Moreover, such kits rarely leverage local materials or contextual knowledge systems, missing critical opportunities to model sustainable science and connect students with place-based inquiry. Parallels from the toy industry are instructive: life cycle assessments of structured playsets like LEGO and

Jenga reveal that plastic-intensive manufacturing (e.g., ABS molding) produces significantly more environmental harm than alternatives using renewable or repairable materials; therefore, the sustainable design concepts should be adopted (Levesque et al., 2022).

Taken together, these insights point to a central imperative: science instructional material design must prioritize sustainability across its entire life cycle. This includes treating reusability, local sourcing, and low-impact materials as core design principles rather than secondary considerations. Without such intentionality, educational tools may inadvertently contradict the ecological ethics they aim to cultivate.

Instructional Materials as Value-Laden Artifacts

Instructional materials are never neutral. They reflect what educators value, whether intentionally or not, and therefore carry ideological, cultural, and epistemological significance. In museum education, materials ranging from tactile kits to take-home manipulatives play a dual role, as they support the learning of scientific concepts while simultaneously modeling broader narratives regarding science, society, and sustainability. As Hooper-Greenhill (1994) argues, museums function as semiotic systems; the objects they deploy are not passive carriers of information but active constructors of meaning. When instructional tools are designed without regard for sustainability, they may tacitly promote consumerism, disposability, and a disconnect between scientific inquiry and ecological responsibility.

This phenomenon is not confined to museums. In broader science education contexts, materials also participate in what is often called the “hidden curriculum,” the implicit values and norms conveyed through pedagogical practices and artifacts (Aikenhead, 1996; Hetherington et al., 2019). Sørensen (2009) emphasizes that the material culture of science classrooms shapes what is perceived as valid scientific activity. Plastic-heavy, mass-produced kits signal efficiency and standardization but rarely cultivate ecological awareness or critical reflection on science-society relations.

From this perspective, science materials function as ideological texts. Their physical composition, sourcing, durability, and design attributes encode messages regarding the environment, the nature of knowledge, and the specific modes of scientific inquiry that are prioritized. Museum educators, therefore, are responsible for transmitting scientific knowledge and the opportunity to design artifacts that reflect ethical commitments to sustainability and justice. This is especially important given the museum’s evolving public role, from a repository of established knowledge to a site of critical engagement with contemporary global challenges (Watermeyer, 2012).

As such, embedding sustainability into instructional material design is not merely a technical adjustment but a philosophical reorientation. It aligns the form of science education with its aspirational content, reinforcing ecological responsibility in what is taught and how learning is materially enacted.

Sustainability as a Pedagogical Model

If instructional materials are not neutral but value-laden, as discussed, then it follows that their design can be mobilized intentionally to model sustainability. This shifts the discussion from critique to possibility by treating sustainability not simply as a topic within science education, but as a pedagogical orientation that shapes the design and use of learning environments. When materials are designed for sustainability, they cease to be static tools and become a pedagogical model; they teach through their making and use processes. This perspective aligns with arguments that pedagogical environments should be constructed to cultivate the specific epistemic practices educators wish to instill (Duschl, 2008; Stroupe, 2014). Materials locally sourced, designed for reuse, or crafted for durability offer more than environmental benefits. They serve as tangible enactments of sustainability, making abstract principles accessible to learners. When students engage with materials they can reuse, repair, or adapt, they learn sustainability through action, not just discussion.

Moreover, sustainable material practices challenge the dominant norms of disposability and convenience in science education. As Sterling (2001) argues, coherence between educational means and ends is essential for deep, transformative learning. When instructional tools are aligned with sustainability principles, they support content knowledge and foster ethical awareness and systems-based reasoning.

In this way, sustainability becomes more than a topic to be covered, serving instead as a guiding philosophy that shapes the teaching and learning of science. Through conscious material choices, educators can design experiences that model the specific futures they seek to cultivate.

Museums' Role in Modeling Sustainable Science in Action

Given that instructional materials function as a pedagogical model, museums are uniquely positioned to lead a shift toward sustainable practice. The modern museum is no longer viewed as a neutral repository of objects but as a purposeful institution that can act as an agent of social change (Sandell, 2003). Museums occupy a unique position in the public sphere to model sustainability through exhibitions and the material culture they generate. As Hansson and Öhman (2021) highlight, museums possess the potential to function as key public pedagogies for sustainable development by harnessing the power of hands-on and place-based engagement.

However, even many museums have begun aligning operational practices with environmental goals, but their role as epistemic designers of material culture often remains unexamined. As some scholars argue, while museums readily embrace sustainability in programming, they rarely attend to the implications of the artifacts they produce (Logan and Sutter, 2012). For instance, take-away kits, workshop props, and classroom materials can reinforce or undermine ecological values depending on how they are designed, sourced, and reused. Therefore, the museum's material culture and educational practices must be examined and redesigned

to reflect the values it aims to promote (Hansson and Öhman, 2021).

