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A SPIRAL APPROACH TO INTEGRATING SUSTAINABLE DEVELOPMENT IN COMPUTER ENGINEERING EDUCATION: FROM INDIVIDUAL ACTION TO COLLECTIVE REFLECTION

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Abstract – *Digital technologies account for 10% of global electricity use and 4% of greenhouse gas emissions, yet sustainability remains marginal in engineering education. This paper presents a spiral pedagogical approach implemented across two consecutive computer engineering courses (INF1600 - Computer Architecture and INF3500 - Digital Systems Design) to integrate sustainable development.*

The approach progresses from individual awareness through Digital Cleanup Day participation and scientific article submissions in the introductory course, to collective reflection through thematic capsules synthesized from student contributions in the advanced course.

Implementation data from five course offerings across three academic sessions demonstrates strong student engagement, with 379 Digital Cleanup Day participations across all offerings, 268 scientific articles submitted, and evidence of transformative learning through student-initiated civic engagement.

The practice creates an intergenerational learning cycle where students co-create Open Educational Resources that benefit future cohorts, positioning them as vectors of change for sustainable development in computer engineering.

Paper Type: *Educational Practice*

Keywords: sustainable development, computer engineering education, digital sobriety, transformative learning, spiral pedagogy

1. INTRODUCTION

The digital sector's environmental footprint is substantial and growing: 10% of global electricity consumption, 4% of greenhouse gas emissions, and over 60 million tonnes of electronic waste annually with only 20% properly recycled [1]. Despite this reality, sustainability often remains an add-on in engineering curricula rather than a core competency [2][3]. This gap is particularly acute in computer engineering, where students rarely connect their technical learning to environmental consequences.

The challenge extends beyond knowledge transmission. Traditional sustainability education often fails to foster the worldview shifts necessary for engineers to become agents of change [4][5]. Students may learn about environmental issues without developing the agency, critical consciousness, and commitment to drive sustainable transformation in their professional practice.

This paper presents a spiral pedagogical approach that addresses both challenges by integrating sustainable development progressively across two consecutive computer engineering courses at Polytechnique Montréal. The approach is guided by a central question: Can a spiral curriculum, moving from individual awareness to collective reflection across consecutive courses, build both technical competence and environmental consciousness, preparing students as vectors of sustainable change?

Drawing on Bruner's spiral curriculum [6] and Mezirow's transformative learning theory [7][8], the practice cultivates student autonomy and critical engagement through two interconnected phases. Students begin with hands-on Digital Cleanup Day participation and scientific article submissions in INF1600 (Computer Architecture), then progress to collective analysis of thematic capsules in INF3500 (Digital Systems Design), capsules enriched with prior students' research contributions. This creates an intergenerational learning cycle where students co-create Open Educational Resources (OER) that benefit future cohorts while developing their own capacity as change agents.

Implementation began with a pilot in Fall 2024, expanded in Winter 2025, and achieved full-cycle integration in Fall 2025 and Winter 2026. This paper presents quantitative participation data and qualitative indicators of transformative learning outcomes, demonstrates scalability through institutional integration, and discusses implications for embedding sustainability across engineering disciplines.

2. BACKGROUND

2.1. Theoretical Framework

This practice synthesizes two complementary pedagogical frameworks. Bruner's spiral curriculum [6] advocates revisiting core concepts with increasing complexity across courses, allowing learners to build progressively deeper understanding. Applied to sustainability education, this means students progress from personal action (Digital Cleanup Day) to scholarly engagement (article research) to collective exposure (capsule discussions), with their contributions continuously enriching institutional knowledge resources.

Mezirow's transformative learning theory [7][8] provides the mechanism for deep change. Transformative learning occurs when learners critically examine their assumptions, leading to shifts in worldview and perspective. In sustainability education, this means moving beyond information acquisition to fundamental changes in how students understand their role as engineers and their relationship to environmental systems. The theory emphasizes disorienting dilemmas, critical reflection, and rational discourse as catalysts for transformation.

Recent scholarship emphasizes that sustainability integration must go beyond knowledge transmission to cultivate agency and capacity for change [9][10]. Rodríguez Aboytes and Barth [10] identify key dimensions of transformative sustainability learning: building connections between local and global issues, developing critical thinking about systemic relationships, and fostering capacity to become active contributors to sustainability transitions. This spiral approach operationalizes these dimensions through progressive engagement and student co-creation of learning resources.

