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Sustainable computing in STEAM generative education: integrating biology, art, science of design and engineering with nature

Ronnie Videla[1,2] · Maybritt Aros[3] · Eduardo Sandoval-Obando[4] · Andri Velásquez[5] · Paola Rámirez[6] · Alexis Sarzosa[2] · Carola Cerpa[3] · Paulina Veas[3] · Daniela Carvajal[2] · Daniela Jorquera[1,3] · Marcelo Chávez[2]

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Abstract
This study explores how Generative STEAM Education fosters the co-creation of sustainable, interdisciplinary learning environments in Chilean schools. Through a qualitative multiple-case study in four educational communities in the Coquimbo Region, we examine how students and teachers engage with digital and non-digital technologies, such as biomaterials, recycled filaments, creative electronics, and augmented reality, to address socio-environmental and cultural challenges. Findings reveal the emergence of 21st-century skills, such as collaboration and critical thinking, ecological awareness, and material engagement through project-based learning, design thinking, and inquiry in the participating children. The exposed cases highlight diverse contextualized pedagogical purposes, including marine conservation, generative justice, and Indigenous heritage, showing how sustainability and technological inclusion can be grounded in local challenges. Rather than offering a fixed model, Generative STEAM Education emerges as a flexible and context-sensitive framework that connects material ecology, embodied learning, and community regeneration. This research contributes to rethinking STEAM education as a catalyst for socio-ecological transformation and provides methodological orientations for sustainable, situated, and inclusive teaching practices.

Keywords STEAM education · Sustainable computing · Project-based learning · Learning by making · Material ecology · Generative justice

Introduction

In the context of STEAM (Science, Technology, Engineering, Arts and Math) education and sustainable computing, the traditional separation between physical and digital realms in design is challenged, proposing a transformative pedagogical approach in which the material properties, behaviors, and forms of nature are treated as inseparable entities (Ito, 2018). This idea is particularly relevant to the new global challenges of sustainable innovation, as the world is becoming increasingly complex and volatile, unlike any other

Extended author information available on the last page of the article

period in our history (Ito & Howe, 2016). The exploration and experimentation with the structures, components, and design of nature using digital design tools provides an invaluable field for education in the Anthropocene era (Guyotte, 2020). The notion of"material ecology", which proposes a design approach that considers computation, manufacturing, and the material itself as inseparable dimensions informed by nature (Antonelli & Burckhardt, (United 2020)), proposes a new paradigm for sustainable design, with a revolutionary approach that merges biological and computational processes (Doordan, 2021). This integration fosters a design methodology where geometry, material properties, and their reactions are interwoven, providing a deeper understanding of how materials behave under different environmental interactions (Oxman, 2015).

Contemporary notions of material ecology, rooted in the interdisciplinary approaches of the Massachusetts Institute of Technology (MIT), provide a fertile framework for STEAM education to address the complexity of the world and break the inertia of monolithic disciplinary educational systems (Ito, 2017). MIT's"Cycle of Creativity,"which integrates science, engineering, design, and art (Oxman, 2016), alongside the approach of generative justice can be combined to reinforce sustainable educational innovation from a generative, inter- and transdisciplinary framework, enabling the tackling of 21st-century challenges (Eglash, 2021). Educational practices in design, based on the synergy between nature and the digital, not only provide pathways to address sustainable development goals (Bokova, 2015), but also allow for the reconfiguration of transmissive educational paradigms, from a holistic cognition and learning approach that considers the brain-body-environment integration, such as the 4E Cognition: embodied, enacted, embedded, and extended (Newen et al., 2018) or the 3E Cognition: embodied, enacted, and environmental scaffolding (Parada et al., 2024). This entails moving away from the dominant dualistic epistemologies in educational communities and embracing an epistemological pluralism that provides a relational ontological framework for educational design practices integrating nature, people, culture, and technologies (Abrahamson, 2014; Blikstein & Moghadam, 2019; Turkle & Papert, 1991). Furthermore, the STEAM approach fosters the development of 21st-century skills (creativity, collaboration, critical thinking, communication, and digital citizenship) through challenging projects that address and engage with the issues affecting communities (Videla et al., 2023). This underscores the importance of promoting teaching methodologies that encourage creativity with materials and technologies, pushing beyond the boundaries of traditional engineering problem spaces (Cheng et al., 2023). It drives students to think"outside the box,"innovating through educational practices embedded in programming within ecological environments for exploration, design, and creation with nature and culture.

Generative STEAM education is based on the virtuous circularity between nature, culture, and social justice (Videla et al., 2024). This approach aligns perfectly with the ideas of material ecology and MIT's Krebs Creative Cycle to generate solutions to existing and future problems. Existing evidence on interdisciplinary STEM/STEM +/STEAM educational approaches has driven significant educational changes, presenting a promising proposal to strengthen sustainable innovation practices with technologies in light of the 2030–2050 challenges (Han et al., 2021). These approaches have emphasized the use of active learning methodologies such as project-based learning, design thinking, and gamification, as well as curricular integration and the incorporation of new technologies into educational processes. However, the effects of these approaches are nuanced, as STEM approaches tend to marginalize essential disciplines needed to cultivate the practice of design and the expression of nature and culture (Halverson & Sawyer, 2022). This is why the STEAM approach, by incorporating the"A"for art, advocates for a disciplinary

integration that brings together diverse perspectives from sculpture, crafts, architecture, literature, and dance, involving different stakeholders and maximizing the engagement and representativeness of the educational community (Aguayo et al., 2023). The emerging STEM + approach offers an open framework for all disciplines, with an inclusive and territorial educational focus; however, its theoretical and epistemological core has not yet resulted in substantial modifications regarding cognitive and didactic aspects (Ioannou et al., 2024).

In this study, we choose Generative STEAM education, integrating material ecology, generative justice, and post-cognitivist approaches, as they offer a transformative pedagogy based on teaching and learning by doing, from a relational ontological perspective of educational practice in which cognitive, didactic, technological, ethical, and aesthetic elements are intertwined (Eglash et al., 2020a). From this standpoint, attention is focused on how teachers create enriched environments in which students can prototype solutions which entails different approaches by incorporating sustainable computing through biomaterials, electronics, sensor systems, augmented reality, and 3D design and fabrication, to understand, protect, and express sustainable forms of the planet (Cheng et al., 2023; Sengupta et al., 2019). To justify the idea of"Generative STEAM"education, this study highlights cases of projects in which communities are involved in the creation and expression of sustainable solutions, such as students and teachers resisting the use of plastic (Smil, 2020), concrete construction (Smil, 2019), and whale marine conservation (Corkeron, 2004). Furthermore, the passive response of conventional STEM/STEM + approaches to the role of art and indigenous culture in design with noble technologies and materials is also discussed (UNESCO, 2021). In this article, the concept of sustainable computing is explored in the sense that programming, craftsmanship, and nature-inspired methods can converge to create sustainable design solutions that are both technologically feasible and mindful of the environment and local culture.