By integrating sustainable design into these public-facing materials, museums can ensure coherence between institutional messaging and material embodiment. This move transforms instructional artifacts into active demonstrations of sustainable practice, effectively bridging the institutional agenda with material action. Thus, museums become platforms for both knowledge transmission and value-led public engagement. By intentionally designing instructional materials according to sustainability principles, museums move beyond simply discussing sustainable science and begin to model it actively. This alignment between material practices and institutional messaging transforms instructional artifacts into visible and authentic enactments of ecological values. In doing so, museums embody a form of epistemic agency, as they do not just convey what science is, but how science ought to be practiced in a responsible and sustainable manner.

Such alignment is not incidental but strategic. It affirms the museum's role as a trusted public actor in times of ecological urgency and provides a replicable model for educators in other settings. To do so effectively, however, requires a clear and actionable framework to guide the integration of sustainability principles into the design of educational materials, a challenge that the following section addresses.

A FRAMEWORK FOR SUSTAINABLE INSTRUCTIONAL DESIGN

The preceding analysis establishes that the design of instructional materials is a potent, yet underexamined, dimension of ESD. Building on this foundation, this section proposes a conceptual framework of five design principles intended to guide the development of science instructional materials with sustainability at their core. The framework draws from reflective design practices at the NSTM and is informed by emerging literature on sustainability education, material culture studies, and epistemic design.

Principle 1: Material Circularity and Regeneration

The first design principle advocates for using recycled and regenerative materials to construct instructional tools. This principle recognizes that sustainability is not merely a topic of instruction but must be embodied in the media through which instruction occurs. In science education, the materials used for teaching are often overlooked as vehicles for modeling ecological consciousness. When these materials are sourced from repurposed waste or designed for biodegradability and reusability, they transform from mere carriers of knowledge to active agents of sustainability education. In the context of museums and other educational institutions, adopting recycled materials in instructional design represents more than operational efficiency; it signals institutional coherence. Bugallo-Rodríguez and Vega-Marcote (2020) argue for integrating circular economy practices within educational

environments as a form of “teaching for action.” Their work demonstrates that embedding reduction, reuse, and recycling practices into teacher training can shift learners’ ecological values and behaviors. Applied to museum education, this suggests that intentionally using regenerative materials is not merely symbolic but transformative, reinforcing the institution’s public commitment to sustainability.

Instructional tools created from recycled components engage learners in a narrative of resource transformation. Museum educators can build on this by incorporating materials that learners recognize from everyday waste, such as plastic bottles, fabric scraps, and repurposed electronics, thereby encouraging systems thinking and hands-on creativity. By confronting learners with the afterlives of materials, this principle fosters deeper engagement with the ecological dimensions of science. It makes visible the embedded energy, social labor, and environmental consequences of consumption, linking scientific inquiry with critical reflection.

Principle 2: Low-Carbon and Localized Production

Instructional materials should not only be designed with sustainability in mind but also sourced, fabricated, and distributed in ways that minimize carbon emissions and root learning in local contexts. This principle emphasizes the integration of low-carbon logistics and regional material economies into the production of educational tools, shifting away from global supply chains and toward community-based production networks. Low-carbon production is more than a logistical adjustment. It is also a pedagogical statement about the spatial and ecological relations embedded in science learning. As noted by Kioupi and Voulvoulis (2022), ESD is most effective when it is localized, particularly when learners actively adapt global sustainability goals within their communities. In museum contexts, generating instructional materials via local artisans, small fabricators, or in-house workshops lowers carbon footprints and strengthens the institution’s connection to the local ecological and economic fabric.

When learners participate in the local fabrication of instructional tools, including processes of assembly and repair, they gain embodied knowledge of production systems, material economies, and carbon awareness (Droubi et al., 2023). This aligns with emerging frameworks in sustainability education that frame learning as situated practice (Kioupi and Voulvoulis, 2022). Participation in localized production enhances ecological literacy: learners understand the origins of their materials, the labor involved, and the emissions embedded in every component.

Moreover, low-carbon production chains significantly reduce embodied emissions, especially when powered by renewable energy or utilizing regionally available materials (Droubi et al., 2023). Through strategic partnerships with local makerspaces or community workshops, museums can prototype and scale instructional tools without incurring high transportation or manufacturing emissions. Moreover, this principle fosters

resilience and adaptability, which is key attributes facing global environmental instability.