2.2. Digital Sustainability Context

The concept of digital sustainability, central to our approach, encompasses the environmental impacts of digital technologies. In this context, digital sobriety promotes mindful consumption of digital resources across device lifecycles, energy efficiency, and data management [11]. This imperative is urgent: the digital sector mobilizes 10% of global electricity production, generates 62 million tonnes of electronic waste annually with only 20% properly recycled, and if the Internet were a country, it would rank third globally for electricity consumption after China and the United States [11][12]. Critically, 80% of a smartphone's carbon footprint stems from manufacturing rather than use, requiring at least five years of operation to amortize production impacts [13]. These realities underscore the need to address both consumption patterns and device longevity.

Digital Cleanup Day, an international initiative coordinated by Let's Do It World, provides a concrete entry point for students to measure their own digital footprint through practical action: deleting unnecessary files, unsubscribing from unused services, and optimizing digital storage [14]. Since 2020, the global movement has engaged over 1.7 million participants who collectively deleted 16.8 million GB of data, avoiding approximately 4,200 tonnes of CO_2 emissions annually [14]. This demonstrates scalability and measurable environmental impact beyond individual institutions.

Engineering education faces persistent challenges in sustainability integration [2][3][15]. Sabri [3] calls for systemic change, noting that conventional approaches treat sustainability as peripheral. Thürer et al. [15] identify significant knowledge gaps in how engineering programs integrate environmental considerations. Our approach addresses these gaps by embedding sustainability within technical courses rather than creating separate sustainability modules.

2.3. Course Context

INF1600 (Computer Architecture) is a 2nd-session core course for Computer Engineering and Software Engineering students. The course covers fundamental computing concepts including digital logic, processor architecture, assembly programming, and memory systems. INF3500 (Digital Systems Design) is a 3rd-session course for Computer Engineering students focusing on hardware description languages, FPGA programming, and digital system implementation. Most students follow the regular pathway: INF1600 in Winter (session 2) and INF3500 in Fall (session 3), creating a natural six-month progression where the same cohort of students experiences both phases of the spiral approach consecutively.

3. DESCRIPTION OF PRACTICE

The practices below were intentionally designed using Bruner's spiral curriculum and Mezirow's transformative learning theory. Sustainability concepts are introduced, revisited, and deepened across two consecutive courses through structured progression from individual experience to collective meaning-making, fostering both cognitive development and critical awareness.

3.1. INF1600: Individual Awareness and Contribution

In INF1600, students engage with digital sustainability through two optional but incentivized activities that replace lower-performing assignments. Before introducing these activities, students attend two brief presentations that establish the sustainability context. The first presents Digital Cleanup Day alongside statistics on e-waste, energy consumption, and resource depletion. The second introduces the 5R framework for digital sobriety (Refuse, Reduce, Reuse, Repair, Recycle, Reconnect), challenging assumptions about technology as inherently sustainable progress. These presentations create what Mezirow [7][8] identifies as a disorienting dilemma by exposing the disconnect between students' daily digital practices and their environmental consequences, catalyzing critical reflection and subsequent engagement with the activities. Figure 1 illustrates this spiral progression across both courses.

