

Article

Developing Sustainability Competencies Through Active Learning Strategies Across School and University Settings

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Abstract

The transition toward sustainable production requires engineering and science education to adopt active, interdisciplinary, and practice-oriented teaching strategies. This article presents a comparative analysis of two educational initiatives implemented in Panama aimed at fostering sustainability competencies at the university and secondary school levels. The first initiative, developed at the Technological University of Panama, integrates project-based learning and circular economy principles into an extracurricular module focused on production planning, sustainable design, and quality management. Students created prototypes using recycled HDPE and additive manufacturing technologies within a simulated startup environment. The second initiative, carried out in two public secondary schools, applied project- and challenge-based learning through the Design Thinking framework, supporting teachers and students in addressing real-world sustainability challenges. Both programs emphasize hands-on learning, creativity, and iterative development, embedding environmental awareness and innovation in both formal and informal educational settings. The article identifies key opportunities and challenges in implementing active methodologies for sustainability education. Challenges such as limited infrastructure and rigid schedules were identified, along with lessons learned for future implementation. Students connected local issues to global goals like the SDGs and saw themselves as agents of change. These initiatives offer practical models for advancing sustainability education through innovation and interdisciplinary collaboration.

Keywords: active learning methodologies; design thinking; sustainable development education; sustainability competencies



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1. Introduction

The need for transformative education in the face of climate change is becoming increasingly evident in the recent academic literature [1,2]. Education plays a crucial role in equipping individuals with the knowledge, skills, and values necessary to comprehend and address the complex challenges of sustainability [1–5]. As climate change becomes a central concern in the educational discourse [2,6,7], there is a growing need to integrate it meaningfully into curricula through creative and inclusive frameworks capable of addressing global environmental issues [8,9]. These frameworks must also be equity-driven, since climate impacts are unequally distributed and disproportionately affect children and vulnerable populations in low- and middle-income regions [10].

In this context, scholars advocate for transformational approaches that move beyond traditional teaching methods. Perspectives such as posthumanism emphasize the interconnectedness of human and non-human systems, enriching environmental education. Other contributions highlight the critical role of digital tools, community building, and co-creation [2,4,5,8,11–15]. Together, these works emphasize the development of global competencies, such as systems thinking [16–19], collaborative problem solving [20–26], and the ability to advocate for sustainable change, which is essential for learners to navigate the multifaceted nature of the climate crisis [27]. Furthermore, participatory, interdisciplinary, and creative approaches are indispensable for effectively involving youth, as well as for developing their agency and fostering profound engagement in climate action [28]. The literature is consistent in stressing that transformative education is vital for equipping current and future generations to navigate the complex challenges posed by climate change.

While these global debates underscore the urgency of educational change, vulnerable areas such as Panama Oeste, a province located west of Panama Province, where the capital is situated, illustrate how such challenges manifest locally. This region faces recurring hydrometeorological disasters, including floods, landslides, and strong winds, which severely impact local communities and underscore the urgent need for effective disaster risk management and robust land-use planning [29]. Climate change further exacerbates these risks, with urban areas experiencing an increase in flood and landslide events that threaten the safety of thousands of residents and jeopardize future energy and water security [30]. Additionally, socioeconomic vulnerabilities are especially pronounced among Indigenous communities and farmers, who are disproportionately impacted by climate variability. Their reliance on natural resources and the limited support they receive from government programs place them at higher risk of consumption shocks and livelihood disruptions [31]. Coastal zones, such as Punta Chame, are also increasingly exposed to sea level rise and erosion, making them highly susceptible to long-term climate change impacts [32]. Collectively, these previous studies highlight the complex and multifaceted vulnerabilities of Panama Oeste, underscoring the need for inclusive and resilient development strategies that prioritize sustainability and social equity.

Responding to these vulnerabilities requires education that not only addresses immediate technical needs but also fosters broader socio-ecological transitions. In this regard, the role of technical and vocational education and training (TVET) is increasingly acknowledged as essential for advancing sustainable practices and supporting the ecological transition. The recent literature emphasizes the importance of integrating sustainability into TVET curricula to promote technological innovation and facilitate the adoption of renewable energy, particularly in contexts such as Nigeria, where local capacities need to be strengthened [33]. Beyond technical preparation, vocational education equips individuals with the professional and social competencies needed in a rapidly changing ecological landscape [34]. TVET also fosters links between sustainability and social justice, supporting more inclusive and equitable development [35]. These contributions highlight

the transformative potential of TVET in enabling communities to actively participate in climate action.

At the same time, higher education faces parallel challenges. A major concern is the lack of alignment between academic preparation and industry needs, leading to persistent skill gaps among graduates. Career failures often stem from deficiencies in essential soft skills, including honesty, cooperation, decision-making, and problem-solving. While some institutions attempt to incorporate such skills, many lack a structured approach [36–44]. This issue is particularly pressing in engineering education, where the complexity of contemporary industrial and environmental challenges calls for professionals equipped not only with technical knowledge but also with sustainability-oriented and digital competencies [36,45–48], capable of handling a broad panorama of challenges [48].

Training in sustainability and technological competencies thus plays a pivotal role in preparing a workforce capable of addressing contemporary industrial and environmental challenges [45,49–54]. As industries increasingly align with global sustainability goals, such training ensures that employees possess the necessary skills to implement sustainable practices and innovative technologies [55–58]. Additionally, digital and sustainability-related skills significantly enhance graduates' employability in an evolving job market [45,59–62]. Beyond technical expertise, training also cultivates essential soft skills, such as communication and problem-solving, which are crucial for effective teamwork and the successful implementation of sustainability initiatives [63]. Continuous training fosters innovation and responsiveness to regulatory shifts, supporting individual career development and long-term sustainability objectives at the organizational level [64,65].

Meeting these demands requires a pedagogical transition. Engineering and STEM education must evolve from traditional teaching-centered approaches, characterized by passive memorization and limited interaction, toward learning-centered models where instructors act as facilitators. Active methodologies such as problem-based learning (PBL), project-based learning (PjBL), and case studies foster autonomy, reflection, and the construction of meaningful knowledge [66–68]. These methods contrast with passive lectures by engaging students in reflection, analysis, and communication [67,69].

In the context of sustainable production, active methodologies have proven particularly effective. They not only improve student engagement but also foster critical thinking and bridge theory with real-world application. Approaches such as PBL and PjBL actively involve students in their learning process, which is essential for grasping the multifaceted nature of sustainability challenges [70]. These methods cultivate critical problem-solving abilities, empowering students to develop innovative, context-relevant solutions to complex environmental and industrial problems [71]. By linking academic content with hands-on projects, students gain practical experience that strengthens their capacity to implement sustainable practices in professional settings [72].

Among the active approaches, Design Thinking (DT) has gained particular prominence in STEM education. The Design Thinking in Class (DITC) model, for example, has shown significant improvements in students' problem-solving and teamwork skills within flipped classroom environments, while also enabling deeper engagement with real-world issues [73]. By promoting PjBL, DT fosters competencies in problem identification, product development, and creative ideation, as demonstrated by its successful integration as a core subject in engineering programs [74–78]. Furthermore, DT fosters interdisciplinary collaboration by bridging the engineering and design disciplines, thereby enhancing students' capacity to navigate complex, open-ended problems and cultivate versatile, workforce-ready skills [75].

Building on this background, the present study compares educational initiatives at two academic levels, secondary school and university, to evaluate how active methodologies fos-

ter sustainability-oriented mindsets. Through continuous feedback, hands-on experiences, and interdisciplinary integration, these projects contribute to more practical and impactful models of engineering and STEM education. The findings inform recommendations for scaling these methodologies, reinforcing the role of active learning in shaping the next generation of problem solvers aligned with sustainability goals.

2. Theoretical Background

Environmental education and the development of competencies for sustainability are crucial in training individuals who can effectively address current environmental challenges [1,7,52,79–83]. The integration of these concepts into educational programs fosters not only critical awareness but also practical skills among students [2,10,84,85].

Research on sustainability professionals highlights two complementary groups of competencies: sustainability research competencies and sustainability intervention competencies. Together, these enable both a deep analysis of sustainability issues and the ability to design effective solutions [86]. When environmental education incorporates these dimensions, it transcends theoretical knowledge and equips students to apply what they have learned in real-world contexts.

Evidence from teacher education further illustrates this potential. For example, studies in the Philippines reveal both successes and persistent challenges in integrating environmental education into teacher training programs [87]. This suggests that, despite significant efforts, it is essential to continually evaluate and adjust programs to maximize their effectiveness.

Similar concerns are reflected in higher education. Hakiki and Saputra [88], through a systematic review, concluded that environmental education programs are essential for advancing the Sustainable Development Goals. Their work emphasizes the need for multidisciplinary approaches that integrate theory with practice, providing students with authentic learning experiences.

In summary, environmental education and the development of competencies for sustainability are interdependent and must be effectively integrated into educational programs. Such integration prepares students to confront environmental challenges and promotes a societal shift toward more sustainable practices. Ongoing adaptation and evaluation are therefore critical to ensure the continued relevance and effectiveness of these programs in a rapidly changing world.

2.1. Education for Sustainable Development (ESD)

Education for Sustainable Development (ESD) or education for sustainability has evolved significantly over the past decade, closely with the United Nations' Sustainable Development Goals (SDGs) [60,89,90]. Recent studies highlight its role in fostering critical competencies such as critical thinking, communication, system modeling, problem solving, environmental empathy, and socio-emotional and interpersonal skills essential for sustainability [6,19,22,52,79,91–102]. The literature on ESD has grown steadily, with a notable increase in publications since 2016, despite the disruptions caused by the COVID-19 pandemic [103]. Emerging themes include the adoption of innovative pedagogies, the importance of community engagement, and the need for supportive policy reforms [104].

Empirical studies illustrate how ESD can be embedded across multiple dimensions. At the cognitive and technological levels, Venegas-Mejía et al. [102] demonstrated that integrating Learning and Knowledge Technologies promotes collaborative learning and values associated with ethical citizenship. Frey et al. [19] demonstrated that qualitative system models, especially those representing time dynamics, enhance elementary students' systems thinking. In the socio-emotional domain, Mieres-Chacaltana et al. [97] found

that teacher resilience and self-efficacy in Chile significantly influence prosocial behavior, underscoring the role of emotional competencies in sustainability-oriented classrooms. Spangenberg et al. [96], using immersive virtual reality, revealed that compassion-driven experiences can deepen environmental awareness and motivate pro-environmental behavior. At the institutional level, Baqués et al. [95] analyzed ESD integration in European engineering programs, identifying enabling factors such as transdisciplinary curricula, faculty support, and systemic change.