Based on the above, the general objective of this research is to understand the types of teaching methodologies, skills, and forms of learning that emerge from the application of Generative STEAM Education in various case studies focused on addressing socio-environmental and cultural challenges through the integration of both digital and non-digital technologies. To achieve this, a qualitative approach is employed, using a multiple-case study design to describe and contrast the use of diverse educational practices that integrate technologies, materials, and digital and non-digital tools according to eco-environmental and cultural contexts. This research seeks to promote alternative applications of Generative STEAM Education, contributing to the emerging body of knowledge on school projects that incorporate sustainable computing through the creative synergy of biomaterials, material reuse, and digital technologies.

The specific objectives of the research are as follows:

- To identify the characteristics of primary and secondary educational communities based on their educational purposes and sustainability challenges within the framework of Generative STEAM Education.
- To describe the types of teaching methodologies, skills, and forms of learning that emerge from Generative STEAM educational practices incorporating the use of digital and non-digital technologies.
- To contrast the patterns and differences in the application of Generative STEAM Education across different educational communities facing socio-environmental and cultural challenges, in order to develop a situated and expanded understanding of sustainable computing.

Theoretical framework

Foundations of interdisciplinary research in sustainable education

Interdisciplinary education oriented towards sustainable innovation highlights the need to integrate various fields of knowledge, such as science, engineering, design, and art, to address solutions to environmental, social, and economic problems (Milara et al., 2020). Sustainability must be understood in systemic and complex terms, in which environmental, sociocultural, and economic factors are interwoven, requiring responsibility in present-day actions so as not to sacrifice future generations (Charter & Tischner, 2017). The complex challenges humanity faces, which demand sustainable and generative visions, involve "thinking about the future of science in the context of design, as well as design in the context of science" (Ito & Howe, 2016:4). These ideas allow for a reevaluation of the role of design in hyper-specialized fields, where interdisciplinarity and transdisciplinarity are relegated to singular actions by small groups of restless minds opposing the centralization of knowledge (Videla et al., 2021). MIT's Krebs Cycle of creativity, driven by interdisciplinary work, has reconfigured the conventional approach to sustainable innovation, in which nature and digital technologies intertwine through a biomimetic design process (Bader et al., 2016). This involves considering connections at different scales, for example, microbial and astrophysical, as well as a symbiotic interaction between biology and digital fabrication, such as synthetic biology to create sustainable products that emulate natural systems.

In the context of sustainable education, these ideas could play a fundamental role, however, they require deep paradigm shifts that contribute to breaking down disciplinary silos and foster creative and technological skills (Videla & Veloz, 2023). These new paradigms not only propose a shift in teaching methods and the use of technologies, but also in how cognition and learning are conceived (Macrine & Fugate, 2022). An ecological and holistic vision of cognition and learning can better guide changes in teaching that reinforce our commitment to the planet through the relational ontology of brain/body/environment (Pessoa, 2023). On contrast with tradittionals approach, where the solutions to environmental require a single answer These new approaches can contribute to an interconnected understanding between people, organisms, and environments, overcoming traditional dichotomies: subject/object, body/mind, matter/information, landscapes/things, and now natural/artificial (Malafouris, 2013). Maker education has catalyzed these different perspectives through active learning methodologies based on project-based learning and gamification, preparing young people with relevant challenges and community needs, rather than prescribing problems and one-size-fits-all solutionsand perhaps, trying to find a unique one solution (Konopasky & Sheridan, 2020). Therefore, the aim is working under complexity problems solving that allow multiples perspectives. This movement has roots in tinkering, which emphasizes the active role of youth in generating creative solutions with technologies, exploring new paths and designing new possibilities (Resnick, 2017).

In Chile, the context in which this study is situated, the prioritized national curriculum promotes interdisciplinary learning and collaborative work as key strategies for understanding complex phenomena (Ministerio de Educación de Chile, 2023). The Maker Education movement, driven by the Innovation Center of the Chilean Ministry of Education, emphasizes the use of active methodologies such as project-based learning, design thinking, and gamification to prepare young people to face real-world challenges and respond to the needs of their educational communities, rather than prescribing fixed problems and solutions (Red de Innovación Educativa, 2024). This movement highlights the active role

of students in generating creative solutions through the use of technologies, fostering 21st-century skills through meaningful and hands-on learning. To support its effective pedagogical implementation, educational approaches such as STEM, STEM+, and STEAM are promoted (Ioannou & Gravel, 2024). These approaches are grounded in constructionist and post-cognitivist theories that advocate for the democratization of learning through technologies that empower students as agents of change, enabling them to develop interdisciplinary projects with local impact (Videla & Veloz, 2023). Active methodologies with a STEAM focus provide fertile ground for engagement with diverse artifacts, materials, and digital tools, creating dynamic environments in which students can explore, play, and experiment with disciplinary knowledge through deep, experiential learning (Timotheou & Ioannou, 2021).

Interdisciplinary research increasingly underscores the importance of integrating fields such as technology, design, and social reflection to address environmental, social, and economic challenges (Charter & Tischner, 2017). This approach not only supports the development of technical skills but also emphasizes the ethical, aesthetic, and epistemological dimensions of decision-making in the design of evidence-based solutions (Moore & Tillberg-Webb, 2023).Over the past three years, Chile's curriculum has undergone reforms to align with global challenges outlined in the 2030 Agenda and the United Nations Sustainable Development Goals (UN, 2015), as well as with the development of 21st-century skills (Organization for Economic Co-operation and Development [OECD], 2022). These reforms promote a culture of innovation centered on planetary well-being, social justice, and the formation of conscious and responsible citizens capable of contributing to a more equitable and sustainable future (Gravel & Puckett, 2023).

STEAM education: generative justice and material ecology

Generative STEAM education emerges as a transformative approach that integrates science, technology, engineering, art, and mathematics, fostering sustainable innovation and generative justice in the context of digital design and fabrication (Eglash, 2023). Achieving this requires the integration of diverse disciplines and traditions, creating a synergistic space where cultural and scientific knowledge coexist to address contemporary ecological challenges. The generative STEAM education model expands the restrictive boundaries of STEM and STEM+by reconfiguring conventional teaching and learning practices through technologies in interdisciplinary projects, considering the circular flow of all forms of value exchange in educational practice: natural, cognitive, cultural, social, economic, and ecological. This entails moving away from imperative dualisms and instrumental active methodologies, which overlook the emergence and complexity of educational processes embedded in socio-material, technological, and culturally situated environments (Penny, 2017). Generative STEAM education demonstrates greater engagement and interest from educational communities, as well as improved STEM learning outcomes, due to the promotion of agency through materials and technologies that foster potential alternatives for a more just, sustainable, and equitable world (Eglash et al., 2020b). Indigenous knowledge systems have historically provided a deeper understanding and sophisticated techniques for maintaining circular value flows that enhance the productivity of nature without damaging or compromising its sustainability (Eglash et al., 2024).

The integration of diverse fields of study is crucial to providing a broader and deeper understanding of the complexity of natural phenomena (Jacobson & Wilensky, 2022). In light of the cultural heritage of communities and the incorporation of new technologies,

a critical capacity can be developed to address complex problems, creating solutions that consider the social and ecological impact of decisions. Generative justice holds that most of our problems stem from an economy centered around the extraction of ecological, labor, and social value (Sentell, 2015). Generative perspectives on sustainable innovation, which generate value in non-alienated forms, can be characterized by new forms of "DIY citizenship" that span various spaces creating value in different ways and meanings, inspired by nature's form and indigenous knowledge, such as biomorphic and biomimetic designs (Eglash, 2024). Material ecology combines biology, art, and technology to develop designs that adhere to principles of ecological sustainability, aligning with generative justice by supporting a sustainable approach to digital design and production (Oxman, 2015). The intertwining of biology, art, design science, and engineering with nature provides a cutting-edge ethical and aesthetic framework that governs futuristic and sustainable design, characterized by a reevaluation of the relational ontology of people, organisms, and environments, see challenging work with bees, silkworms, fungi, and bacteria through bioengineering (Museum of Modern Art [MoMA], 2020).