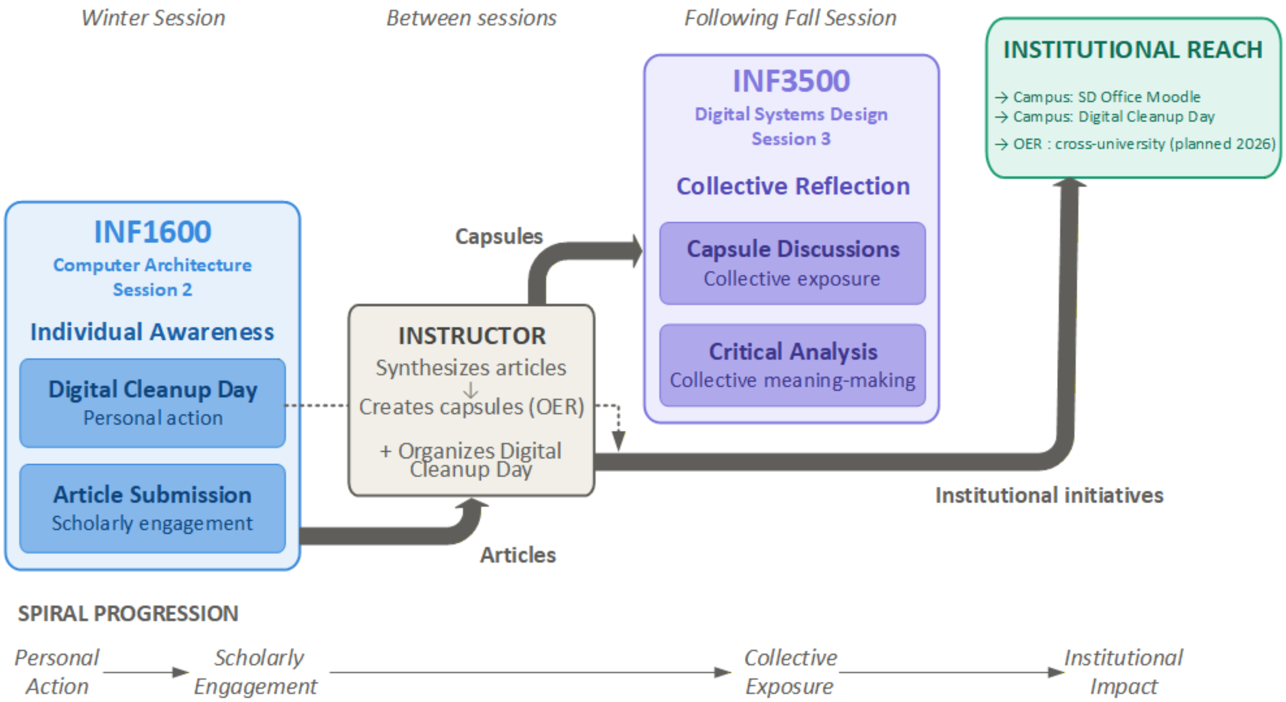

Figure 1: Spiral Integration of Sustainability Across Two Technical Courses

3.1.1. Activity 1: Digital Cleanup Day.

Students participate in digital cleanup activities aligned with the annual institutional Digital Cleanup Day event held each March by performing digital hygiene tasks on their personal devices: deleting unnecessary files, unsubscribing from unused services, clearing browser caches, and organizing digital storage. Students in fall sessions complete the activity and contribute to the institutional totals for the following year. They document space freed (in GB), record observations about their digital habits, and submit results via Excel spreadsheet. Individual contributions are then aggregated to measure the collective institutional impact. This concrete activity makes abstract environmental impact tangible and personal.

3.1.2. Activity 2: Scientific Article Submission.

Each student selects a recent article related to digital sobriety, circular economy in technology, or sustainable innovation. The article must be from credible sources (reputable newspapers, professional publications, government reports, research organizations, or peer-reviewed journals), published during the current academic session to ensure currency, and address a unique aspect not yet covered by other students. Students write a structured summary including article metadata, key concepts, main findings, and implications for engineering practice. This activity broadens students' information sources beyond social media, connects coursework to current events in science, geopolitics, and environmental issues, and introduces scholarly and professional literature while encouraging critical thinking about technological impacts.

3.1.3. Individual Discovery and Peer Awareness

Both activities emphasize individual discovery and contribution. Students work independently, exploring aspects of digital sustainability that resonate with their interests. The uniqueness requirement for articles encourages peer awareness—students must check what others have submitted, creating informal knowledge sharing. These individual contributions become the raw material for the collective phase in INF3500.

3.2. INF3500: Collective Reflection and Knowledge Co-Creation

In INF3500, the instructor presents four thematic capsules initially developed during the Fall 2024 pilot using scholarly literature and subsequently enriched with findings from student-submitted articles from INF1600:

1. The Semiconductor Technology Race and Its Impacts: Examines the global competition for chip dominance, Moore's Law limits, supply chain vulnerabilities, and the environmental cost of semiconductor manufacturing including water consumption, energy use, and carbon emissions.

2. Digital Sobriety: Examines principles of mindful digital consumption, data center energy use, software efficiency, and practices for reducing digital environmental footprint.

3. Device Lifecycle and Circular Economy: Analyzes material extraction, manufacturing impacts, product longevity, e-waste management, and circular design principles.

4. Artificial Intelligence and Environmental Sustainability: Investigates AI's dual role as both environmental problems (training energy costs, computational resources) and potential solutions (optimization, monitoring, prediction).

Each capsule is presented in class by the instructor, who synthesizes key themes and findings from student articles. This is followed by structured exchanges where students discuss implications and connect concepts to their technical work. While time is limited for in-depth debate, these interactions expose students to diverse perspectives from their peers' research. Assessment occurs through exam questions that require synthesis of capsule content, ensuring students engage meaningfully with the material and remain accountable to their collective contributions.