Principle 3: Multi-Functionality and Reusability

Efficient instructional design leverages multi-functionality and reusability, representing principles that maximize resource value while tangibly underscoring sustainability. Educational materials that can be adapted for multiple purposes or reused across sessions reduce ecological impact and enrich learning. As Stroupe (2014) argues, learning environments, including their material components, should be intentionally designed to foster epistemic agency – the learners’ ownership of the knowledge-building process. When a tool can be repurposed, learners witness the principle of adaptability first-hand, reinforcing a view of science as a creative and resourceful practice.

Evidence from out-of-school science programs demonstrates that the repeated use of instruments in varied contexts enhances both engagement and efficacy (Trott and Weinberg, 2020). When students encounter materials multiple times – first in guided settings, and later in independent explorations – their scientific understanding deepens. Reusable and multi-functional tools thus serve a dual role: they reinforce scientific concepts through repeated application and model the value of sustainable lifespan use, which is essential for ecological citizenship.

Life-cycle analyses further reveal that the environmental costs of materials are amortized across their use; a tool deployed in multiple learning contexts reduces the per-use resource burden (Levesque et al., 2022). Institutions such as science museums can maximize this impact by designing modular kits whose individual components can be recombined to support various inquiries. This approach economizes material usage and strengthens programmatic flexibility, allowing educators to respond to evolving learning needs and sustainability constraints.

Principle 4: Durability and Repairability

This principle mandates that instructional materials be designed for long-term use, requiring them to be robust enough for repeated handling and easy to maintain and repair. Sustainable design is about reducing the environmental footprint during production and extending the material lifespan through intentional care and renewal. This reflects a deeper institutional philosophy centered on care, resilience, and stewardship. As Mesa et al. (2022) argue, incorporating repair practices into design is a critical step in shifting educational institutions from consumption models to stewardship cultures. When science museums prioritize long-lasting and repairable tools, they communicate an ethic of responsibility that aligns with the core values of sustainable development.

From a pedagogical perspective, repairable tools create unique learning opportunities. When a component fails, the moment of breakage is transformed into a meaningful pedagogical event. It becomes an opportunity for learners to engage in diagnostic reasoning, problem-solving, and collaborative

restoration, affirming science as a process of inquiry and iteration (Terzioğlu and Wever, 2021). This approach reduces waste and is a powerful tool for building learner agency and resilience. Furthermore, life-cycle assessments demonstrate that extending the use phase of educational materials through durability and repair dramatically reduces environmental impacts compared to disposable alternatives (Mesa et al., 2022). Museums can institutionalize this principle by designing modular kits with replaceable components and training educators to perform basic repairs. This strategy enhances sustainability while reducing long-term operational costs.

Principle 5: Digital Integration for Dematerialization

While the previous principles emphasize material reduction through circularity and longevity, this final principle focuses on dematerialization, which entails the strategic shift of instructional content from physical to digital formats. Digital integration, when thoughtfully designed, is more than a shift from paper to pixels. It also represents a change in epistemic media that can support sustainable practice across environmental, economic, and social dimensions (Rosário and Dias, 2022). By embedding learning experiences in digital formats – such as interactive simulations, online tutorials, or data collection apps – museums can dematerialize components of instructional kits, thereby reducing resource footprints while reinforcing sustainability through form and content.

Digital media offer unique affordances for scientific inquiry. Interactive simulations, for instance, enable learners to model complex scientific phenomena without physical material consumption, supporting systems thinking and experimentation (Rosário and Dias, 2022). Furthermore, mobile learning tools, such as sensor-based apps or virtual labs, allow learners to collect and analyze environmental data without requiring disposable physical sampling kits, preserving hands-on engagement while reducing resource use (Almén and Bagga-Gupta, 2023).

This process of dematerialization effectively reduces both embodied emissions and material waste. While digital tools require energy, frameworks such as sustainable human-computer interaction emphasize energy-efficient design, and institutions can further mitigate environmental impact by choosing low-power platforms and maintaining devices for long-term use (Rosário and Dias, 2022). By intentionally integrating digital elements, museums can prototype science tools that are both pedagogically effective and sustainably responsible. This principle completes the framework by demonstrating how sustainability can be embedded not only in materials and production processes but also in the very nature of knowledge delivery.

AN ILLUSTRATIVE CASE: THE BALLOON GUITAR

Overview

The Balloon Guitar is a hands-on instructional tool developed by the NSTM in Taiwan to support inquiry-based learning

in acoustics (Figure 1). Designed for use in museum workshops and informal science education programs, this tool demonstrates fundamental principles of sound through playful construction and manipulation. Its core components include a 10-inch round balloon, a long balloon (commonly used for balloon twisting), rubber bands, and a simple air pump. Alternative materials, such as elastic cords or fishing line, can be substituted for the vibrating element to enable further experimentation with acoustic properties.