STEAM education, by incorporating the principles of generative justice and material ecology, becomes an essential platform for cultivating environmental responsibility and ethical innovation, opening new possibilities for a sustainable future. In this way, it proposes a transformative pedagogy in which creativity and decentralized, project-based environments with environmental and natural impact engage new frameworks for ethical educational practice, reaffirming the inseparable relationship between brain/body/environment (Stolz, 2021). In this regard, interdisciplinary and anti-disciplinary approaches offer a form of learning that articulates both the cultural and scientific knowledge of students by integrating digital technologies, biomaterials, and ancestral knowledge (Bourn et al., 2017). Generative STEAM education for transformative pedagogy should consider: (i) a contemporary cognitive dimension that can highlight the relational ontology of brain/body/environment, such as 4E and 3E Cognition; (ii) a decentralized, interdisciplinary didactic dimension for generating socio-material, technological, and cultural environments, in which teachers facilitate hands-on learning through non-alienating active methodologies, driven by bioengineering design projects; (iii) an ethical/aesthetic dimension in which education incorporates sustainability issues facing communities, combining approaches of material ecology and generative justice to support the integration of sustainable computing practices.

Sustainable computing: biomaterials and digital technologies

The cases addressed in this study pertain to issues that threaten the sustainability of the planet, such as the use of plastic and cement, as well as raising awareness about marine conservation of whales and promoting Indigenous culture. Evidence has shown that global plastic production has exceeded 8.3 billion tons since the 1950 s, with approximately 60% of this becoming waste, resulting in a massive accumulation in the oceans, where more than 5.25 trillion plastic pieces are floating (Wang et al., 2018). Cement, on the other hand, is responsible for 8% of global CO2 emissions, releasing approximately 1.6 billion tons annually (Smil, 2021). In terms of marine conservation, whale protection continues to present regional challenges aimed at minimizing risks to cetacean populations and maintaining ecological balance (Baulch & Perry, 2014). Regarding the promotion of Indigenous culture, identity, and heritage, evidence reports that 70% of Indigenous communities in Latin America use digital platforms to revitalize their languages and traditions, fostering a sense of belonging among youth (López et al., 2022).

The practice of Generative STEAM education requires new explorations that lead to the creation of new materials, technologies, and processes that minimize environmental impact while fostering cultural heritage (Shernoff, 2024). This involves a deep commitment to 21st-century skills such as creativity, collaboration, communication, critical thinking, and digital citizenship, to address climate, social, and cultural challenges. The material ecology approach not only redefines how products are designed, but also introduces a new relationship between the designer, the material, and the natural and cultural environment (Oxman, 2016). Material ecology, combined with generative justice and post-cognitive paradigms, seeks not only to mitigate environmental harm but also to reclaim the relational ontology between people, organisms, and materials to foster a deep, systemic planetary awareness. This approach entails a dual benefit for Generative STEAM education based on sustainability: (1) reconfiguring conventional teaching and learning practices with technologies and materials through an ethical and aesthetic framework, and (2) impacting the positive, regenerative lifecycle of materials by using principles of nature and advanced technologies that contribute to the sustainability of the planet. Sustainable computing is conceived as the potential of hardware and software to be energy-efficient and environmentally responsible, requiring that technological innovation be guided by principles of sustainability (Pazienza et al., 2024). By merging perspectives from sustainable computing with the emerging field of biomaterials, a space is created for the development of digital systems that respect and enhance the natural cycles of the environment. This involves designing with an emphasis on minimizing carbon footprints, biodegradability, and the responsible use of resources, fostering generative justice that enables communities to adopt more conscious and resilient lifestyles.

Modern digital fabrication, where new products and interfaces can be created using DIY techniques, prompts STEAM educators to continuously reevaluate the role of materials beyond their apparent limits, such as the properties of algae integrated with electronic programming technologies like Arduino and Raspberry Pi (Scharon et al., 2024). Algae, composed of polysaccharides, can be processed to create bioplastics and biocomposites that are not only biodegradable but also capable of incorporating conductive properties when mixed with conductive inks (Gobbi et al., 2020). This versatility allows for the creation of interactive surfaces that respond to electrical stimuli, facilitating the development of educational and artistic projects that combine art and technology (Peppler et al., 2023). For example, by using an Arduino to program sensors that detect changes in the properties of algae-based biomaterials, interactive multimodal resources can be generated, promoting an integrated educational experience. Additionally, the Raspberry Pi board can be used to process real-time data, enabling designers and engineers to experiment with the interaction between biomaterials and programming, and opening new possibilities for research in sustainability and ecological design.

Materials and methods

Research context

The approach or methodology adopted in this study is qualitative, framed within the constructivist paradigm (Huyler & McGill, 2019). Its objectives are to identify, describe, and contrast teaching practices, skills, and types of learning in various educational communities that implement sustainable computing within the framework of Generative STEAM

education. Given that the focus of qualitative research is to adopt a holistic approach, with researchers primarily interested in the genesis of processes rather than outcomes, this research adopts an inductive model (Stake, 1995).The process of this qualitative research is descriptive-comprehensive, based on immersion in the daily life of primary and secondary education communities in the IV Region of Coquimbo, Chile, where initiatives of Generative STEAM education are implemented, integrating Biology, Art, Science of Design, and Engineering with Nature.

Research design

The research design used corresponds to a multiple case study. This design involves investigating multiple cases to describe relevant information, identify patterns, or contrast key aspects (Yin, 2013). To provide a detailed description of the cases, the case study design is complemented with an ethnographic approach, which contributes through observation techniques and interviews to describe the reality of a community (Creswell, 2014). Typically, multiple case studies seek to understand the differences and similarities between cases, as well as to explore research questions and theoretical development in greater depth."The case study method explores a contemporary limited system (a case) in real life or multiple limited systems (cases) over time, through detailed and in-depth data collection involving multiple sources of information and informs a description of the case and case themes"(Strauss, 1987). The study of cases is emerging as an increasingly relevant methodological strategy for gaining an in-depth understanding of the contextual and situated dynamics of embodied learning (Hanchett-Hanson & Ross, 2025). In this multiple case study, the aim is to identify characteristic aspects of the application of Generative STEAM education in various contexts, with the goal of describing and contrasting the educational practices underlying sustainable computing.

Data collection techniques

For this multiple case study, the descriptive record of systematic observation was chosen to refer to the practice of sustainable computing through Generative STEAM education. Field notes, videos, and photographs are used as data collection techniques to systematize the processes of development and implementation of sustainable education projects. The combination of multiple data collection techniques allows for an effective illustration and characterization of the practical learning relationships in socio-material, technological, and culturally embedded environments.