Taken together, these studies highlight the multidimensional nature of ESD, combining systems thinking, emotional engagement, socio-professional well-being, and institutional transformation. They show that ESD can be embedded at all educational levels to foster sustainability competencies among both learners and educators. Furthermore, ESD contributes not only to SDG 4 (Quality Education) but also to interconnected goals related to climate action and sustainable cities [105]. However, disparities in ESD implementation across different regions suggest a need for targeted strategies to ensure equitable access to quality education for all [103].

In summary, ESD is essential for equipping learners with the skills and knowledge required to address complex sustainability challenges. Building on this foundation, the next section explores Design Thinking as a pedagogical approach that operationalizes these principles through creativity, collaboration, and iterative problem-solving.

2.2. Design Thinking in STEM and Sustainability Education

Design Thinking (DT) has gained prominence in STEM and sustainability education over the past decade, serving as a transformative approach to enhance problem-solving and creativity among students [84,106–109]. It has been widely recognized for fostering critical thinking and innovation, both of which are essential for addressing global challenges such as climate change, resource scarcity, and pollution [109–111].

Empirical evidence highlights the versatility of DT across educational levels. In K–12 settings, DT has been used to promote sustainable entrepreneurship, computational thinking, and hands-on STEM learning through real-world problem solving and collaboration with external stakeholders [51,108,112–114]. These interventions demonstrate DT's capacity to cultivate creativity, empathy, and environmental awareness among young learners. In higher education, DT has been applied in curriculum reform, circular economy education, and teacher development, encouraging transdisciplinary engagement, systems thinking, and innovation-oriented mindsets [76,108,115,116]. Together, these applications confirm DT's relevance for both resource-rich and under-resourced contexts.

Systematic and empirical studies further reinforce these findings. A review by Arifin and Mahmud [117] identified effective DT teaching strategies, including problem-solving, collaborative learning, and design-based tasks. The integration of DT with transformative learning has also been shown to nurture sustainability mindsets [57].

Research indicates a steady increase in publications on Design Thinking (DT) in STEM education, with a focus on interdisciplinary approaches that enhance student engagement and learning outcomes [118]. This evidence suggests that DT significantly improves students' ability to apply STEM knowledge in practice, thereby strengthening iterative learning processes [108].

Specific studies illustrate these benefits. In secondary education, Nguyễn et al. [108] reported gains in problem solving and critical thinking, while Bentz et al. [112] found that DT-based activities enhanced creativity, empathy, and environmental awareness. Kee et al. [119] and Tramonti et al. [120] emphasized DT's role in sustaining motivation and innovation capacity through hybrid and digital learning environments. In higher education, Kurucz et al. [121] and ElSayary [114] highlighted DT's potential to cultivate innovative

mindsets when combined with reflective practice and service learning. Wilkerson and Trellevik [55] demonstrated that coupling DT with systems thinking enhances the definition of complex sustainability problems, while Ijassi et al. [119] showed its value as a methodological backbone in circular economy and sustainable manufacturing education. Similar benefits were noted by Rusch [51], who documented student-led DT courses that fostered institutional and environmental innovation, and by Sobieraj et al. [118] who applied DT to curricular reform in pharmaceutical education, increasing transparency, trust, and engagement.

Overall, the literature consistently links DT with the development of cross-cutting competencies, including empathy, creativity, critical reflection, collaboration, resilience, and systems thinking. Table 1 summarizes these competencies and the supporting evidence. Building on these insights, DT is presented in this study as a key pedagogical strategy that operationalizes Education for Sustainable Development and provides a framework for comparing sustainability-oriented initiatives across educational levels.

Table 1. Key competencies supporting the literature, and how Design Thinking fosters their development.

Competency	Action from DT	Source
Empathy and a user-centered mindset	DT begins with the “empathize” phase, which requires learners to gain a deep understanding of users’ needs and perspectives, often through interviews, observation, or role-playing exercises.	[112,114,119,122]
Creativity and innovation	Through ideation and prototyping, DT encourages students to generate novel ideas, break mental patterns, and explore non-linear thinking, fostering original and feasible innovations.	[108,122,123]
Critical thinking and reflection	DT requires students to define problems clearly, test hypotheses, and evaluate feedback critically, thus nurturing analytical reasoning and reflective learning at each iteration.	[119,121,124]
Collaboration and communication	DT is typically implemented in team-based settings where learners must co-create, listen, negotiate, and communicate ideas effectively across disciplinary or cultural boundaries.	[51,108,121]
Iteration and resilience	DT embraces failure as a learning opportunity. Iterative prototyping helps students become comfortable with ambiguity, revise their work, and build resilience through feedback loops.	[114,120]
Systems and sustainability thinking	DT helps students visualize problems within broader systems, consider environmental and social impacts, and design interventions aligned with sustainable development principles.	[51,77,121]

In sum, the current literature illustrates a growing consensus on the pedagogical value of DT in both STEM and sustainability education. It functions not only as a framework for solving ill-defined problems but also as a mechanism to scaffold interdisciplinary, collaborative, and experiential learning. Its capacity to integrate empathy, iteration, and systems thinking positions DT as a vital strategy for preparing learners at all levels to become proactive innovators and sustainability-oriented changemakers in an increasingly complex world.

2.3. Territorialization of Environmental Education

The concept of territorialization of environmental education emphasizes the importance of integrating local materials and engaging vulnerable communities in the learning

process. This approach enhances the relevance of education while empowering communities to take ownership of their natural resources. Studies have shown that non-formal educational practices can strengthen skills and ethical values for sustainable transformation. For instance, initiatives in Brazil demonstrated that school-based gardening programs fostered sustainable food practices and engagement with local socio-environmental challenges [125].

Community engagement has also proven effective in building resilience and environmental awareness. A program in Guerrero, Mexico, trained community environmental leaders who successfully mobilized local populations for advocacy and clean-up campaigns. This experience underscores the significance of participatory leadership and local knowledge as key drivers of environmental governance and social change [126]. Beyond community practices, the integration of digital tools has expanded the scope of environmental education. A recent study on ICT integration proposed models that emphasize collaboration and tailored interventions, showing how technology can enhance engagement and bridge educational gaps [127]. Complementing these findings, a systematic review on civic engagement outcomes concluded that community-based and participatory approaches significantly enhance civic skills, resilience, and social capital [128].

Thus, territorialized and community-oriented environmental education is crucial for fostering sustainable practices and enriching learning experiences. By combining local knowledge, participatory leadership, and technological innovation, this approach not only addresses the unique challenges faced by vulnerable communities but also contributes to broader environmental sustainability goals. Such perspectives reinforce the need for adaptable and context-sensitive educational models, a concern that this study addresses by comparing initiatives at different academic levels.

2.4. Active Methodologies in STEM and Sustainability Education

Active methodologies have gained growing relevance in STEM and sustainability education over the past decade, as they promote student engagement and enhance learning outcomes. Approaches such as project-based learning, challenge-based learning, flipped classrooms, and gamification foster critical skills, including problem-solving, creativity, and collaboration [26,43,89,112,129–139].

Empirical evidence supports their effectiveness in improving academic performance and knowledge retention, while also revealing challenges related to resistance from educators and students [140]. The integration of technology has further expanded their potential, creating more dynamic learning environments that encourage personalization and collaboration [141]. Successful implementation, however, requires not only pedagogical innovation but also adequate teacher training and institutional support [71]. These conditions are essential to prepare students for the complex sustainability challenges of contemporary society.

The literature, therefore, reflects a broader trend toward inclusive and participatory practices, reinforcing the alignment between active methodologies and the goals of sustainability education [142]. In summary, these approaches are vital for equipping learners with both technical and transversal competencies, enabling them to address global issues through collaborative and experiential learning. Table 2 outlines the main active learning methodologies, supported by illustrative case studies and references.

Table 2. Active learning methodologies, along with case study examples and supporting literature references.

Active Methodology	Description	Case Studies	Source
Project-Based Learning	A student-centered pedagogy that involves students working on real-world projects to gain knowledge and skills.	1. Teaching Robotic Concepts: Students learn industrial automation by working on a real project with a partner company, enhancing engagement and practical skills.	[143]
		2. Computer-Aided Design (CAD)/Computer-Aided Engineering (CAE) Tools in Mechanical Engineering: Students used integrated design software to solve industrial design problems, enhancing their practical skills.	[144]
		3. Project-Based Learning in Mechatronics: Students improved technical competence and problem-solving skills through PBL in engineering courses.	[145]
Flipped Classroom	An instructional strategy where students learn content at home and engage in activities in class.	1. Heat Transfer Course: A flipped classroom model improved student engagement and performance in a core mechanical engineering course.	[146]
		2. Flipped Classroom in ICT Engineering: A personalized model enhanced student learning and engagement in Information and Communication Technology courses.	[147]
		3. Flipped Classroom in Mechanical Engineering: Students reported better learning experiences and performance compared to traditional lecture formats.	[148]
Maker Spaces	Collaborative spaces where students can create, innovate, and learn through hands-on engineering projects.	1. University Maker Space Impact: A study showed that access to a maker space significantly improved students' confidence and motivation in engineering design.	[149]
		2. Innovative Projects in Maker Spaces: Students engaged in interdisciplinary projects, winning awards in national competitions through their maker space activities.	[150]
		3. Maker Spaces in Engineering Education: The establishment of maker spaces at various universities has fostered creativity and innovation among engineering students.	[151]
Problem-Based Learning	An instructional method where students learn through the exploration of complex, real-world engineering problems.	1. Aerospace Engineering at MIT: Students engaged in hands-on projects, designing and building aircraft, enhancing their problem-solving and teamwork skills.	[152]
		2. PBL in Software Engineering: This approach helped students develop essential soft skills while tackling real-world problems in a collaborative environment.	[153]
		3. PBL in Digital Fabrication: Middle school students used PBL in FabLabs to solve design challenges, enhancing their engineering skills and teamwork.	[154]
Challenge-Based Learning	A collaborative learning approach that engages students in solving real-world engineering challenges.	1. Sustainable Development Goals in Engineering: Students worked on projects addressing SDG 11, enhancing their problem-solving and teamwork skills.	[155]
		2. Industry Collaboration in Electronics Engineering: Students partnered with industry to develop technological solutions, improving their engagement and learning outcomes.	[156]
		3. CBL in Industrial Engineering: Students tackled real-life challenges, integrating technology and user experience analysis in their projects.	[157]

2.5. Challenges in Multilevel Educational Implementation (K-12 vs. Higher Education)

Implementing educational initiatives across K–12 and higher education presents persistent challenges rooted in cultural, policy, and pedagogical differences. A cultural divide often generates misaligned expectations and practices, complicating collaboration and disrupting curricular continuity between the two stages [158]. Policy frameworks also

diverge: K–12 systems emphasize standardized testing and compliance, whereas higher education prioritizes critical thinking, research skills, and academic autonomy [159]. These contrasting goals make it difficult to create coherent learning experiences for students transitioning between levels.