Functionally, the Balloon Guitar operates by stretching a balloon or string across the surface of an inflated round balloon, which serves as the resonating body. When the string is plucked, its vibrations transfer to the balloon membrane, amplifying the sound. Through this design, learners can explore how variables such as string tension, length, and balloon pressure affect pitch, volume, and timbre. These interactions support experiential learning about sound waves, resonance, and vibration.

The NSTM deploys the Balloon Guitar in various formats, including guided workshops and self-directed kits. Its simplicity and low-cost design make it accessible to a broad audience, while its variability supports iterative experimentation. Learners are encouraged not only to observe but also to construct, modify, and test their own instruments, thereby reflecting the museum's commitment to interactive and material-based science education. The tool exemplifies how everyday materials can be transformed into vehicles of scientific inquiry and sustainability-conscious design.

The Principles in Practice

In many informal science learning settings, hands-on sound activities are commonly implemented through single-use or pre-packaged instructional kits. These approaches prioritize convenience and standardization but often generate unnecessary material waste and limit opportunities for reuse. In response to these limitations, the NSTM redesigned the Balloon Guitar as a sustainability-oriented instructional tool. The redesign focused on simplifying material composition,



Figure 1: Balloon guitar

enabling repeated use through easily replaceable components, encouraging the use of locally available or repurposed materials, and integrating digital resources to reduce reliance on printed instructions. Sustainability was therefore treated as a core design consideration rather than an additional feature.

Building on this redesign, the Balloon Guitar serves as a concrete illustration of the five sustainability-oriented design principles introduced in Section 3. Each principle is reflected in the tool's material choices, construction process, and patterns of educational use.

Material circularity and regeneration

The Balloon Guitar is constructed from widely available, low-cost materials, including balloons, rubber bands, and elastic cords. These materials are easy to access and lend themselves to repeated use and adaptation. The instructional design encourages students to experiment with alternative components, such as fishing line or repurposed packaging materials, thereby promoting a mindset of material reuse. In later iterations, repurposed plastic containers have been incorporated as resonators, demonstrating how everyday objects can be reconfigured for scientific purposes. Through these practices, the design makes visible the possibility of extending the life cycle of materials within educational contexts and encourages learners to consider the afterlife of commonly discarded objects.

Low-carbon and localized production

The Balloon Guitar is designed to minimize carbon-intensive production and distribution processes. Its materials are lightweight, widely available, and do not require specialized manufacturing. The tool can be assembled manually using a simple air pump, eliminating the need for energy-intensive equipment. This approach supports localized production, allowing educators and learners to source and assemble materials within their own communities. By reducing dependence on centralized manufacturing and long-distance transportation, the design also reinforces the connection between scientific learning and local material practices.

Multi-functionality and reusability

The Balloon Guitar supports multiple learning purposes within a single design. Students can manipulate variables such as string length, material type, and tension to explore key properties of sound, including pitch, volume, and timbre. After initial use, the tool can be retained and modified for further experimentation or informal play, often evolving into a simple musical instrument. This capacity for continued use across different learning contexts reduces material consumption while supporting repeated engagement with scientific concepts. The design, therefore, functions both as an instructional aid and as an adaptable learning object.

Durability and Repairability

Although some components, such as balloons, have inherent limitations in durability, the overall design emphasizes ease of repair and replacement. When parts fail, students can quickly

substitute materials with minimal cost and effort. More durable alternatives, such as cardboard boxes or plastic containers, can be used to replace or reinforce key components like the resonator. This approach shifts the focus from disposability to maintenance, allowing moments of breakage to become opportunities for problem-solving and iterative improvement. In this way, repair is integrated into both the material design and the learning process.

Digital integration for dematerialization

To further reduce material use, the NSTM has developed digital resources to support the Balloon Guitar, including instructional videos and downloadable guides. These resources replace printed manuals and enable wider dissemination without additional material production. In addition, learners can use mobile applications such as tuning and sound measurement tools to analyze acoustic properties. These digital elements complement the physical design by reducing reliance on consumable materials while extending the analytical depth of the activity.

Integrated application and design implications

Overall, the Balloon Guitar illustrates how the five design principles can be operationalized in practice. Taken together, these design choices demonstrate how a simple instructional tool can be reconfigured to better align material practices with sustainability goals. This alignment helps bridge the gap between environmental messaging and educational implementation, showing how sustainability can be embedded directly into the design and use of instructional materials.

Meanwhile, the Balloon Guitar also reveals certain limitations. The reliance on fragile materials such as balloons highlights ongoing tensions between accessibility, durability, and sustainability. These tensions suggest that while the current design represents a meaningful step toward more sustainable instructional practices, further refinement is needed to balance these competing considerations in future iterations.