Procedure and sample

In this context, the participants in the multiple case study were selected based on a non-probabilistic or purposive sampling procedure. This was due to the application of Generative STEAM education in different cases based on sustainable computing. The type of sampling used is criterion sampling, characterized by the fact that all cases share a common criterion, and the understanding of the phenomenon of interest is enriched by the similarities and differences that deepen the study (Miles et al., 2013). The study cases consist of groups of primary school students and teachers from the Carlos Condell de la Haza School (Caleta Los Hornos) and secondary school students and teachers from Francis School (Coquimbo) and Antonio Varas School (Vicuña), in the IV Region of Coquimbo. Access to

the participants of the cases was obtained through personal contacts by each research team for each case, with all students, teachers, and parents expressing their willingness to participate in the study, following the ethical criteria applicable to working with minors, such as assent and informed consent.

Criteria for scientific rigor

In this multiple case study with an ethnographic orientation, the scientific rigor criteria of credibility, saturation, and reliability were considered (Yin, 1993). Credibility refers to whether the findings are plausible and is achieved through the integrity of data collection, triangulation of diverse perspectives, and verification of information. Saturation refers to the point at which sufficient data have been collected and no new categories or variations in descriptions emerge, indicating that the study has reached depth. Reliability, on the other hand, seeks to ensure the stability and consistency of the results through an audit that documents the research process for potential replicability and validation by others. These three criteria combined help strengthen the robustness and legitimacy of this study.

Data analysis

The main approach to data analysis initially involved reading the transcriptions of the observations. The first step in this process began with reviewing the field notes based on observations, videos, and photographs obtained during the application of Generative STEAM education in each case. Subsequently, a case-by-case description (intra-case) was conducted to identify teaching practices, skills, and types of learning in dynamic environments where sustainable computing was applied. The next step involved contrasting the practices of Generative STEAM education to identify patterns and differences that would contribute to a situated and expanded understanding of sustainable computing across different educational communities.

Results

Intra-case analysis of four educational communities in the IV Region of Coquimbo

Sustainable computing: multisensory panel for marine conservation of whales

In the town of Caleta Los Hornos, located in the IV Region of Coquimbo, Chile, a young fin whale was found stranded. According to community members, the incident was caused by a collision with a marine vessel, which resulted in the whale being stunned and subsequently pushed by ocean currents to the shore. This event caused a stir within the community, as it was not the first time such an incident had occurred. This led various local groups, including the local educational community, to reflect on whale conservation along the coastal shore. Moved by this case, the research team, together with community representatives and the local school, decided to create a multisensory panel using sustainable biomaterials and advanced technology to raise awareness among primary school students about the types of whales that exist and their conservation, with a focus on their physical and functional characteristics.

For this, different types of multimodal perception were used within the framework of 4E cognition and hands-on learning through projects. In the context of Generative STEAM education

based on sustainable computing, design thinking activities were organized to ideate, in a playful and experimental way, a prototype that would help students understand and raise awareness about the whales that come to the coast during different seasons of the year. Within the project-based learning framework, the creation of an interactive multisensory panel was proposed, made from conductive biomaterials developed from conductive inks mixing graphite, algae derivatives like agar–agar, and sodium chloride. This allowed for the design of bio-artificial surfaces capable of conducting electrical impulses generated by Arduino and Raspberry Pi boards. Together, educators, researchers, and students first investigated the types of whales commonly found near the coast, which can be observed from local boats on tourist trips through the bay during the spring and summer seasons. From this process, the fin whale, humpback whale, and blue whale were identified. Once the types of whales were identified, their images were engraved onto plywood using laser engraving with a CNC router. Later, experiments were conducted with different types of conductive materials to paint the whales and establish connections with Arduino and Raspberry Pi. Additionally, 3D modeling was advanced to create augmented reality and 3D printing of the whales. Part of these experiences can be observed in Fig. 1.

The material participation and engagement with different technologies led to various hands-on learning experiences in which researchers, educators, and students created interactive, multimodal perceptual situations. By opting for biodegradable materials and manufacturing processes that minimize environmental impact, the project not only addressed the need for education on marine conservation, but also demonstrated how biomaterials can function as sustainable electronic interfaces. To generate whale sounds through haptic perception, a pressure sensor was used. The pressure sensor detected the force applied by users, allowing sounds to be produced when the panel was touched or pressed. For component integration, the sensor was connected to the analog inputs of an Arduino, while audio modules such as the DFPlayer Mini were connected to the digital outputs of the Arduino, enabling the playback of pre-recorded sounds.

Subsequently, with the aim of promoting sustainable computing, various biomaterial tests were developed to emulate the sounds of different whale species (blue, fin, and humpback), sourced from real-world recordings. The main goal was the creation of complex, custom-designed surfaces combined with conductive biomaterials made from agar–agar, sodium

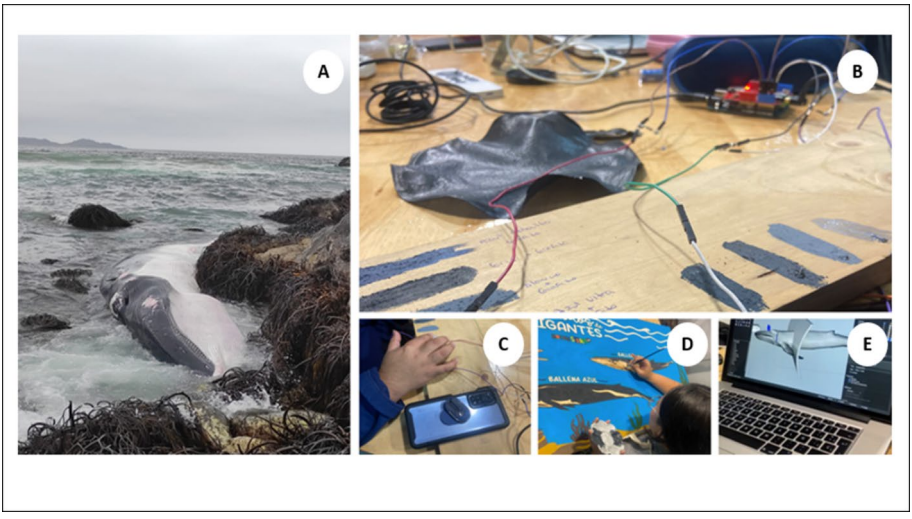

Fig. 1 Exploration, experimentation, and 3D design with conductive materials

chloride, and glycerin. This combination not only allowed the creation of detailed, personalized structures but also ensured that the biodegradable and sustainable components served as the electrical conductors, programmed with Arduinos and Raspberry Pi. Teachers and research teams facilitated various forms of learning through teacher-centered practices, utilizing biomaterials and technological design, which fostered different levels of programming. Regarding the sound generation programmed with biomaterials, the project envisioned the production of soft, harmonic melodies activated by the use of multiple sensors, providing interactive sounds that responded to the intensity and duration of user interaction. To implement this system, a programming algorithm was designed that read data from each sensor and established specific thresholds, triggering the sounds associated with the biomaterial surfaces, as shown in Fig. 2:

Finally, these sustainable computing experiences were complemented by immersive technologies such as augmented reality and 3D printing, offering a complete multimodal experience. To create the augmented reality design, students and teachers collaborated with part of the research team, who are experts in 3D design using Rhino software and Vuforia in Unity. Once the 3D model was obtained, it was essential to correctly configure the Vuforia and Unity environments to generate the augmented reality of the whales. This process involved designing the app's interactions, such as touch or motion detection, and ensuring that virtual objects were accurately placed within the 3D space in relation to the physical objects. As users interacted with the surface, they were able to visualize properties and characteristics of the whales in various ways, enhancing opportunities for hands-on learning.