Structural and resource disparities add further complexity. K–12 institutions frequently lack the funding and infrastructure required to adopt innovative practices that are more feasible in higher education settings, limiting alignment and scalability [160]. Initiatives such as dual enrollment programs have sought to bridge this gap; however, inconsistent policies and administrative fragmentation often yield uneven results [161]. The historical separation between these systems has thus entrenched barriers that hinder sustained collaboration.

Addressing these multifaceted challenges requires coordinated efforts to align goals, harmonize policies, and ensure equitable distribution of resources. More importantly, they underscore the value of comparative studies: analyzing both K–12 and higher education contexts makes it possible to identify not only differences but also transferable strategies for embedding sustainability competencies. This perspective frames the rationale for the present study, which examines initiatives at both educational levels to highlight commonalities, divergences, and implications for scaling active methodologies in sustainability education.

2.6. Industry 4.0 and 5.0 Tools in Educational Settings

The literature on Industry 4.0 emphasizes the transformative impact of digital technologies, including cyber-physical systems, the Internet of Things (IoT), and big data, on teaching and learning. These tools are reshaping educational paradigms by promoting principles like interoperability, real-time data access, and modularity within academic frameworks [52,137,162–164]. A key focus has been the integration of Industry 4.0 with Education 4.0, emphasizing curricula that embed digital skills and competencies aligned with the demands of the labor market. Such integration is viewed as essential for preparing students for emerging job roles and ensuring adaptability in dynamic industrial environments [164,165].

Despite these opportunities, several barriers persist, including limited institutional digital culture and insufficient teacher training. Research emphasizes the importance of further investigating how digital literacy can be effectively integrated with pedagogical innovation, which is crucial for implementing Industry 4.0 tools in education [166,167]. Looking forward, the challenge lies in developing methodologies that fully leverage these technologies to keep education agile and responsive to rapid industrial change [168].

Industry 5.0 builds on these foundations but shifts the emphasis toward sustainability, resilience, and human-centered innovation [169]. It is expected to gain prominence as climate change and geopolitical challenges demand new approaches [170,171]. Although infrastructure and resource constraints pose difficulties, particularly in regions such as Latin America, Industry 5.0 offers opportunities to reduce digital exclusion and foster educational and industrial innovation [172,173]. Its transition underscores the importance of collaboration between universities and industries to cultivate graduates with both technological and human-centered competencies [174,175]. Universities, in particular, are positioned to align education and research with societal needs, advancing sustainable and inclusive innovation.

Universities play a crucial role in advancing toward Industry 5.0 by aligning education and research with societal needs [176,177] and fostering close collaboration with industry [178] to promote more human-centered and sustainable innovation [179].

Industry 5.0 requires engineers to develop digital, ethical, and technical competencies, such as data science and lean thinking, to adapt to the new industrial landscape [176,180–182]. This evolution requires combining technical knowledge with transversal skills and a human-centered approach to achieve sustainable development [177] and the effective integration of technologies such as artificial intelligence [183]. Industry 5.0 also emphasizes the importance of lifelong learning, digital skills, and resilience in adapting to technological changes and the modern work environment [182], particularly following the acceleration of online learning due to the COVID-19 pandemic [184].

In summary, the integration of Industry 4.0 and 5.0 tools in education represents a vital step toward cultivating a digitally competent and industry-ready workforce that can effectively address the complexities and demands of modern production systems.

3. Materials and Methods

This study employed a qualitative comparative case study design, grounded in a participant-action research framework. The methodological design was developed to address the following research question: how do active learning methodologies, specifically Design Thinking and project-based learning, contribute to the development of sustainability competencies in secondary and tertiary education in Panama, and what common implementation challenges emerge across these contexts?

Both initiatives sought to engage students in practical, creative, and reflective experiences focused on sustainability-related challenges. The design emphasized collaborative learning, critical thinking, and the use of accessible technological tools within broader frameworks of sustainability and innovation. By analyzing both contexts, the study aimed to capture similarities, divergences, and transferable lessons across educational levels.

Methodological triangulation was applied through the combination of multiple data sources and methods. Evidence was collected from teacher logs, structured classroom observations, reflective accounts, and student-produced deliverables. These complementary perspectives enabled a richer understanding of how active methodologies were implemented and how they supported the development of sustainability-oriented competencies. Thematic analysis was conducted in two steps. First, the competencies targeted by each activity were explicitly identified, providing an initial set of deductive categories. Second, evidence collected from classroom documentation, facilitator notes, and student outputs was coded against these categories, while allowing additional inductive codes to emerge from the data. This combination of deductive and inductive coding cycles ensured that the analysis was both theoretically grounded and open to context-specific insights.

All interventions were implemented in alignment with the institutional protocols of the participating universities and schools. Participation was voluntary, and informed consent was obtained from all adult participants. In the case of minors, parental authorization was secured prior to their involvement, with explicit information about all activities. These procedures complied with the requirements established for educational research of the supporting institutions.

This section outlines the specific methods used across both initiatives, including the technical and digital resources that supported the activities, the design and rollout of learning sequences at each educational level, participant selection criteria, and the documentation strategies used to trace learning progress. Overall, these efforts were geared toward creating meaningful, student-centered experiences that directly connect to real-world sustainability issues.

Thematic analysis was applied, allowing categories to emerge inductively from the data and to be systematically refined into broader themes. This process ensured both rigor and coherence in the interpretation of findings and provided the basis for identifying the

key themes regarding the development of sustainability competencies, which are presented in the following section.

3.1. Active Methodologies

To foster student autonomy, critical thinking, and meaningful engagement with sustainability challenges, a comprehensive set of active learning methodologies was implemented. These approaches moved beyond traditional lecture-based instruction, promoting collaborative, hands-on, and reflective learning experiences across both educational levels. The strategies included:

- Flipped classroom: Core concepts were delivered via instructional videos and assigned readings on the university's Learning Management System (LMS), ecampus (Moodle 3.0), enabling students to explore content before class and use in-person time for practical, team-based application of knowledge.
- Mirror classroom: Synchronous, technology-supported sessions allowed remote participation across campuses. Real-time collaboration, content sharing, and project documentation were facilitated through tools such as Microsoft Teams version 25227.205.3936.6644, supporting joint workshops without requiring co-location.
- Project-based learning (PBL): Interdisciplinary teams designed and prototyped solutions for real or simulated sustainability problems, integrating technical and contextual knowledge.
- Problem-based learning: Learners addressed open-ended questions to develop problem-solving and critical thinking skills grounded in real-world complexity.
- Challenge-based learning (CBL): Students tackled locally relevant sustainability challenges through inquiry, co-investigation, and action-oriented project development.
- Design Thinking: A human-centered, iterative process guided students through Empathize, Define, Ideate, Prototype, and Test, encouraging empathy, creativity, and continuous refinement of ideas.
- Agile methodologies: Progress was organized through sprint-based reviews and collaborative feedback loops to promote adaptability, iteration, and continuous improvement.
- Co-creation and participatory design: Students and educators collaborated as partners in solution development, reinforcing ownership, agency, and contextual relevance.
- Maker-centered learning: Hands-on experimentation using digital fabrication tools, such as 3D printers (Creality and Bambulab from Shenzhen, China), recycled materials, and electronics like Arduino, supported creativity, systems thinking, and technical skill development.
- Service learning: Selected projects integrated community needs to enhance civic engagement and the social relevance of the learning experience.
- Experiential learning and reflective practice: Direct experience was followed by structured reflection to consolidate learning through feedback, iteration, and self-awareness.
- Peer learning: Structured peer interviews, team-based ideation, and peer-to-peer feedback were employed to foster shared learning, effective communication, and mutual support.

Together, these methodologies created participatory environments that encouraged creativity, responsibility, and the development of sustainability-oriented competencies, providing a common pedagogical thread across secondary and higher education contexts.

3.2. Tools and Technologies Used

The implementation of the program integrated a diverse set of tools aligned with Industry 4.0 and 5.0 principles, emphasizing human-centered innovation, collaboration, and

sustainability. These tools included both digital platforms that supported content delivery and teamwork, as well as physical resources that enabled prototyping and experimentation.

Digital platforms played a central role in facilitating flexible and interactive learning. The LMS was used to host pre-class instructional videos and assigned readings, allowing students to prepare independently before active sessions. Microsoft Teams complemented this structure by enabling synchronous collaboration across campuses, supporting real-time discussions, group work, and feedback. Additionally, online visualization and co-creation platforms, such as Miro and Canva, provided dynamic spaces for brainstorming, concept mapping, conceptual design, and the iterative refinement of ideas.

Practical experimentation was made possible through access to a variety of technical tools and laboratory resources. CAD and CAE software, such as Autodesk Fusion 360 version 2601.0.90 x86_64, the former version of Autodesk Fusion, allowed students to design, simulate, and test solutions in virtual environments. These designs were subsequently realized through 3D printing, with an emphasis on utilizing recycled materials to connect innovation with sustainability principles. Arduino-based electronics and related components further supported hands-on experimentation, enabling students to integrate basic automation and sensor systems into their prototypes. Access to fabrication laboratories expanded opportunities for technical skill development and encouraged interdisciplinary project work.

By combining digital platforms with technical tools, the program fostered experiential and interdisciplinary learning environments. This integration strengthened students' technical proficiency while also cultivating sustainability-oriented competencies, effectively bridging digital innovation with human-centered and environmentally conscious practices.

3.3. Sources of Data and Documentation

The implementation process was documented through multiple qualitative sources, allowing for a comprehensive understanding of both pedagogical execution and student engagement. Teacher logs and facilitation journals captured methodological decisions, instructional adaptations, and reflections on classroom dynamics. Learning materials and student-produced deliverables, including worksheets, diagrams, prototypes, and digital files, provided tangible evidence of conceptual development and creative output. Direct classroom observations further enriched the dataset by focusing on student participation, collaboration, and problem-solving behaviors during hands-on sessions and group activities. Additionally, open feedback sessions provided valuable insights into students' learning experiences, motivations, and perceived challenges.