DISCUSSION AND CONCLUSION: REFRAMING SUSTAINABILITY THROUGH INSTRUCTIONAL DESIGN

Introducing ECO-INSTRUCT: A Framework for Sustainable Instructional Design

This study proposes the ECO-INSTRUCT framework, short for Ecological and Contextual Optimization for Instructional Design, as a conceptual model to guide the development of sustainable instructional materials in science education (Figure 2). Synthesized from reflective practice at the NSTM and grounded in five principles, the framework is designed to achieve three primary outcomes: reducing the ecological footprint of educational activities, fostering key sustainability competencies in learners, and enhancing pedagogical practice itself. As illustrated in Figure 2, ECO-INSTRUCT can be understood as a structured system in which five interrelated design principles form the foundation of the framework and

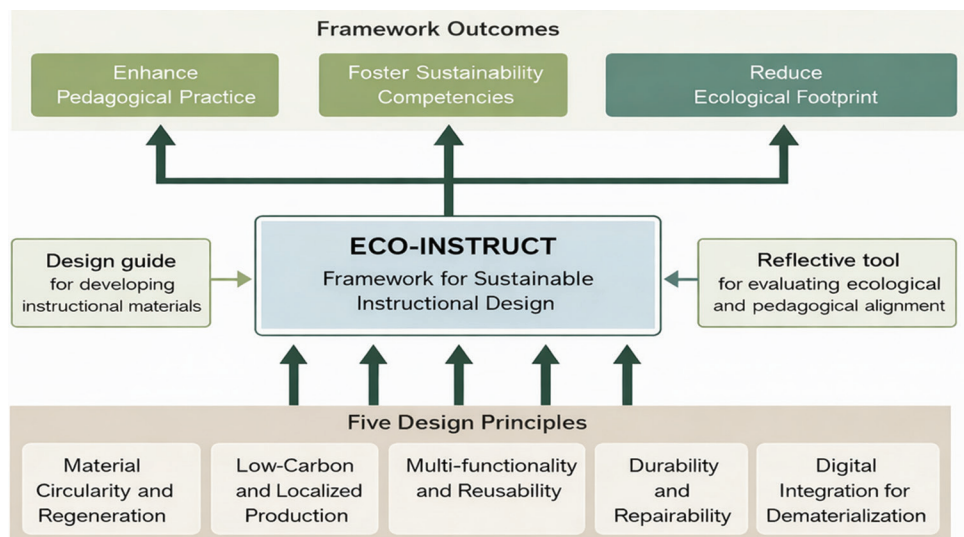


Figure 2: The ECO-INSTRUCT framework for sustainable instructional design

collectively contribute to these broader pedagogical and ecological outcomes.

The ECO-INSTRUCT framework offers two key contributions to the field: first, as a design guide for educators developing materials, and second, as a reflective tool for examining how such materials function as carriers of ecological and pedagogical values. These two functions are also reflected in Figure 2, which presents the framework not only as a forward-looking design structure but also as a mechanism for evaluating the alignment between material practices and sustainability-oriented educational goals.

As a design guide, ECO-INSTRUCT encourages educators to consider the full life cycle of educational materials, from material sourcing and energy consumption to reusability and digital integration. In doing so, it operationalizes the philosophical underpinnings of ESD, offering clear and actionable pathways to reduce environmental impacts while enriching learning experiences that foster sustainability competencies (Vare and Scott, 2007). Rather than treating instructional materials as isolated tools, the framework positions them as integral components of broader ecological and educational systems, thereby encouraging a more systemic and context-sensitive approach to instructional design.

As a reflective tool, ECO-INSTRUCT foregrounds the epistemic and ethical dimensions of material design. It invites educators to question what materials they use and why, and how those choices align with their educational values. This aligns with broader calls in sustainability education to cultivate pedagogical intentionality and educator agency (Ayers et al., 2020). It also reflects an emerging view in science education that materials mediate knowledge and are integral to how learners engage with disciplinary ideas (e.g., Kelly and Cunningham, 2019), thereby contributing to pedagogical practice.

This pedagogical shift can also be understood in terms of the hidden curriculum, whereby instructional materials implicitly

shape students' perceptions of what counts as legitimate scientific practice (Aikenhead, 1996; Hetherington et al., 2019). When materials are designed for reuse, repair, and local adaptation, they communicate that scientific practice involves responsibility, resourcefulness, and ecological awareness rather than efficiency and standardization alone. In this sense, sustainable instructional materials not only support learning outcomes but also influence how science is perceived and enacted by learners.