Biomaterials: design and indigenous culture

In an inspiring educational project focused on aesthetics and cultural heritage preservation, students and teachers came together through the integration of science, engineering, art, and design to foster various forms of learning, with an emphasis on aesthetic and ethical values for the educational community of Caleta Los Hornos, IV Region of Chile. In the case of

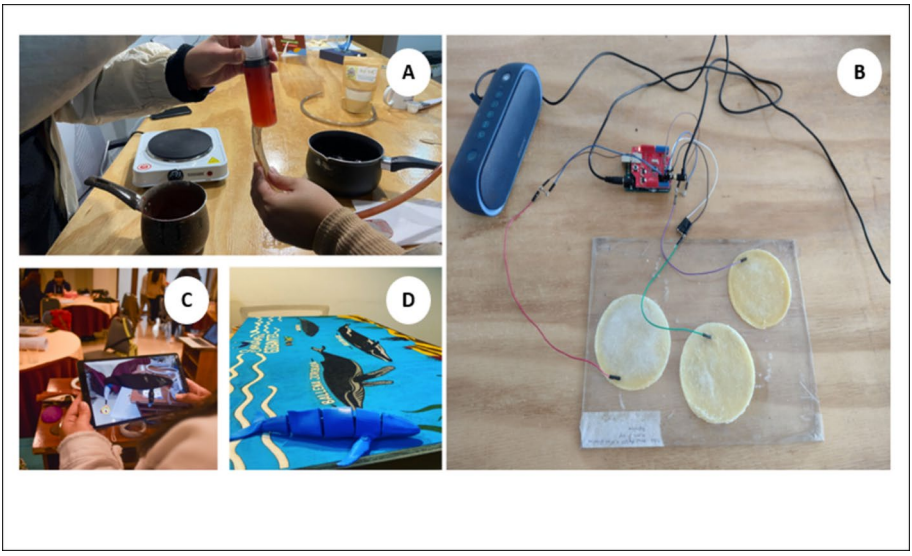

Fig. 2 Electronic programming with biomaterials, augmented reality, and 3D printing

cultural heritage preservation, the design of biomaterials was proposed to recreate the traditional sea Wolf Hide Raft of the Changa indigenous community, who once settled in the area, using sustainable materials and contemporary manufacturing techniques. The process began with the exploration and creation of coffee-based biolaminates, using an innovative composite material made of agar–agar, water, glycerin, and natural pigments in yellow, blue, and red tones. These biolaminates were designed to mimic the strength and texture of sea lion leather used by the Changa indigenous communities, providing an environmentally friendly alternative free from animal products. In this way, students, teachers, and researchers aimed to recreate, in an eco-friendly manner, the cultural heritage of the coastal indigenous community, encouraging sustainable and culturally relevant alternatives for environmental care.

Throughout the project, students experimented with different ingredient mixtures and proportions, allowing them to optimize the flexibility, durability, and strength of the biolaminates. This process not only resulted in an aesthetic and structurally faithful reconstruction of the traditional rafts, but also facilitated a deep learning experience about the properties of biomaterials and their application in the context of cultural preservation. The collaboration between students and teachers also fostered a greater respect for the ancestral knowledge of the Changa community, creating a space where sustainability and cultural heritage intertwine. For further details, see Fig. 3.

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Biocement: explorations for sustainable construction

In an innovative educational project, a group of high school students and teachers from Colegio Francis School in Coquimbo embarked on creating a sustainable biocement by combining a variety of biocomponents such as algae, sand, eggshells, and cork. Through hands-on activities with these materials, the students proposed, using design thinking and project-based learning, an alternative to traditional cement blocks. With a practical, learn-by-doing approach, the students aimed not only to develop an alternative material to conventional cement but also to evaluate its structural properties of strength and insulation. In this process, they explored the properties of eggshells, based on their calcium content in the form of lime, and cork, due to its insulating properties that help reduce sound transmission. As the students experimented with different proportions of components, they made significant progress in developing a biocement structure that, although initially not as rigid as expected, laid the groundwork for future experiments that would minimize water use—an issue currently contributing to a regional sustainability crisis. The progress made through these experiments generated both material results and deep learning. One of the key insights the students discovered was the potential of algae, which provide organic compounds and can act as natural binders to reduce water consumption in the construction industry. Sand, on the other hand, showed resilient qualities based on its structure and the biocement's strength. The students also realized that eggshells, rich in calcium carbonate, improved the strength of the biocement, while cork contributed lightness and sound-insulating properties.

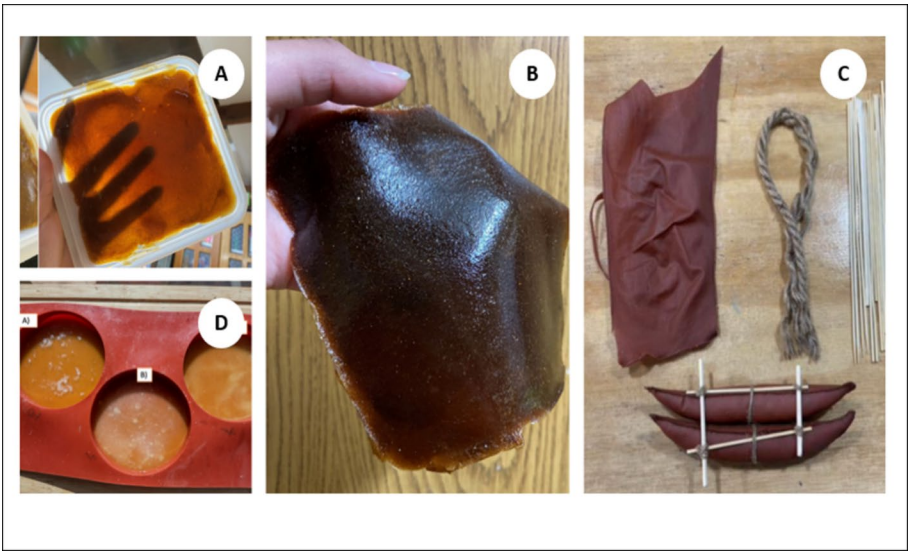

Fig. 3 Exploration, creation, and testing of coffee biolaminates for the recreation of the sea wolf hide raft of the Chango Indigenous People

Through this project, the students reflected on the materials they used, understanding that not only did they serve specific functions in the mixture, but they also contributed to sustainability by incorporating waste products, thus promoting a circular economy and generative justice. From their initial experiments, they concluded that the mixture should consist of 30% water, 10% algae, 40% sand, 15% crushed eggshell, and 5% crushed cork. The mixture was prepared in an appropriate container to ensure uniform distribution. Curing took place under high humidity (70–80%) and moderate temperatures (20–25 °C) for at least seven days, allowing the algae's properties to aid in hardening. To assess the mechanical properties of the resulting biocement, compression and bending tests were planned. For further details, see Fig. 4.