Together, these complementary sources ensured a triangulated perspective that supported iterative improvement of the program and enabled a robust qualitative evaluation of its educational impact.

3.4. Type of Study

This is a qualitative–descriptive study, based on the practical implementation of active methodologies at two educational levels, secondary school and university, to foster sustainability competencies using the Design Thinking approach, active methodologies, and tools from Industry 4.0/5.0.

3.5. Implementation Scenarios

3.5.1. Higher Education Level, Case A

This intervention was conducted with final-year Industrial Engineering students at the Technological University of Panama, across three campuses (Panama City, Azuero, and Chiriquí). The objective was to foster interdisciplinary competencies related to sustainable design, production systems, and project planning by applying active methodologies in

a hybrid learning environment through the development of a didactic module rooted in sustainable engineering principles. The module on Sustainable Project Planning (MPPS) emphasized collaborative learning, practical application, and student-centered design.

The implementation spanned one academic semester, comprising weekly theoretical and practical sessions, and concluded with a one-week intensive workshop between semesters. Participants were selected from a pool of applicants based on their availability, academic background, and motivation to participate. Efforts were made to ensure a representative sample from the three campuses.

- **Module Design and Structure**

The module was structured into three interrelated components: (1) practical sessions, (2) creative sessions, and (3) a production workshop. The practical and creative sessions ran in parallel during the academic semester, while the workshop was conducted as an intensive block during the inter-semester period. To reduce reliance on traditional lectures and promote student autonomy, two pedagogical approaches were adopted: the flipped classroom and the mirror classroom. In the flipped classroom, students alternated between self-guided online study and collaborative group work across four key thematic areas—Sustainable Design, Quality Management, Project Planning, and Production Systems. The mirror classroom enabled real-time, face-to-face interaction via video conferencing technology, allowing professors to remain on different campuses while maintaining direct engagement with students. All course content and recorded sessions were made available through the university's learning platform.

Prior to implementing the module, a curricular analysis of the Industrial Engineering Bachelor's program was conducted to identify the foundational knowledge and tools students would need for the module. The courses identified as relevant included Project Management, Work Studies, Production Planning, Quality Management I and II, and Manufacturing Processes. To further align the module content with student and faculty experience, structured questionnaires were developed for each course and administered to final-year students and lecturers who had taught the courses in the past four years. The questionnaires were distributed via email and publicized in classrooms. Each questionnaire included sections on respondent profile, content/tool coverage, and explanations for any content not addressed during the course. The data informed the design of the module's subject content.

The structure of the module followed a progression of five thematic areas, each designed to build core competencies aligned with sustainability and digital manufacturing: quality management for production systems, project planning, production sustainability, and production planning. The Sustainable Design subject was developed in collaboration with a partner professor from the Rochester Institute of Technology.

- **Participant Selection and Training**

A total of eight final-year students were selected through an application and interview process. Eligibility criteria included enrollment in the final semester and successful completion of the core prerequisite courses. Participants engaged in preparatory online lectures and accessed all learning materials via the university platform. Practical and creative sessions were conducted both asynchronously and synchronously. Creative sessions, which emphasized sustainable product redesign, were held in a virtual mirror classroom and guided by an expert facilitator. Students were divided into two working groups and tasked with collaboratively developing product designs in response to user-centered sustainability challenges.

- **Project Development and Fabrication**

Following the training period, students worked in groups of four to conceptualize and design a sustainable solution for a specific user scenario. They applied qualitative and quantitative tools in a systematic manner and participated in iterative “agile” review meetings where instructors provided targeted feedback. Each team was required to prepare a CAD model of their proposed solution in advance of the production workshop.

The workshop was held as a one-week intensive session, during which students developed physical prototypes using recycled High-Density Polyethylene (HDPE). The production process was divided into five stations: (1) sorting and crushing, (2) washing and drying, (3) filament extrusion, (4) 3D printing, and (5) post-processing. With the support of faculty and design experts, students configured machinery and extrusion settings to produce usable HDPE filament, successfully fabricating their prototypes.

- **Implementation Structure and Schedule**

A timetable was established based on the instructor’s availability and the course sequencing. Teaching methods included flipped classroom and mirror classroom approaches to maximize engagement and flexibility. Instructors conducted knowledge quizzes, diagnostic assessments, and conversational evaluations throughout the module.

Key milestones were set, and students participated in both synchronous and asynchronous learning activities. A kickoff meeting was held with the research team to coordinate responsibilities, assign facilitators, and finalize logistics.

This approach enabled students from different campuses to collaborate remotely in real time. Instructors facilitated workshops across sites using video conferencing and collaborative tools, such as Teams, to support joint learning without requiring physical presence.

Design Thinking Phases in Practice

The product development process followed the five phases of Design Thinking:

- **Empathize:** Students conducted peer interviews and developed empathy maps to identify user needs within their communities.
- **Define:** Insights were synthesized into “*How Might We*” questions, supported by tools such as root cause analysis to explore underlying systemic issues.
- **Ideate:** Engaged in structured brainstorming using Post-its, affinity diagrams, and divergent thinking to generate solution concepts.
- **Prototype:** Created low-fidelity and digital prototypes using the Autodesk Fusion 360 CAD suite and basic materials. Practiced filament extrusion from HDPE waste and utilized 3D printers.
- **Test:** Prototypes were presented to peers and faculty for critique. Students incorporated feedback and iterated through their designs to improve technical feasibility, usability, and alignment with user needs.
- **Technical Setup and Fabrication Labs**

A dedicated lab was established in the Chiriquí campus for hands-on sessions. The equipment included shredders, extruders for making filaments from recycled HDPE from Felfil Evo (Turín, Italy), 3D printers, and CAD-enabled laptops. Students explored Thingiverse and similar repositories to adapt and remix open-source models. CAD instruction was followed by slicing, G-code generation, and troubleshooting for 3D printing.

- **Final Workshop and Prototyping Challenge**

Students worked in teams designing and fabricating sustainable solutions for specific user groups. Each group produced a CAD model, manufactured their prototype using HDPE filament, and iterated based on real-world constraints. The production workflow included sorting and cleaning recycled materials, filament extrusion, slicing, and printing.

An expert-led colloquium concluded the program, during which participants presented their final products and received technical and conceptual feedback. This hands-on experience reinforced the connection between sustainability, engineering design, and digital fabrication. Figure 1 depicts the methodological flow of the university-level intervention, highlighting how hybrid pedagogy, digital fabrication, and Design Thinking were integrated to develop sustainability competencies.

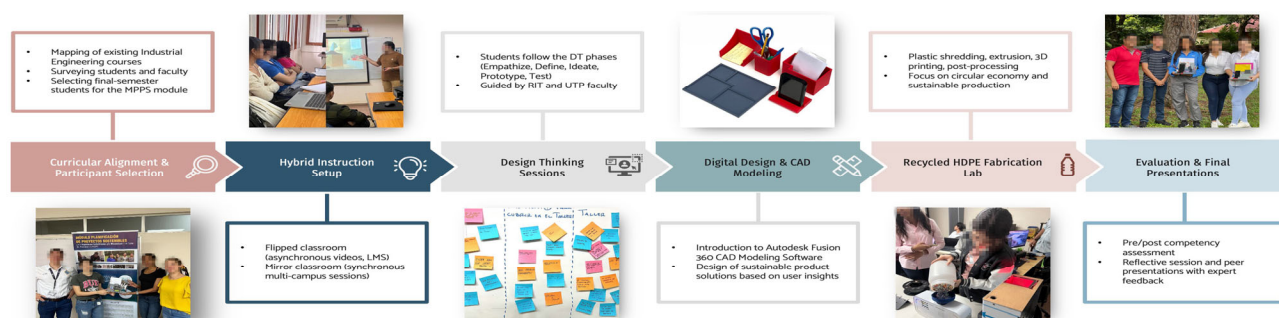


Figure 1. Methodological flow of the university-level intervention (MPPS), illustrating hybrid pedagogy, digital fabrication, and Design Thinking in the development of sustainability competences, Sequence of the module structure and student activities. Stages include: Curricular Alignment & Participant Selection (mapping Industrial Engineering courses and surveying students/faculty), Hybrid Instruction Setup (flipped and mirror classrooms using asynchronous and synchronous sessions), Design Thinking Sessions (students follow Empathize, Define, Ideate, Prototype, and Test phases; sticky notes show brainstorming prompts in Spanish, e.g., “¿Cómo se te ocurre...?” = How do you come up with...?, “Involucrar a los Tutores” = Involve the Tutors), Digital Design & CAD Modeling (use of Autodesk Fusion 360 for sustainable product solutions), Recycled HDPE Fabrication Lab (plastic shredding, extrusion, 3D printing, and post-processing for circular economy applications), and Evaluation & Final Presentations (competency assessments, reflection, and peer/expert feedback).

3.5.2. Secondary Education Level, Case B

The intervention at the secondary education level was conducted in two public schools located in Panama Oeste. The initiative aimed to foster sustainability and innovation competencies, as well as student engagement through hands-on innovation, low-cost prototyping, and creative problem-solving. The pedagogical framework was rooted in project-based learning and challenge-based learning, with an emphasis on Design Thinking as the overarching methodological approach.

The implementation spanned a full academic year, during which some active periods occurred, and involved weekly or biweekly sessions adapted to each school’s schedule. Students were selected by their teachers based on availability, motivation, and commitment to long-term participation. Efforts were made to ensure gender balance among participants. The program was organized into thematic modules that progressively introduced sustainability concepts, scientific and technical literacy, and DT practices.

Each school followed a similar sequence of thematic modules:

- **Sustainability and SDGs:** Here, students explored the UN Sustainable Development Goals to identify local problems and connect them with global sustainability challenges.
- **Innovation and Ideation:** Through structured brainstorming, students generated context-aware solutions.
- **Introduction to Scientific and Technical Literacy:** Participants were introduced to the scientific literature and trained in basic research and information sourcing, including popular scientific databases.