By advancing ECO-INSTRUCT, this study reframes the role of educators from users of externally supplied kits to active designers of material learning environments. This repositioning highlights the responsibility and capacity of educators to shape sustainability-oriented practices through everyday instructional decisions. It further suggests that sustainability in science education is not only a matter of content but also of form, where the design and use of materials become central to how scientific knowledge and values are communicated. Such a shift aligns closely with calls to embed sustainability thinking in curricular content and the way science is taught (Bernert et al., 2025).

Implications for Practice and Research

The ECO-INSTRUCT framework carries broad implications that extend well beyond its initial application within a single museum setting. As a conceptual and practical tool, it offers a flexible architecture that can inform institutional strategy, instructional design, and future research across informal and formal science education contexts.

For museum educators, ECO-INSTRUCT encourages a more deliberate and reflective engagement with the material dimension of their practice. Rather than treating instructional kits as peripheral to exhibitions or content delivery, the framework positions these materials as central carriers of both environmental and pedagogical meaning. Accordingly, it invites education teams to assume ownership of both the

content they deliver and the physical forms that mediate that content. In doing so, it facilitates deeper collaboration between education, exhibition, and operations staff, thereby supporting a shift from fragmented, task-based work toward more collaborative, sustainability-oriented design. The framework also offers a rationale for pursuing funding or internal support for sustainable design initiatives, which may otherwise be seen as outside the core mission of museum education.

In the formal education sector, the framework serves as a heuristic for teachers and curriculum specialists to assess whether existing materials successfully reduce their ecological footprint and enhance pedagogical practice through hands-on, inquiry-based activities. The framework supports iterative redesign of classroom kits, encourages the use of local and reusable materials, and can be integrated into teacher training programs to cultivate material literacy alongside content knowledge. For educators operating in resource-constrained environments, the emphasis on locally available, low-cost, and repurposable materials is particularly meaningful, as it opens new possibilities for place-based science learning that is both ecologically grounded and pedagogically rich.

For researchers, ECO-INSTRUCT offers fertile ground for empirical and design-based studies. It can serve as a foundation for investigating how sustainable materials influence student engagement, conceptual understanding, and environmental attitudes. It also invites comparative work across cultural contexts – examining how different communities adapt the principles in response to local constraints and opportunities. In addition, the framework can structure action research within institutions seeking to reform their material practices or develop open-source repositories of sustainable instructional tools. By providing a shared language and conceptual scaffold, ECO-INSTRUCT can support transdisciplinary collaboration among educators, designers, and sustainability specialists.

Finally, by positioning material design as a form of public pedagogy, ECO-INSTRUCT reframes what it means to teach science in the twenty-first century. It asserts that instructional materials are not mere accessories to learning but are themselves sites of meaning-making and value transmission. This reframing challenges educators to consider what science is taught, how it is materially enacted, and what kinds of futures those enactments help make possible.

Navigating Challenges and Enabling Conditions

While the ECO-INSTRUCT framework offers a clear conceptual pathway toward sustainable instructional design, translating its principles into practice is neither automatic nor without barriers. Science museums, schools, and other educational institutions operate within complex ecosystems of budget constraints, regulatory requirements, professional norms, and resource limitations. Acknowledging these constraints is essential, not because they undermine the value of the framework, but because they clarify the practical challenges that educators may encounter in implementation and the conditions needed to address them.

Quality control and material safety represent two critical challenges. When adopting recycled, regenerated, or repurposed materials, institutions face concerns about consistency, durability, and safety standards. Museums and schools have ethical and legal obligations to ensure the materials they provide – particularly those handled by children – meet strict safety regulations. While the flexibility and creativity inherent in ECO-INSTRUCT are strengths, educators must balance these against practical concerns, such as whether a reclaimed plastic container or locally sourced textile meets institutional safety and hygiene criteria. Thus, successful implementation requires clear institutional policies, safety protocols, and possibly partnerships with specialists who can certify and guide sustainable material selection.

Institutional inertia and resistance to change present additional hurdles. Educators and designers may encounter skepticism or reluctance from administrators, colleagues, or the public, especially when sustainable practices appear more costly, time-consuming, or complex. Adopting the ECO-INSTRUCT framework requires institutional commitment from individual educators as well as from the leaders and stakeholders who allocate resources, approve curricula, and establish institutional priorities. Without this support, even well-designed materials may fail to achieve widespread adoption or sustained impact. Building coalitions within and across institutions can mitigate this barrier, as can professional development programs that explicitly address sustainability as a collective educational and institutional value.