To improve the consistency and stability of the biocement, the students decided to incorporate agar agar, a polysaccharide derived from algae known for its gelling properties. The addition of agar agar resulted in a significant improvement in the material's rigidity and cohesion, allowing mixtures containing eggshell and cork to develop characteristics more similar to traditional cement, but in a sustainable manner. Ultimately, the students reflected and shared that the combination of water, algae, sand, agar agar, and other natural elements presents a sustainable alternative that not only meets the demand for eco-friendly construction materials but also offers a practical approach to addressing sustainability challenges in the construction industry. This project not only provided the students with valuable hands-on experience in experimental research and materials analysis but also promoted awareness of reducing environmental impact, aligning with the principles of material ecology that advocate for sustainability and the responsible use of natural resources.

Reutilization and construction of 3D filaments: generative circular economy in educational communities

At Colegio Antonio Varas de Vicuña, high school students and teachers carried out an educational project aimed at repurposing discarded plastic bottles to create recycled

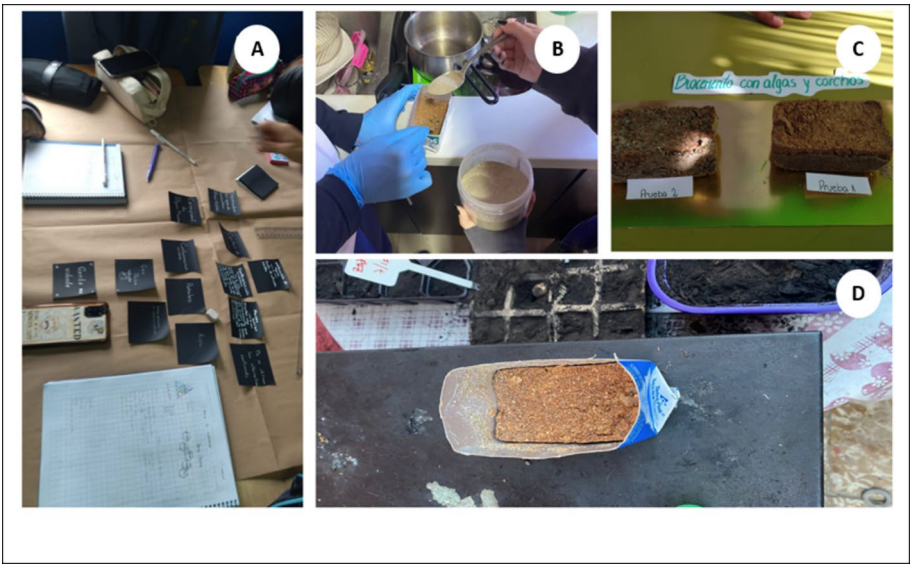

Fig. 4 Creation of biocement using biomaterials and household waste components

PET filament, promoting sustainability and innovation in the classroom. In response to the issue of single-use plastic waste generated at the school, the students and teachers decided to design and build an extruder machine capable of transforming bottles into filament for 3D printing. The process began with identifying the materials needed to build the extruder, followed by researching models and guides in academic articles and tutorials. The students then proceeded with prototyping and testing the machine, using 3D printed parts and accessible materials, following YouTube tutorials and expert guidance provided by researchers and technology development advisors. In this project, the students combined knowledge of engineering, recycling, and industrial design, offering a hands-on, collaborative learning experience to understand the principles of circular economy and waste reduction.

The students started with early explorations and experiments using 2D sketches, then moved on to hands-on engagement with the components of the extruder machine. After three iterations of prototyping, the students succeeded in creating an extruder that included an extrusion system with a heating module (hotend) that operates at temperatures between 220 °C and 250 °C, fitted with a 1.75-mm diameter nozzle. The plastic bottles are first cut into 5-mm-wide strips, which are then fed into the extrusion system. This system heats the material until it melts into filament, which is driven through a gear system powered by a stepper motor (NEMA 17), achieving continuous and stable traction of the molten material. After several optimization tests on the resulting product, the recycled filament was used in 3D printers to create new objects, allowing students to design and print prototypes and functional parts. This demonstrated how waste can be transformed into valuable resources. The experience not only fostered practical construction learning but also raised environmental awareness and a commitment to sustainability from the perspective of a circular economy. See Fig. 5 (Table 1).

Coding and categorization of the case studies

Dynamic network of codes and categories

Based on the coding and categorization results from the within-case analysis, the following conceptual network is presented as a synthesis. It illustrates the interrelationships between the central category, Education for a Sustainable Future and its eight key thematic subcategories: Active and Participatory Methodologies, Key 21 st Century Skills, Types of Learning, Contextualized Educational Purposes, Sustainable and Inclusive Computing, Situated Contexts and Materialities, Relationship with Technology, and Ethical and Political Dimension. Each subcategory is linked to a set of emergent codes, represented as colored nodes according to their thematic cluster. The size of the nodes reflects the relative conceptual weight or prominence of each subcategory within the studied context. The network also highlights conceptual connections between specific codes. This visualization supports a systemic understanding of how sustainable, ethical, and technologically integrated approaches to education intertwine with skills, methodologies, materials, and sociocultural purposes relevant to 21st-century learning and justice-oriented innovation (Figs. 6 and 7).

Inter-case analysis of four educational communities in the IV Region of Coquimbo

Based on the inter-case qualitative analysis, following an inductive logic, patterns and differences were identified regarding teaching methodologies, skills, learning types, educational goals, sustainable computing approaches, and the contexts in which educational initiatives based on the STEAM framework (Science, Technology, Engineering, Art, and Mathematics) are developed. Regarding teaching methodologies, project-based learning, Design Thinking, and inquiry-based learning were identified as