- Design Thinking: Once foundational competencies were established, students applied the five stages of Design Thinking (Empathize, Define, Ideate, Prototype, and Test) to co-develop solutions. Through a series of dedicated sessions. Each stage was explored in a separate class, combining conceptual understanding with hands-on exercises tailored to their school context.
 - In the Empathize phase, students conduct peer-to-peer interviews to explore real problems faced by their classmates in their school or community environment. These dialogues were supported by empathy maps and active listening exercises, allowing participants to identify emotional and practical needs from a first-person perspective. The activity helped students build awareness of diverse experiences and deepen their understanding of environmental and social issues.
 - During the Define session, participants synthesized their findings into clear and focused problem statements using tools such as point-of-view (POV) frameworks and How Might We questions. In addition to these scaffolding tools, students were guided through exercises aimed at identifying the root causes of the problems uncovered during the Empathize phase. Through techniques such as the “Five Whys” and causal mapping, they learned to distinguish between symptoms and underlying issues. This process emphasized the importance of not jumping to solutions prematurely, helping students recognize that misidentifying a problem often leads to misguided or ineffective interventions. By grounding their problem definitions in both user needs and systemic understanding, students were better equipped to formulate meaningful and contextually relevant design challenges, particularly those related to the sustainability issues observed in their school or community.
 - In the Ideate phase, students participated in structured brainstorming sessions where they were encouraged to generate a wide range of creative responses to the problem statements defined earlier. Using Post-it notes and visual boards, they externalized individual ideas before engaging in group discussions to cluster, connect, and prioritize proposals. Facilitators guided students through divergent thinking exercises, emphasizing quantity over perfection and suspending judgment during the early stages of idea generation. Diagramming techniques such as idea mapping and affinity grouping were used to identify common themes and organize potential directions for prototyping. A key principle during this phase was that no idea would be excluded, regardless of how simple, unconventional, or unrealistic it might initially seem, to foster an open and creative environment. This encouraged students to express themselves freely, take intellectual risks, and collaboratively explore a broad spectrum of solutions to sustainability-related challenges.
 - In the Prototype stage, students translated their selected ideas into tangible, low-fidelity models using recycled materials, cardboard, paper, and basic electronics. The goal was to quickly explore form, function, and usability. To strengthen their understanding of how ideas could transition from concepts to real-world applications, students also participated in a dedicated module on digital design and fabrication, which introduced core concepts of CAD, Computer-Aided Manufacturing (CAM), and Computer-Aided Engineering (CAE). In this module, students learned about both additive and subtractive manufacturing techniques, including 3D printing, laser cutting, and CNC machining. The prototyping process thus became not only a creative exercise but also a gateway to developing technical and digital fabrication skills relevant to sustainable innovation.

- Finally, the Test phase involved presenting prototypes to peers, teachers, and facilitators for feedback. Students were guided through feedback loops and encouraged to reflect on user needs, iterating their designs accordingly.

This structured and experiential approach allowed students to internalize each stage of Design Thinking while progressively building confidence in their ability to tackle sustainability challenges through creative, user-centered design.

- CAD–CAM–CAE: To deepen technical competencies, students participated in a specific module on digital design and manufacturing, facilitated through the school-based “Laboratorio de Ideas e Innovación.” They were introduced to open repositories, such as Thingiverse, Printables, Cults3D, MakerWorld, Yeggi, Thangs, and Instructables, among others, as entry points to analyze and adapt existing 3D models. They were then guided in creating their own designs using CAD software, including Tinkercad (<https://www.tinkercad.com/>) and Autodesk Fusion (v.2.0.18477). Subsequent CAM sessions included slicing workflows for 3D printing and an introduction to G-code configuration. Beyond additive manufacturing, students were introduced to subtractive methods, including CNC machining, through simulations and demonstrations. This module emphasized the relationship between materials, geometry, and process selection, reinforcing principles of design for manufacturing and sustainability.

Through this progression, students developed functional and conceptual prototypes while gaining foundational competencies in digital design, systems thinking, and production processes. To support implementation, each school received educational materials and equipment, including laptops, 3D printers, and consumables. The methodological design was co-developed with participating teachers, and students were supported by university-level engineering students serving as mentors and technical facilitators.

Observations from facilitators and participants revealed strong engagement, increased awareness of sustainability challenges, and evidence of creativity and collaboration throughout the prototyping process. Figure 2 illustrates the methodological flow of the secondary-level intervention, which integrates Design Thinking with active learning modules to foster student engagement and sustainability competencies.



Figure 2. Methodological flow of the secondary-level intervention integrating Design Thinking and active learning modules, Learning framework for design-based education integrating sustainability and technical literacy. The stages include: Sustainability and SDGs (students explore UN Sustainable Development Goals and local challenges, e.g., “Ejemplos de problemas: Playa Chiquita” = Problem examples: Playa Chiquita, where the * stands for some industries in the European contexts), Innovation and Ideation (structured brainstorming activities; exposure to real-world problem-solving; “Economía

Lineal vs. Economía Circular” = Linear Economy vs. Circular Economy), Scientific and Technical Literacy (students build critical thinking skills for evidence-based design), Design Thinking Cycle (students advance through Empathize, Define, Ideate, Prototype, and Test phases, building low-fidelity prototypes and refining them through peer feedback), Digital Design and Fabrication (application of CAD, CAM, and CAE in sustainable additive and subtractive manufacturing), and Implementation and Reflection.

4. Results and Analysis

This section presents the outcomes of the two educational case studies: one implemented at the university level and the other in secondary schools. It highlights how active learning strategies, combined with sustainability-focused content and hands-on digital fabrication, shaped students’ skill development, creativity, and engagement. The results are organized by key competencies, including systems thinking, interdisciplinary collaboration, and critical reflection, illustrating how each group progressed through the learning process. To preserve analytic coherence across both interventions, results are reported in aggregated form and supported by multiple complementary sources of evidence (teacher logs, structured classroom observations, reflective activities, and student-produced artifacts). This integrated approach emphasizes patterns and educational implications rather than isolated indicators. These materials provided an independent basis for subsequent analysis, allowing conclusions to be drawn from verifiable evidence rather than from the facilitation process itself. The patterns reported here were consistently derived from triangulated documentation and student outputs, ensuring reliability across contexts. Special attention is given to how students applied design thinking, worked with recycled materials, and used digital tools to develop innovative, real-world solutions. This section also discusses common implementation challenges and outlines lessons learned that can inform future educational programs.

4.1. Outcomes from the University-Level Initiative (Case A)

The implemented module for sustainable project management aimed to enhance the understanding of product development methodologies among Industrial and Mechanical Engineering bachelor’s students, enabling them to create customer-oriented products through additive manufacturing. These products were developed with filaments produced from recycled plastic materials (HDPE), following the principles of the circular economy.

A total of eight students participated in the module, divided into two groups. They were guided by seven professors, who not only taught the sessions but also contributed to evaluating the students’ work. Attendance was consistently strong, averaging 77.3%.

4.1.1. Active Methodologies Implemented

The university initiative employed a hybrid learning model combining Project-Based Learning (PjBL), Design Thinking (DT), and agile methodologies. Key strategies included the following:

- **Flipped and Mirror Classrooms:** Students engaged in self-guided online learning followed by collaborative, real-time sessions across campuses, fostering interdisciplinary teamwork.
- **Hands-On Prototyping:** Teams developed sustainable products using recycled HDPE and digital fabrication tools (CAD/CAM, 3D printing), aligning with principles of the circular economy.
- **Iterative Design Cycles:** The DT framework (Empathize, Define, Ideate, Prototype, and Test) guided students through user-centered problem-solving, reinforced by sprint-based feedback loops.

4.1.2. Skills Developed

Students demonstrated proficiency in integrating circular economy principles into product design, such as repurposing waste materials into functional prototypes. Through this module, the following sustainability competencies were developed:

- **Systemic Thinking:** The ability to identify and understand interactions between systems and people in diverse contexts, as well as to anticipate problems in relation to sustainability. Table 3 presents the various activities carried out to foster the development of this competency.
- **Integrated Problem-Solving:** The ability to address complex sustainability issues and develop viable and equitable solutions that promote sustainable development, considering various dimensions and needs. The various activities implemented to promote the development of this competency are detailed in Table 4.
- **Interdisciplinary Collaboration:** The ability to effectively collaborate in interdisciplinary teams, respecting the opinions and needs of other members, managing conflicts, and promoting participation in problem-solving. Table 5 presents the various activities carried out to encourage the development of this competency.
- **Normative Expertise:** The ability to understand and reflect on the norms and values that guide actions, as well as negotiate sustainability values and principles in situations of conflicting interests. The various activities implemented to cultivate the development of this competency are summarized in Table 6.
- **Self-Awareness:** The ability to reflect on one's own role in the community and society, evaluating actions and personal emotions related to sustainability. Table 7 presents the various activities undertaken to promote the development of this competency.
- **Strategic Thinking:** The ability to develop and implement innovative actions to promote sustainability in response to environmental and social challenges. The various activities undertaken to promote the development of this competency are outlined in Table 8.
- **Impact Assessment/Forecasting:** The ability to understand various possible futures, apply the precautionary principle, and assess consequences and risks. Table 9 highlights the various activities carried out to promote the development of this competency.
- **Critical Thinking:** The ability to question norms, practices, and opinions in the context of sustainability, reflect on personal values, and take an informed stance in sustainability discourse. The various activities performed to promote the development of this competency are presented in Table 10.
- **Technical Skills:** Mastery of CAD software, such as Fusion 360, 3D printing, and HDPE filament extrusion enabled students to translate theoretical knowledge into tangible solutions.
- **Soft Skills:** Peer evaluations highlighted growth in collaboration, critical thinking, and adaptability, particularly during iterative design reviews and cross-campus teamwork.

Table 3. Systemic thinking competency acquired within the MPPS Case Study.

Evidence	Activity	Competency Link
Sustainability Review and Stakeholder Mapping (Initial Phase of the Module)	Students conducted an initial assessment of local plastic waste streams, identifying sources (e.g., households, university), flow patterns, and stakeholders involved (e.g., waste collectors, recyclers, campus management).	This activity fostered an understanding of the interactions between social, environmental, and economic systems in the local context. Students had to map relationships between actors and anticipate where system failures (e.g., lack of collection, contamination) would hinder recycling efforts.