Moreover, the framework requires a level of educator agency and expertise that may not exist across all educational settings. Educators accustomed to off-the-shelf kits may initially feel overwhelmed by the responsibilities of sourcing, evaluating, and maintaining sustainable materials. Therefore, professional development and capacity-building are critical, as is fostering a culture of collaboration, experimentation, and reflective practice among educators. Institutions might support educators by creating internal design teams, hosting sustainability-focused workshops, or providing incentives for innovation in instructional material design.

Despite these challenges, the potential opportunities arising from ECO-INSTRUCT's adoption justify efforts to navigate these complexities. Initial implementations may prioritize small-scale, manageable pilot projects, such as the Balloon Guitar workshops at NSTM, where educators can prototype, evaluate, and refine materials within controlled contexts. Documenting these pilot experiences and sharing outcomes broadly can provide tangible evidence of feasibility and effectiveness, thereby building institutional and professional confidence. Collaborative models, such as open-source material repositories, cross-institutional design laboratories, or public-private partnerships, offer additional pathways to address constraints collectively and sustainably.

In navigating these constraints thoughtfully and proactively, educators and institutions support sustainable practices and

model the critical, creative, and collaborative problem-solving skills essential for the broader transition toward sustainable societies.

Concluding Remarks

This paper began by recognizing that instructional materials, far from being neutral pedagogical tools, carry ethical, ideological, and environmental meanings. This paper has argued that instructional materials embody and transmit values, whether consciously or not, and therefore play an important role in shaping learners' relationships to science and sustainability. By introducing the ECO-INSTRUCT framework, the study has offered educators practical design guidance and a deeper conceptual lens through which to reflect on the material dimensions of their teaching practice.

The ECO-INSTRUCT framework underscores the interconnectedness of pedagogical practice, institutional policy, and ecological responsibility. It positions educators – especially museum educators – as active agents capable of shaping more sustainable and ethically coherent futures through conscious and intentional material choices. Rather than seeing sustainable materials as peripheral to education or burdensome to implement, ECO-INSTRUCT encourages educators to recognize that materials are integral to the educational process, mediating learners' engagement with scientific concepts, environmental awareness, and cultural values.

In embracing this perspective, educators step into critical reflection and creative innovation roles. They become sustainability designers, modeling the very principles and practices they aim to cultivate in learners. This approach to instructional design can enrich scientific learning while also contributing to broader societal efforts toward sustainability.

The challenges of implementing ECO-INSTRUCT are real, yet they are surmountable with institutional commitment, collaborative strategies, and a willingness to rethink traditional practices. Educators and institutions that adopt this framework do more than optimize their instructional tools – they actively participate in the project of reimagining science education as a practice rooted in ecological ethics, collective responsibility, and sustainable innovation.

In closing, this study calls upon educators and institutions to embrace the principles embodied by ECO-INSTRUCT, recognizing that the materials chosen for teaching science represent opportunities for profound ethical and environmental action. By consciously and systematically designing instructional materials, educators enact sustainability not only as curricular content but also as lived educational practice, thereby modeling the futures they seek to build.