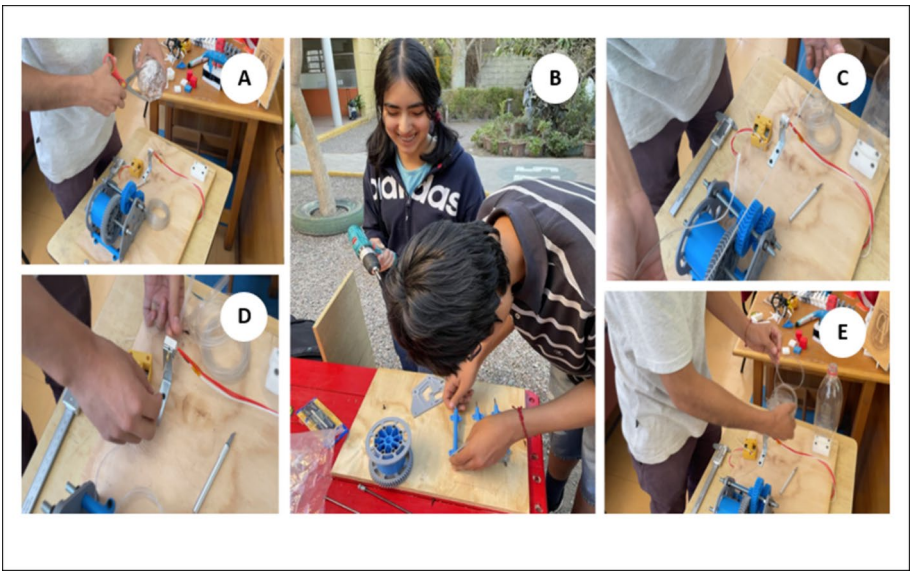

Fig. 5 Creation of the extruder machine for recycled filament generation

Table 1 Education for a sustainable computing

Categories	Codes
Active and Participatory Methodologies	Project-Based Learning
	Design Thinking
	Inquiry-Based Learning
	Co-Design Between Community and School
	Exploration
	Creation
Key 21 st Century Skills	Collaboration
	Digital Citizenship
	Analytical Thinking
	Empathy
Types of Learning	Critical Thinking
	Hands-on Learning
	Learning by Making
	Deep Learning
	Haptic and Sound-Based Learning
	Tinkering
Contextualized Educational Purposes	Marine Conservation
	Indigenous Cultural Heritage
	Circular Economy
	Generative Justice
Sustainable and Inclusive Computing	Biomaterials
	Creative Electronics
	3D Modeling and Fabrication
	Augmented Reality
	Biomaterials as Educational Interfaces
	Programming with Biodegradable Materials
Situated Contexts and Materialities	Local Dynamics
	Ecological Materialities
	Cultural Frameworks
	Biofabrication Inspired by Ancestral Knowledge
	Plastic Waste Transformation
	Technology for the Common Good
Relationship with Technology	Low-Impact Aesthetics
	Immersive Technologies
	Sustainable Aesthetics
	Accessible Ecotechnology
Ethical and Political Dimension	Ethical Knowledge Appropriation
	Generative Justice
	Critical Environmental Education

key approaches that promote practical, student-centered learning. In terms of skills, a gradual coupling flow of material engagement with digital technologies and resources was observed, which included exploration, creation, collaboration, and application, all framed within an embodied and scaffolded environmental approach.

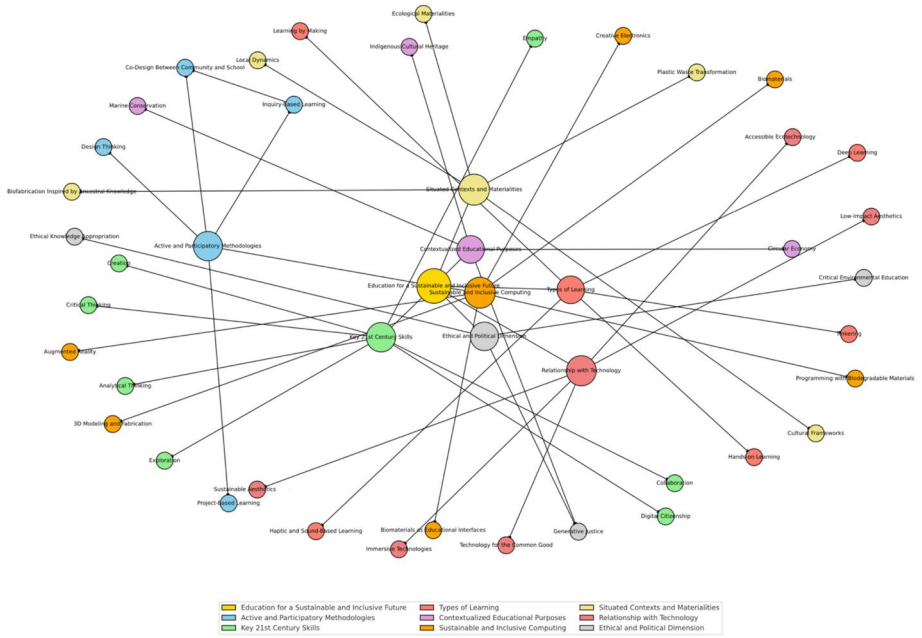

Fig. 6 Dynamic network of codes and categories

Emerging patterns across cases

a Active and Participatory Methodologies with a Situated Approach

A cross-cutting pattern observed is the use of active methodologies such as project-based learning, design thinking, and guided inquiry, combined with co-design processes between schools and communities. This methodological convergence fosters hands-on learning and collaborative creation, enabling students to develop critical and creative skills through exploration and the resolution of real-world problems rooted in their local context.

b Technological Appropriation and Sustainable Computing

The projects demonstrate a critical appropriation of accessible and low-cost technologies (Arduino, Raspberry Pi, 3D printing, augmented reality), with a strong emphasis on sustainable computing. This appropriation promotes a relationship with technology oriented toward the common good and generative justice, blending sustainable aesthetics with low technological footprint.

iii. Contextualized Educational Purposes: Ecological and Cultural Justice

Another shared pattern is the orientation toward educational goals that integrate marine conservation, circular economy, indigenous cultural heritage, and local ecological materialities. These aims reflect a commitment to critical environmental education and the inclusion of diverse cultural frameworks, particularly through biofabrication practices inspired by ancestral knowledge.

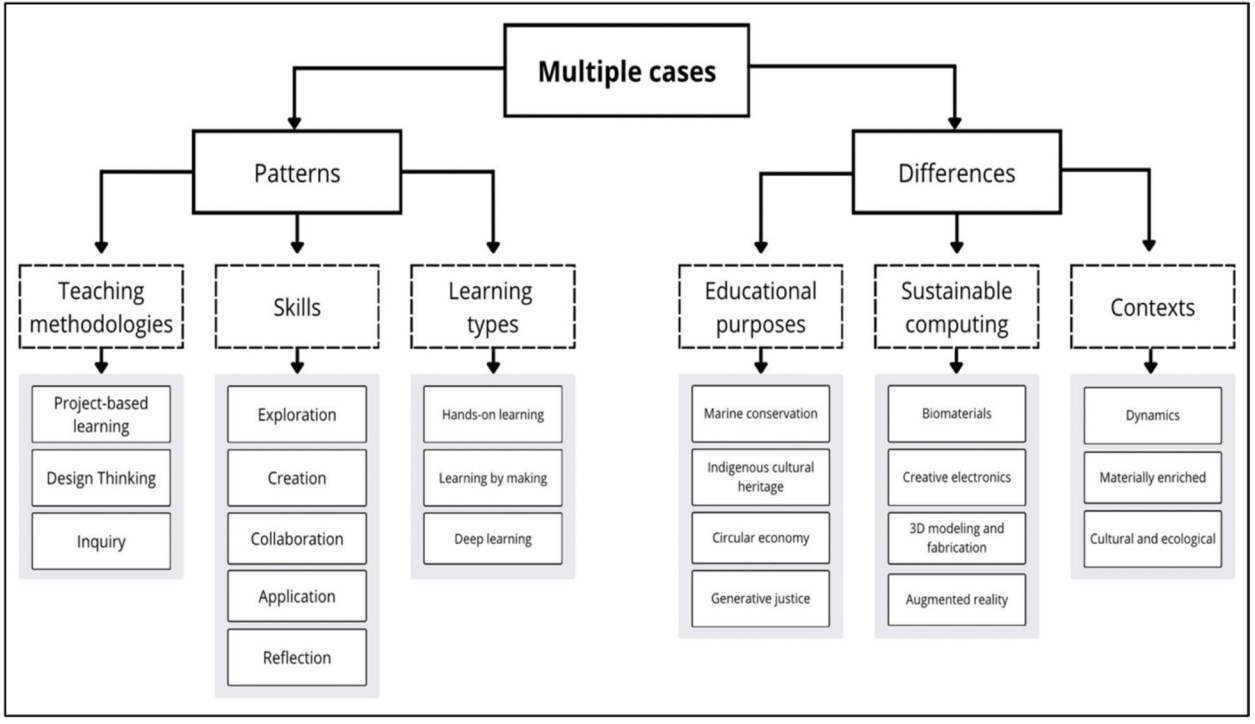

Fig. 7 Analytical representation of the inter-case model

iv. Development of 21st-Century Skills through Doing

All cases promote competencies such as digital citizenship, critical thinking, empathy, and collaboration, embedded in immersive and sensory experiences. These practices support situated learning and position students as agents of sociotechnical transformation.