Table 3. *Cont.*

Evidence	Activity	Competency Link
Design of Sustainable Products Using Recycled HDPE	Students designed prototypes using HDPE waste collected and processed in the university lab. The design phase required students to consider the environmental impacts of product life cycles, user needs, and material limitations.	This process developed systemic thinking by requiring learners to anticipate how design choices would interact with sustainability goals, user behavior, and production constraints. It encouraged thinking across the entire value chain, from material sourcing to end-of-life disposal.
Simulation of a Circular Startup Model	In teams, students simulated running a startup focused on sustainable production. They had to align design, production planning, quality assurance, and communication strategies with circular economy principles.	Through this simulation, students examined the interdependence of technical processes (e.g., additive manufacturing), business decisions (e.g., pricing and market positioning), and sustainability outcomes (e.g., waste reduction).
Presentation and Peer Feedback on Sustainability Strategies	Students presented their prototypes and sustainability strategies to peers and faculty for critique and iterative refinement.	This reflective practice encouraged learners to reconsider how their projects interacted with broader systems (e.g., user acceptance, social impact, resource availability), promoting deeper awareness of system-level dynamics and emergent issues.

Table 4. Integrated problem-solving competency acquired within the MPPS Case Study.

Evidence	Activity	Competency Link
Problem Framing and Challenge Definition	Students began the module by identifying sustainability-related challenges associated with plastic waste on campus. They analyzed the social, environmental, and operational aspects of local HDPE disposal.	This activity promoted integrated problem-solving by requiring students to frame sustainability issues as multifaceted problems, considering environmental pollution, user behavior, institutional constraints, and community impact.
Prototyping Functional Products Using Recycled HDPE	Teams designed and fabricated functional objects (e.g., office supplies) from HDPE waste using additive manufacturing. They had to ensure usability, material efficiency, and product relevance to real users.	This task engaged students in developing viable and context-sensitive solutions, balancing technical feasibility (e.g., 3D printing settings and material performance).
Iterative Design Reviews and Multi-Stakeholder Feedback	Students followed agile methodologies for the development and presented initial prototypes to peers, instructors, and potential users (e.g., professional or office staff), then iterated based on feedback regarding functionality, aesthetics, and user needs.	This activity cultivated integrated problem-solving by prompting students to revise solutions based on input from multiple perspectives, ensuring the final product aligned with diverse stakeholder expectations and sustainability goals. Additionally, students applied organizational skills by following Agile methodologies, which facilitated structured planning, iteration, and collaboration.

Table 5. Interdisciplinary collaboration competency acquired within the MPPS Case Study.

Evidence	Activity	Competency Link
Co-Design of Sustainable Product	Teams collaboratively designed 3D-printable products. The design process involved balancing environmental, ergonomic, aesthetic, and functional considerations as well as customer-specific requirements.	This task required the negotiation of ideas, division of roles, and consensus-building, fostering an environment where students practiced inclusive decision-making and learned to integrate multiple viewpoints to solve a shared problem using structured customer requirement analysis methodologies.
Conflict Management during Iteration and Testing	During prototype testing and refinement, teams encountered challenges such as printing errors or disagreements on product features. These moments were intentionally used as learning opportunities.	Students had to manage interpersonal tensions, reassign tasks, and mediate technical disagreements to move forward collaboratively. This cultivated emotional intelligence, active listening, and constructive conflict resolution.
Final Presentations	Teams delivered a final presentation of their prototype to peers and instructors.	These sessions strengthened communication skills. Teams had to collectively justify their design and respond thoughtfully to external viewpoints, reinforcing shared accountability and mutual respect.

Table 6. Normative expertise competency acquired within the MPPS Case Study.

Evidence	Activity	Competency Link
Stakeholder Analysis in Prototype Development	During product design, students had to consider the needs and preferences of end users (e.g., university staff or students). They elaborated detailed customer requirement analysis to identify the specific needs. Focus groups and surveys were also implemented.	This required students to reconcile potentially conflicting interests (e.g., user expectations vs. performance), reflecting on whose needs were prioritized and why, and how to communicate the value of sustainable trade-offs.
Introduction to Circular Economy and Sustainable Design Principles	At the start of the module, students received workshops on circular economy concepts and sustainable design considerations. These sessions emphasized the social and environmental dimensions of sustainability.	This foundational learning prompted students to critically examine the values behind their design choices and reflect on the broader normative frameworks that guide responsible innovation and production.

Table 7. Self-awareness competency acquired within the MPPS Case Study.

Evidence	Activity	Competency Link
Hands-on Experience with Recycled Materials	Students personally participated in collecting, sorting, and shredding HDPE waste to create usable filament for 3D printing.	This tactile process made the consequences of waste visible and personal, helping students connect their actions with environmental impact. Many expressed a change in perspective regarding consumption and plastic use after physically engaging with waste materials.
Emotional Response to Design Challenges and Sustainability Trade-offs	During prototype development, students often encounter frustration with functional or aesthetic constraints.	These moments enabled students to confront their emotional reactions to compromise, thereby deepening their awareness of how values and emotions influence real-world decision-making.

Table 8. Strategic thinking competency acquired within the MPPS Case Study.

Evidence	Activity	Competency Link
Definition of a Sustainable Business Idea within a Simulated Startup Context	Student teams were asked to conceptualize a startup idea based on sustainable principles. They had to define a value proposition and address a real-world environmental or social need (e.g., alternatives to office supplies).	This required learners to strategically align their product development with market needs and feasible technologies, mirroring the type of strategic foresight expected in real initiatives.
Design and Prototyping of Circular Economy-Based Products	Participants designed 3D-printed product prototypes. They had to ensure functionality, aesthetic appeal, and minimal environmental impact.	This hands-on process challenged students to implement innovative solutions, translating strategic thinking into tangible action.

Table 9. Impact assessment/forecasting competency acquired within the MPPS Case Study.

Evidence	Activity	Competency Link
Life Cycle Thinking Discussions	During sessions on sustainable design, students reflected on the potential life cycle of their products, from sourcing to disposal, and considered how their design choices could influence waste generation, durability, and reparability.	This encouraged a future-oriented mindset, fostering the ability to predict the downstream effects of design decisions and apply systems thinking in risk-aware planning.
Risk Mapping	As part of their training, teams were required to conduct a risk mapping exercise, identifying technical, environmental, and social risks associated with product development.	This activity enabled students to assess consequences and potential setbacks, critically thinking through the short- and long-term implications of their project implementation.

Table 10. Critical thinking competency acquired within the MPPS Case Study.

Evidence	Activity	Competency Link
Sustainability Discussion Session	At the beginning of the module, students participated in guided discussions on the environmental impact of plastic use, the ethics of single-use materials, and the trade-offs of recycling versus reducing.	These sessions encouraged students to question common industrial practices, evaluate conflicting sustainability perspectives, and reflect on their own environmental values, resulting in more nuanced and informed positions.
Redesign Challenge of Everyday Objects	Students were tasked with redesigning everyday office items (e.g., pencil holders, organizers) using additive manufacturing. They had to justify their designs in terms of functionality.	This activity required students to challenge design norms and consider life cycles.
Startup Simulation Pitch and Q&A	As part of the simulated startup experience, students presented their prototypes to peers and professors and responded to critical questions about the feasibility of their solutions.	The challenge of defending their ideas pushed students to critically evaluate the strengths and weaknesses of their proposals and to engage in evidence-based reasoning in support of their decisions.
Peer-to-Peer Feedback Exchanges	During project development, student teams reviewed and provided feedback on each other's prototypes and approaches.	This peer evaluation process encouraged constructive critique of ideas and norms, promoting a culture of reflective dialogue.

Figure 3 shows the activities performed to develop the eight previously mentioned competencies.

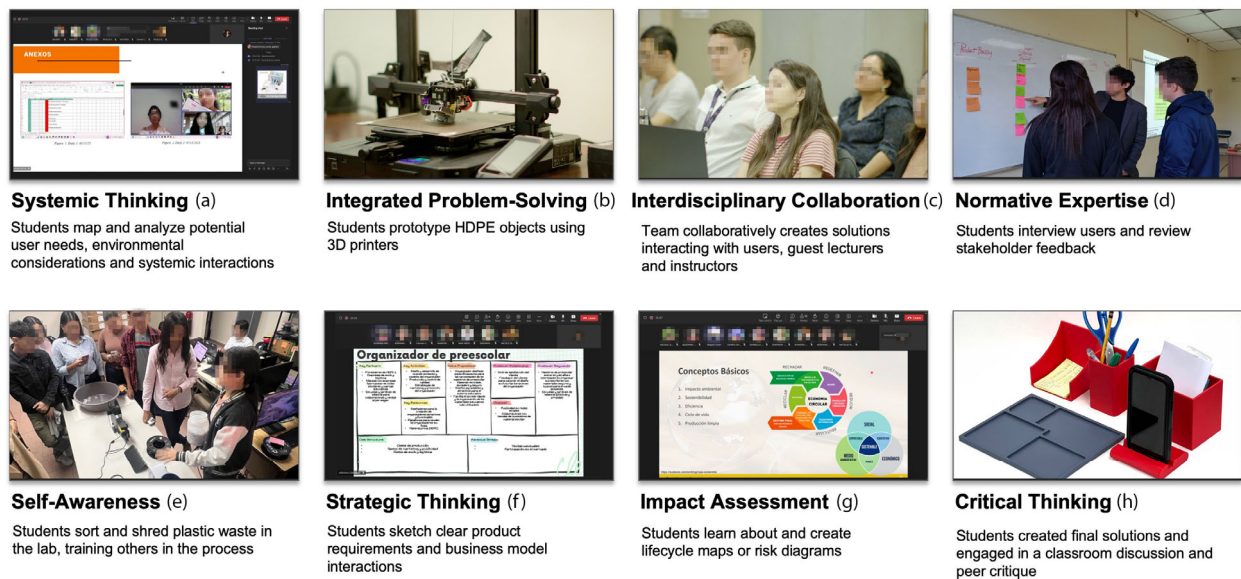


Figure 3. Examples of student learning outcomes. (a) Systemic Thinking—Students map and analyze potential user needs (“Anexos” = Appendices). (b) Integrated Problem-Solving—Students prototype HDPE objects using 3D printers. (c) Interdisciplinary Collaboration—Teams collaboratively create solutions interacting with users, guest lecturers, and instructors. (d) Normative Expertise—Students interview users and review stakeholder feedback. (e) Self-Awareness—Students sort and shred plastic waste in the lab, training others in the process. (f) Strategic Thinking—Students sketch product requirements and business model interactions (“Organizador de preescolar” = Preschool Organizer). (g) Impact Assessment—Students create lifecycle maps or risk diagrams (“Conceptos Básicos” = Basic Concepts, e.g., circular economy, sustainability, efficiency). (h) Critical Thinking—Students create final solutions and engage in classroom discussion and peer critique.