REFERENCES

- Aikenhead, G.S. (1996). Science education: Border crossing into the subculture of science. *Studies in Science Education*, 27(1), 1-52.
- Almén, L., & Bagga-Gupta, S. (2023). Digital tools and social-ecological sustainability: Going beyond mainstream ways of understanding the roles of tools in contemporary educultures. *Frontiers in Education*, 8, 1147402.
- Ayers, J., Bryant, J., & Missimer, M. (2020). The use of reflective pedagogies in sustainability leadership education-a case study. *Sustainability*, 12(17), 6726.
- Bernert, P., Wanner, M., Fischer, N., & Barth, M. (2025). Design principles for advancing higher education sustainability learning through transformative research. *Environment, Development and Sustainability*, 27, 20581-20598.
- Brett, P. (2014). 'The sacred spark of wonder': Local museums, Australian curriculum history, and pre-service primary teacher education: A tasmanian case study. *Australian Journal of Teacher Education*, 39(6), 17-29.
- Bugallo-Rodríguez, A., & Vega-Marcote, P. (2020). Circular economy, sustainability and teacher training in a higher education institution. *International Journal of Sustainability in Higher Education*, 21(7), 1351-1366.
- Chen, S.S., & Chang, H.C. (2010). The strategic policy of national science and technology museum towards a green museum. *Museology Quarterly*, 24(3), 99-115.
- Droubi, S., Galamba, A., Fernandes, F.L., De Mendonça, A.A., & Heffron, R.J. (2023). Transforming education for the just transition. *Energy Research and Social Science*, 100, 103090.
- Duran, E., Ballone-Duran, L., & Haney, J. (2010). Project ASTER III: A model for teacher professional development integrating science museum exhibits with state and national science education content standards. *Curator: The Museum Journal*, 53(4), 437-449.
- Duschl, R. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. *Review of Research in Education*, 32(1), 268-291.
- Filippini-Fantoni, S., & Bowen, J. (2007). Bookmarking in Museums: Extending the Museum Experience Beyond the Visit. In: *Museums and the Web 2007*. Available from: <https://www.archimuse.com/mw2007/papers/filippini-fantoni/filippini-fantoni.html>
- Freese, T., Elzinga, N., Heinemann, M., Lerch, M.M., & Feringa, B.L. (2024). The relevance of sustainable laboratory practices. *RSC Sustainability*, 2(5), 1300-1336.
- Hansson, P., & Öhman, J. (2021). Museum education and sustainable development: A public pedagogy. *European Educational Research Journal*, 21(3), 469-483.
- Hetherington, L., Hardman, M., Noakes, J., & Wegerif, R. (2019). Making the case for a material-dialogic approach to science education. *Studies in Science Education*, 54(2), 141-176.
- Hooper-Greenhill, E. (1994). *Museums and their Visitors*. United Kingdom: Routledge.
- International Council of Museums. (2022). Museum Definition. Available from: <https://icom.museum/en/resources/standards-guidelines/museum-definition/> [Last accessed on 2025 Sep 11].
- Kelly, G.J., & Cunningham, C.M. (2019). Epistemic tools in engineering design for K-12 education. *Science Education*, 103(4), 1080-1111.
- Kioupi, V., & Voulvoulis, N. (2022). Education for sustainable development as the catalyst for local transitions toward the sustainable development goals. *Frontiers in Sustainability*, 3, 889904.
- Levesque, S., Robertson, M., & Klimas, C. (2022). A life cycle assessment of the environmental impact of children's toys. *Sustainable Production and Consumption*, 31, 777-793.
- Ling, Y., Jin, Z., Li, Y., & Huang, J. (2022). Learner satisfaction-based research on the application of artificial intelligence science popularization kits. *Frontiers in Psychology*, 13, 901191.
- Logan, R., & Sutter, G.C. (2012). Sustainability and museum education: What future are we educating for? *The International Journal of the Inclusive Museum*, 4(3), 11-26.
- Mesa, J.A., Gonzalez-Quiroga, A., Aguiar, M.F., & Jugend, D. (2022). Linking product design and durability: A review and research agenda. *Heliyon*, 8(9), e10734.
- Oliveira, J., Neves, L., & Lanceros-Mendez, S. (2021). Kit "energy, environment and sustainability": An educational strategy for a sustainable future. A case study for Guinea-Bissau. *Education Sciences*, 11(12), 787.

- Rosário, A.T.R., & Dias, J.C. (2022). Sustainability and the digital transition: A literature review. *Sustainability*, 14(7), 4072.
- Sandell, R. (2003). Social inclusion, the museum and the dynamics of sectoral change. *Museum and Society*, 1(1), 45-62.
- Sørensen, E. (2009). *The Materiality of Learning: Technology and Knowledge in Educational Practice*. Cambridge: Cambridge University Press.
- Sterling, S. (2001). *Sustainable Education: Re-Visioning Learning and Change*. New Delhi: Schumacher Society.
- Stroupe, D. (2014). Examining classroom science practice communities: How teachers and students negotiate epistemic agency and learn science-as-practice. *Science Education*, 98(3), 487-516.
- Terzioğlu, N., & Wever, R. (2021). Integrating repair into product design education: Insights on repair, design and sustainability. *Sustainability*, 13(18), 10067.
- Trott, C.D., & Weinberg, A.E. (2020). Science education for sustainability: Strengthening children's science engagement through climate change learning and action. *Sustainability*, 12(16), 6400.
- UNESCO. (2020). *Education for Sustainable Development: A Roadmap*. France: UNESCO Publishing. Available from: <https://unesdoc.unesco.org/ark:/48223/pf0000374802> [Last accessed on 2025 Oct 18].
- United Nations. (2015). *Transforming our World: The 2030 Agenda for Sustainable Development*. General Assembly. Available from: <https://sdgs.un.org/2030agenda> [Last accessed on 2025 Oct 18].
- Vare, P., & Scott, W. (2007). Learning for a change: Exploring the relationship between education and sustainable development. *Journal of Education for Sustainable Development*, 1(2), 191-198.
- Vozzola, E., Overcash, M., & Griffing, E. (2018). Environmental considerations in the selection of isolation gowns: A life cycle assessment of reusable and disposable alternatives. *American Journal of Infection Control*, 46(8), 881-886.
- Watermeyer, R. (2012). A conceptualisation of the post-museum as pedagogical space. *Journal of Science Communication*, 11(01), A02.