Key differences and divergent emphases

A. Differentiated Epistemic Anchors: Between Science, Technology, and Culture.

The cases exhibit diverse epistemic orientations. Some focus on scientific and technical knowledge, while others incorporate aesthetic, historical, and ethical–political frameworks. This diversity highlights different modes of knowledge production within STEAM education.

b. Technological Complexity and Material Agency.

The levels of technical complexity and the agency of materials vary. Projects such as recycled filament involve more advanced programming, while others prioritize physical–chemical experimentation. These variations influence the timeframes, resources, and expected outcomes.

c. Degree of Immersion and Embodied Design.

The level of bodily immersion differs across cases: some offer integrated multisensory experiences, while others emphasize tactile and visual manipulation. This reflects different approaches to experience-centered design.

d. Scale and Nature of Community Engagement.

The intensity of community participation varies, ranging from deep connections with indigenous knowledge to initiatives focused primarily within the school. This variation forms a continuum between community-based eco-techno-social projects and territorially grounded school experiences.

Discussion and conclusions

The main objective of this study was to understand the types of teaching methodologies, skills, and forms of learning that emerge from the application of Generative STEAM Education in various case studies focused on addressing socio-environmental and cultural challenges through the integration of both digital and non-digital technologies. To this end, a qualitative multiple-case study was conducted in four primary and secondary educational communities in the Coquimbo Region of Chile. The within-case analysis revealed that the integration of sustainable computing arises from the use of biomaterials and advanced technologies in educational contexts that promote marine conservation, the preservation of Indigenous cultural heritage, circular economy, and generative justice. In these cases, the emphasis is not only on the development of technical skills but also on raising awareness of sustainability and respect for ancestral knowledge. Active teaching methodologies such as project-based learning, design thinking, and inquiry-based learning were identified, shaping sociomaterial learning environments characterized by exploration, creation, collaboration, empathy, and digital citizenship. These hands-on methodologies facilitated material engagement through the manipulation of biomaterials and technological tools such as Arduino programming, Rhino design, 3D printing with Cura, and augmented reality using Unity.

The cross-case findings reveal transversal patterns that position Generative STEAM Education as an approach capable of integrating interdisciplinary learning with a relational body/brain/environment ontology, aligned with the principles of material ecology and generative justice. The creation of complex artifacts using conductive biomaterials, the use of haptic sensors and audio modules to emulate whale sounds, the production of agar–agar-optimized biocement, and the fabrication of recycled filaments for 3D printing are examples of practices that connect sustainability, technology, and deep learning. Additionally, coffee-based biolaminates were developed to reproduce the cultural legacy of sea lion leather rafts from the coastal Indigenous Changa community in Chile, consolidating a pedagogical approach that reclaims the aesthetic, ethical, and political dimensions of education.

These interdisciplinary projects not only served as a platform for cultivating 21st-century skills such as creativity, critical thinking, empathy, digital citizenship, and collaboration, but also enabled the development of practical learning experiences in real-life contexts relevant to contemporary socio-environmental challenges. The practical and experiential focus evident across all cases consolidated a form of transformative teaching oriented toward the embodiment of situated knowledge and student agency in the face of complex problems. The differences among the analyzed cases, in terms of educational purposes, levels of technological complexity, degrees of sensory immersion, and forms of material engagement, further enrich the landscape, demonstrating that Generative STEAM Education does not follow a one-size-fits-all model. Rather, it emerges as a flexible network of practices, knowledges, and material relationships. This diversity offers a valuable methodological framework for replication in other school contexts, allowing it to adapt and regenerate based on socioterritorial specificities. Ultimately, this study highlights the potential of a decentralized, project-based pedagogy that promotes sustainable and situated education, inspired by the principles of material ecology, generative justice, and technological inclusion. The findings align with research advocating for a critical and expanded perspective on the STEM + approach, one that re-evaluates its cognitive, pedagogical, and design foundations (Saputri & Lee, 2021; Loyens et al., 2022; Fernández et al., 2024). This work contributes to strengthening the framework of education for sustainability through the practical implementation of a STEAM approach committed to the social, ecological, and cultural transformation of school communities.

Limitations and future research

The limitations of this study primarily lie in its qualitative nature, which, while allowing for an in-depth understanding of the observed processes and dynamics, makes it difficult to generalize the results to broader educational contexts. The diversity of the case studies, though enriching, also presents challenges when comparing and synthesizing the data, as each Generative STEAM education proposal responds to specific contexts and needs that may not be replicable in other settings. Regarding future directions, this study opens the door to new research that could focus on expanding the analytical framework by incorporating a greater diversity of educational contexts and student groups, as well as evaluating long-term effects. Additionally, the integration of other disciplines and emerging technologies could further enrich Generative STEAM education proposals, offering new perspectives for designing sus-tainable solutions that more effectively address the planet's global challenges.

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Data availability Not applicable.

Declarations

Conflicts of interest The authors declare no conflict of interest.

Institutional review board statement He study was conducted in accordance with the Declaration of Helsinki, and approved by the research Ethics Committee of the Faculty of Education, Universidad Santo Tomás, La Serena, Chile.

Informed consent Informed consent was obtained from all subjects involved in the study.

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Authors and Affiliations

Ronnie Videla[1,2] · Maybritt Aros[3] · Eduardo Sandoval-Obando[4] · Andri Velásquez[5] · Paola Rámirez[6] · Alexis Sarzosa[2] · Carola Cerpa[3] · Paulina Veas[3] · Daniela Carvajal[2] · Daniela Jorquera[1,3] · Marcelo Chávez[2]

✉ Ronnie Videla
rvidelareyes@gmail.com

[1] Escuela de Pedagogía en Educación Diferencial, Facultad de Educación, Universidad Santo Tomás, 1780000 La Serena, Chile

[2] HUB EDUCA STEAM, 1780000 La Serena, Chile

[3] Escuela de Educación, Pedagogía en Educación Diferencial, Universidad Católica del Norte, 1780000 Coquimbo, Chile

[4] Escuela de Psicología, Instituto Iberoamericano de Desarrollo Sostenible (IIDS), Universidad Autónoma de Chile, 17800000 Temuco, Chile

[5] Escuela de Pedagogía en Educación Física, Facultad de Educación, Universidad Santo Tomás, 1780000 La Serena, Chile

[6] Facultad de Ciencias Básicas, Universidad Católica del Maule, 1780000 Talca, Chile