4.1.3. Challenges and Lessons Learned

Among the challenges, one can mention the resource limitations. For instance, uneven access to 3D printers caused delays, while rigid semester timelines occasionally conflicted with the module’s agile workflows. In practical terms, blending flipped/mirror classroom strategies with digital fabrication helped bridge theory and practice for senior engineering students, while also signaling opportunities to more deliberately weave normative and reflective components into technically oriented modules. Practically, aligning agile iteration with fixed academic timetables suggests adopting shorter design sprints, predefined feedback windows, and lightweight documentation to protect hands-on time without compromising curricular pacing.

4.2. Outcomes from the Secondary School Initiatives (Case B)

While the university intervention emphasized advanced competencies in circular economy and entrepreneurship, the secondary school program revealed how similar methodologies can be adapted to an earlier educational stage.

The activities carried out in secondary schools successfully introduced students to sustainability concepts through accessible, hands-on learning experiences. Although prior exposure to design tools and scientific concepts was limited, students showed remarkable creativity, engagement, and adaptability. The secondary program centered on Challenge-Based Learning (CBL) and Design Thinking, adapted for younger learners. Their projects not only addressed real-world challenges but also revealed growing awareness of systems thinking, collaboration, and personal responsibility. The mentoring model, which paired university students with secondary teams, further enriched the experience, demonstrating the value of inter-level collaboration for building sustainability competencies.

A total of 30 students participated in the secondary school initiative, divided into 18 from lower secondary (premedia) and 12 from upper secondary (media). In premedia, students were organized into four teams, each completing the full set of planned activities. In media, the initial plan of four teams was reorganized into three teams to improve collaboration. Both groups were accompanied by four teachers each, who supported classroom dynamics and contributed to the evaluation of student outputs. Attendance remained consistently high, averaging 91.7% in premedia and 85.8% in media, for an overall rate of 89.3%.

The initiative was structured to allow students to progress through the Design Thinking cycle, Empathize, Define, Ideate, Prototype, and Test, while developing foundational skills in CAD/CAM, systems thinking, and reflective practice. Consistent with developmental expectations, abstract constructs aligned with systems thinking and early CAD literacy benefited from explicit scaffolding, chunked activities, accessible tools, and peer mentoring to ensure conceptual accessibility and steady skill progression. As they advanced through these stages, students demonstrated significant growth in the following competency domains and skills:

- **Sustainability Awareness and Systems Thinking:** Through activities such as stakeholder mapping, SDG alignment, and root-cause analysis, students gained the ability to recognize how environmental, social, and technical systems intersect. They were encouraged to frame problems systemically and reflect on the broader implications of their designs. Table 11 highlights the specific activities that contributed to the development of this competency.
- **Sustainability-Driven Technical Decision Making:** Students were consistently required to justify their material choices, prioritize reuse, and evaluate designs based on both technical and environmental feasibility. This process fostered awareness of life cycle thinking and trade-offs, encouraging students to consider the broader implications of their decisions. The competency also extended to team dynamics, as students assumed specific roles, collaborated in prototyping, and engaged in peer review processes that reinforced sustainability principles in collective decision-making. Evidence of this competency is summarized in Table 12.
- **Design and Innovation:** The use of design tools such as “How Might We” statements, ideation maps, and storytelling enhanced students’ creative confidence and ability to generate innovative solutions. Visual tools and prototyping exercises fostered divergent thinking and iterative design processes, promoting a more effective approach to problem-solving. Table 13 provides details of the associated learning experiences.
- **Digital Fabrication and CAD/CAM/CAE:** Students engaged with digital tools such as Tinkercad and slicing software, developing early literacy in 3D modeling and additive manufacturing. They explored online repositories (e.g., Thingiverse, Printables) and prepared simple models for printing using school-based FDM printers. These activities are summarized in Table 14.
- **Creativity and Problem-Solving:** Students generated and refined solutions adapted to real, school-based issues such as waste management, energy use, curricula, and classroom organization. Through structured brainstorming activities, rapid prototyping, and iterative feedback loops, they developed contextually relevant and technically feasible ideas. These creativity and problem-solving competencies were further developed during ideation workshops, visual mapping exercises, and prototyping sessions, processes detailed in the thematic competency tables on design and innovation and sustainability-driven technical decision making.
- **Collaboration and Communication:** Working in interdisciplinary teams, students assumed clearly defined roles and practiced collective decision making in a collaborative

environment. Peer feedback sessions and mentorship by university students further reinforced teamwork, leadership, and oral communication skills. These collaboration and communication abilities were developed throughout the intervention, particularly in group prototyping activities, peer review sessions, and reflective group discussions, as outlined in the competency tables on collaborative problem solving.

- **Strategic Thinking:** Beyond generating solutions, students demonstrated the ability to connect local challenges with global sustainability frameworks, particularly the SDGs. During the early stages of the intervention, they framed design challenges using “How Might We” questions, mapped problems to specific SDG targets, and reflected on the broader societal implications of their work. This promoted a long-term, systemic vision of sustainability and empowered students to see themselves as potential agents of change. Table 15 presents the activities that contributed to the development of this competency.

Table 11. Sustainability awareness and systems thinking competency developed in the secondary-level initiative.

Evidence	Activity	Competency Link
Empathy maps and interview notes.	Students conducted peer interviews to identify everyday challenges at school or home, and visualized insights through empathy mapping.	Recognition of how individual experiences reflect broader systemic issues, such as school infrastructure, waste management, or safety.
Root-cause diagrams and “How Might We” statements.	Teams analyzed the underlying causes of selected problems and reformulated them as design opportunities.	Ability to frame problems systemically and translate strategic thinking into potential solutions.
Project maps linking challenges to SDGs.	Teams linked their chosen challenge to at least one SDG, such as SDG 11 (sustainable cities) or SDG 12 (responsible consumption).	Encouraged thinking beyond the classroom, recognizing how local issues connect to global goals.

Table 12. Sustainability-driven technical decision making.

Evidence	Activity	Competency Link
Reports and presentations with rationale for choosing PET, cardboard, or paper.	Material selection for prototypes.	Decision making for sustainability: weighing cost, reusability, and impact on technical choices.
Physical prototypes incorporating recycled and repurposed materials.	Application of sustainability principles (circular economy ideas during refinement).	Sustainability orientation: embedding environmental values into design logic.
Group logs and teacher observations showing distribution of roles.	Role assignment within teams (designer, sustainability lead, presenter).	Shared responsibility, teamwork, and collaboration in sustainable decision-making.
Peer review feedback discussions.	Peer review of sustainability aspects in designs.	Critical evaluation, collective learning, and refinement of sustainable solutions.

Table 13. Design and innovation competency developed in the secondary-level initiative.

Evidence	Activity	Competency Link
Ideation maps, clustered Post-its, and sketches.	Students engaged in brainstorming sessions, clustering ideas, and creating affinity diagrams to propose solutions.	Development of divergent thinking and creative confidence.
“How Might We” design prompts.	Students re-framed local problems into open-ended design challenges to guide ideation.	Capacity to structure problems for innovation.
Poster boards, storyboards, and presentations.	Students visually documented solutions and explained prototypes through storytelling.	Ability to communicate innovative ideas with user-centered and sustainability rationale.

Table 14. Digital fabrication and CAD/CAM/CAE skills developed in the secondary-level initiative.

Evidence	Activity	Competency Link
Saved and printed models from repositories (Thingiverse, Printables, MakerLab, among others).	Browsing and analyzing open-source repositories for remixing and inspiration.	Digital literacy in 3D design: understanding file structure, model types, and printability.
Basic CAD files created in Tinkercad or Fusion 360, including simple circuit designs.	Creating or modifying digital objects according to project needs.	Foundational CAD/CAM/CAE skills: using digital tools to design and prepare models for fabrication.
Printed objects, slicer configuration screenshots, and troubleshooting notes.	Adjusting slicer settings, preparing prints, and supervising FDM printer operation.	Technical autonomy: translating design into printed objects using additive manufacturing principles.

Table 15. Strategic thinking competency.

Evidence	Activity	Competency Link
Empathy maps and interview notes from peers and community members.	Conducting peer interviews to understand everyday challenges at school or home, and visualizing insights.	Ability to identify how individual experiences reflect broader systemic issues, such as school infrastructure, waste management, or safety.
Records of “How Might We” statements and root-cause diagrams.	Reframing local problems into open-ended design challenges through root-cause analysis.	Strategic thinking: transforming contextual problems into actionable and innovative opportunities.
Project matrices linking challenges to SDG targets.	Mapping school-based issues onto specific Sustainable Development Goals.	Capacity to connect local challenges with global sustainability frameworks and envision long-term impact.

Challenges and Lessons Learned

The implementation of the program in public secondary schools surfaced critical structural and contextual challenges that shaped the learning experience. Notably, while the initiative included the creation of two dedicated “Laboratorios de Ideas e Innovación,” the construction and equipment setup required significant time, causing delays in the full deployment of hands-on modules. These types of spaces remain rare in the public education system in Panama, highlighting a broader infrastructural gap in access to maker-centered learning environments.

Connectivity issues also posed recurring obstacles. Limited or unstable internet access constrained the use of digital platforms, such as Autodesk Fusion, Tinkercad, and open-source model repositories like Thingiverse. As a result, students’ ability to engage with cloud-based CAD tools and digital resources can be uneven, particularly in rural or under-resourced areas.

In addition, teachers faced difficulty aligning the iterative nature of Design Thinking with rigid school timetables and standardized curricular demands. Integrating open-ended, project-based learning into traditional schedules and evaluation frameworks required continuous flexibility and creative facilitation.

Despite these constraints, the initiative generated important professional development outcomes. Participating educators reported increased confidence in implementing active learning strategies and embedding sustainability topics into their teaching practice. Structured reflection sessions highlighted the value of mentoring support from university students and reinforced the importance of inter-institutional collaborations. Teachers also emphasized the need for sustained investment in infrastructure and digital access to ensure long-term scalability of similar initiatives.

These constraints point to a clear scalability agenda: stable connectivity, protected time for iterative work, and sustained mentoring partnerships are preconditions for mainstreaming active sustainability learning in public secondary schools. Figure 4 shows the activities performed to develop the seven previously mentioned competencies.

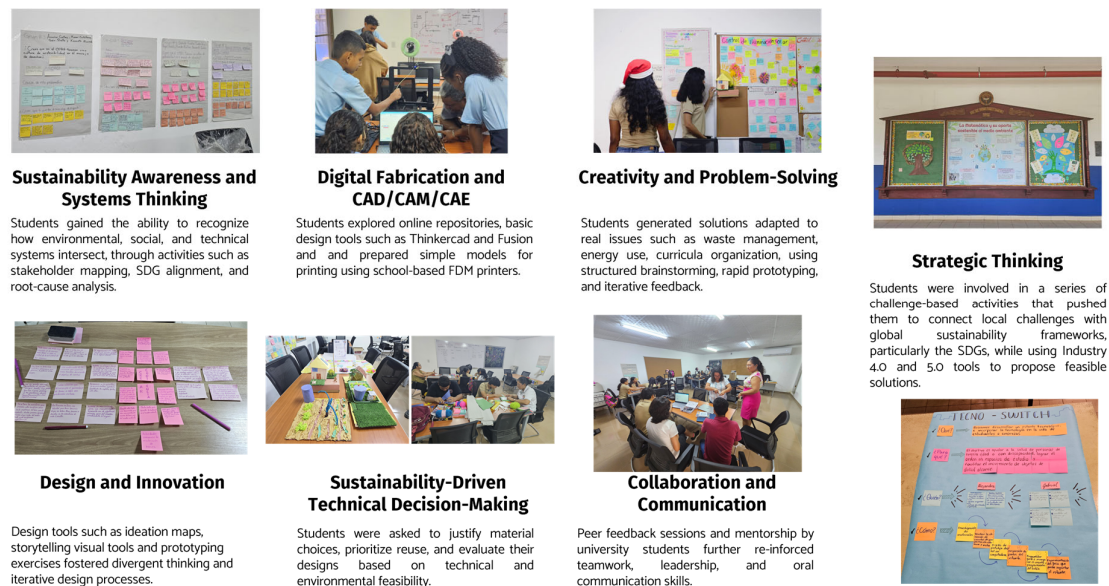


Figure 4. Activities carried out to promote the development of competencies.

4.3. Cross-Cutting Themes

Both the university and secondary school programs focused on learning by doing, getting students involved in real projects that made sustainability feel meaningful and practical. Sustainability was not just a topic; it was woven throughout everything, helping students understand how environmental, social, and economic issues are interconnected, particularly through concepts such as the circular economy and the Sustainable Development Goals. Working together was a big part of the experience, as students from different backgrounds learned how to listen, share ideas, and solve problems as a team. Design Thinking helped guide their creativity, encouraging them to understand users' needs, generate ideas, build prototypes, and refine their designs based on feedback. Technology also played a key role; tools such as 3D printers and design software provided students with hands-on experience in transforming ideas into tangible products. Reflection and critical thinking were encouraged throughout the process, helping students consider their own roles and the consequences of their choices. In secondary schools, having university students as mentors added an extra layer of support and learning, demonstrating how collaboration across age groups can make a difference. Of course, there were challenges as well, such as limited resources, internet issues, and tight school schedules, but everyone involved remained flexible and creative to make the learning experience meaningful and successful. Taken together, these convergences indicate that active, hands-on design cycles constitute a transferable backbone that can be adapted to learners' developmental stage and institutional constraints.

4.3.1. Active Learning as a Catalyst

- Both levels highlighted the effectiveness of learning-by-doing: University students bridged theory and practice through technical iterations, while secondary students embraced empathy and creativity.
- Peer Learning: Secondary students mentored by university teams accelerated skills like CAD basics, demonstrating the scalability of collaborative models.

4.3.2. Sustainability Mindset

- **Systems Thinking:** University teams analyzed product life cycles, while secondary students connected local challenges, such as deforestation, pollution, waste management, food availability, and health, to global SDGs.
- **Community Impact:** Two schools adopted student-proposed solutions, like composting systems, underscoring the real-world relevance of the projects. This approach is depicted in Figure 5.



Figure 5. Cross-cutting themes in active sustainability education.

Although the two interventions were designed in different institutional settings and for distinct age groups, their convergent outcomes highlight the robustness of active methodologies across contexts. This convergence highlights the robustness and transferability of active methodologies, particularly Design Thinking, project-based learning, challenge-based learning, and digital fabrication, which consistently promote growth in entrepreneurial and sustainability-related competencies.

At the same time, the divergences observed between the cases reveal how context and student maturity shape the learning process. In higher education, the integration of circular economy principles and advanced prototyping tools enables students to translate engineering knowledge into tangible solutions that align with green entrepreneurship. By contrast, the secondary education program emphasized scaffolding, introducing sustainability through the SDGs and accessible digital tools, thus fostering creativity, teamwork, and early technical exposure. These differences highlight that while the competencies targeted were similar, the pathways to achieving them must be adapted to the learners' developmental stage and institutional resources.

Comparative perspective adds value by identifying both transferable practices and contextual limitations. Transferable elements include the effectiveness of active, hands-on learning in building entrepreneurial mindsets, the integration of sustainability frameworks into design processes, and the role of digital fabrication in linking creativity with practical problem-solving. Context-specific differences, such as the need for explicit ethical reflection in higher education or additional scaffolding of systems thinking in secondary school, reveal areas where future interventions can be refined. These patterns are summarized in Table 16.

Ultimately, the analysis shows that entrepreneurship rooted in sustainability is not confined to a single educational level. When students are given authentic challenges, appropriate tools, and spaces for experimentation, they begin to see themselves as changemakers capable of designing solutions with social and environmental impact. By capturing these dynamics in both secondary and higher education, the study demonstrates that independent initiatives, when analyzed together, can generate insights that support scalable and adaptable models for sustainability-driven entrepreneurship education. Table 16 provides a structured overview

of these cross-cutting themes, highlighting both commonalities and differences across the two interventions.

Table 16. Cross-cutting comparative assessment.

Dimension	Case A	Case B	Cross-Cutting Insight
Sustainability Framework	Circular economy and green entrepreneurship as guiding principles; application through recycled HDPE prototyping.	Territorial sustainability and SDGs as guiding frameworks; application through community-based problem solving.	Both cases contextualize sustainability at the student level, linking abstract principles with practical challenges.
Active Methodologies	Flipped classroom, mirror classroom, Design Thinking, project-based learning, agile feedback cycles, and maker approach.	Design Thinking, project- and challenge-based learning, introductory CAD/3D printing, reflective exercises, and teacher facilitation.	Design Thinking and project-based approaches are core, but autonomy differs: medium to high at university, scaffolded at secondary.
Infrastructure	Module integrated into engineering curriculum; equipment acquired for HDPE recycling and prototyping.	Creation of Ideas and Innovation Laboratories (L2I) with basic CAD/AM tools to support experimentation.	Both required dedicated infrastructure; the scope was adapted to the context (advanced recycling vs. introductory labs).
Participants	Final-year industrial engineering students selected through application and interviews; diverse regional backgrounds.	Secondary students (8th–11th grades) selected by teachers for motivation and continuity; gender balance emphasized.	Participant maturity and background differ, but both groups engaged through voluntary selection and inclusivity.
Competency Assessment	Structured monitoring through guided reflection, triangulated observations, and systematic feedback cycles.	Mixed methods combining classroom artifacts, teacher notes, and iterative student self-reflection on skills.	Both emphasized systematic, ethical monitoring without over-reliance on quantitative testing, tailored to context.
Observed Outcomes	Growth in strategic thinking, interdisciplinary collaboration, and sustainability integration, though uneven across competencies.	Large perceived gains in teamwork, creativity, innovation, and technical skills, with sustainability competencies improving modestly.	Both contexts demonstrated competency development; complexity of sustainability concepts influenced outcomes.
Limitations	Weaker progress in self-awareness and normative expertise; need for deeper integration of ethics and systems thinking.	Challenges in mastering abstract sustainability and advanced CAD tools; reliance on scaffolding and teacher support.	Limitations stem from maturity and technical background of learners, suggesting need for adapted scaffolding at each level.
Added Value of Comparison	Shows feasibility of embedding circular economy and entrepreneurship into advanced engineering education.	Demonstrates early adoption of entrepreneurial mindsets and technical skills in younger students via SDGs and DT.	Comparison reveals scalability of methodologies, highlighting transferability of active learning and fabrication tools across levels.

5. Conclusions and Outlook

This study shows how active, hands-on learning strategies can effectively build sustainability competencies in both university and secondary school settings. By combining project-based learning, Design Thinking, and circular economy principles, students were able to connect theory with real-world practice, developing skills in systems thinking, collaboration, creativity, and responsible innovation. The university initiative highlighted how deeper technical and strategic competencies can be developed through interdisciplinary teamwork and simulated startup experiences utilizing recycled materials and digital fabrication. Meanwhile, the secondary school program demonstrated the potential of challenge-based learning and mentoring to engage younger students in sustainability challenges relevant to their communities. Both cases revealed common challenges, including limited resources, infrastructure gaps, and curriculum rigidity, that necessitate ongoing adaptation and support from educators and institutions.

Looking ahead, these findings suggest promising directions for expanding sustainability education. Scaling such active learning approaches will benefit from stronger investment in maker spaces, improved digital access, and flexible curricular frameworks that enable iterative student-centered projects. Further research could explore long-term impacts on students'

attitudes and career paths, as well as how to better integrate sustainability competencies across disciplines and education levels. Ultimately, nurturing environmentally responsible and innovative mindsets through active experiential learning will be essential for preparing future generations to address the complex sustainability challenges ahead.

Key Takeaways for Future Implementation:

- **Successes:** Active methodologies fostered practical skills and sustainability competencies across age groups.
- **Areas for Improvement:** Context-sensitive adaptations (e.g., flexible scheduling, equitable resource distribution) are critical for scalability.
- **Live feedback sessions** (e.g., Five-Finger Takeaway) provided additional insight into the learning experience. Students appreciated the practical focus and interdisciplinary collaboration. Key areas for improvement included expanding access to Autodesk Fusion training, hosting more in-person workshops, and allocating additional time for project development.

Key Takeaways for the Discussion Section:

- **Successes:** Active methodologies fostered sustainability competencies and real-world problem-solving across age groups.
- **Gaps:** Infrastructure, training, and curricular flexibility remain critical for scalability.
- **Future Work:** Longitudinal tracking of student outcomes and industry partnerships could strengthen impact.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. In the case of minors, parental authorization was secured prior to their involvement, with explicit information about all activities. These procedures complied with the requirements established by the supporting institutions for educational research.

Data Availability Statement: The data supporting the findings of this study consist of classroom observations, teacher logs, and student-produced materials. Due to confidentiality and privacy considerations, these data are not publicly available. Anonymized excerpts may be provided by the corresponding author upon reasonable request.

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