Revisiting sustainability themes in a subsequent technical course reflects the spiral curriculum principle of returning to core concepts with increased abstraction, systemic perspective, and analytical depth.

Critically, these capsules are shared institution-wide via Polytechnique's sustainable development Moodle portal, accessible to all students and faculty. They will be formalized as Open Educational Resources (OER) in summer 2026, ensuring long-term availability and reuse. This transforms student work from individual assignments into lasting contributions to institutional knowledge.

3.3. Spiral Integration: From Individual to Collective

As shown in Figure 1, the spiral manifests in three dimensions. Temporally, students encounter sustainability first through personal action (cleanup), then scholarly engagement (articles), then collective exposure and discussion (capsules). Cognitively, they progress from concrete experience to abstract analysis to synthesized understanding. Socially, they move from individual contribution to peer awareness through shared resources. Each turn of the spiral deepens engagement: doing → researching → discussing → seeing one's work inform future cohorts.

The intergenerational aspect amplifies impact. Students in INF1600 (session N) create resources that students in INF3500 (session N+1) analyze, who then see their own prior work synthesized when taking INF3500. Meanwhile, new INF1600 students contribute to the next iteration. This creates continuity and demonstrates to students that their work has lasting value beyond course credit.

4. Implementation and Approach

4.1. Timeline and Phases

Implementation followed a progressive rollout across four academic sessions (including Fall 2024 pilot):

Fall 2024 (Pilot): INF3500 piloted capsule discussions with instructor-curated content to validate the approach. Positive student reception confirmed viability.

Winter 2025 (Launch): INF1600 introduced both Digital Cleanup Day and article submissions. 229 students enrolled; 157 participated in cleanup, 90 submitted articles, contributing diverse perspectives on digital sustainability.

Fall 2025 (Full Cycle): INF3500 (64 students) implemented capsules synthesized from Winter 2025 student articles and engaged in critical discussions. Simultaneously, a new INF1600 cohort (72 students) contributed 71 cleanup participants and 46 articles, sustaining the resource pool.

Winter 2026 (Expansion): Both courses ran simultaneously. INF3500 (48 students) engaged with capsules, while INF1600 (207 students) contributed 151 cleanup participants and 132 articles. A second lecturer successfully taught INF3500 using the same capsules, demonstrating transferability across instructors.

4.2. Institutional Context

Digital Cleanup Day became an official annual institutional event at Polytechnique Montréal, coordinated centrally and promoted across departments. The event is open to all community members through an online registration form, supported by promotional campaigns and an information kiosk during Cleanup Week. Participation has grown year-over-year, expanding beyond course participants to include students from other programs and employees. This institutional integration provides continuity, visibility, and legitimacy for the practice.

The sustainable development portal on Moodle serves as the repository for capsules and student-generated resources. All Polytechnique community members can access materials, and faculty can incorporate them into other courses. This infrastructure enables scaling beyond the original two courses.

4.3. Assessment and Ethical Considerations

Both Digital Cleanup Day and article submissions are optional activities that can replace lower-performing assignments. Students appreciate this flexibility. Sustainability engagement becomes opportunity rather than obligation. In INF3500, exam questions assess understanding of capsule discussions, ensuring accountability while respecting diverse participation modes.

This project received an exemption from ethics review by Polytechnique Montréal's Research Ethics Board. All data presented in Table 1, Table 2 et Table 3 are aggregated and anonymized statistics from normal course evaluation activities. No individual student data is disclosed.

Table 1: Student participation across implementation phases

Metric	INF1600 H25	INF1600 A25	INF1600 H26	INF3500 A25	INF3500 H26	Total
Students Enrolled	229	72	207	64	48	620
Articles Submitted	90	46	132	—	—	268
Digital Cleanup Participations	157	71	151	—	—	379

Data excludes Fall 2024 pilot session (INF3500, instructor-curated content).

Table 2: Digital Cleanup Day 2025 institutional impact

Participant Category	Participants	Data Deleted (GB)
INF1600 Students	157	9,858
Other Students	8	873
Polytechnique Employees	6	201
Total	**171**	**10,932**

Environmental impact: ~2,733 kg CO_2 reduced annually

Table 3: Digital Cleanup Day 2026 institutional impact

Participant Category	Participants	Data Deleted (GB)
INF1600 Students	222*	20,203
Other Students	30	6521
Polytechnique Employees	16	3460
Total	**268**	**30,184**

Environmental impact: ~7,546 kg CO_2 reduced annually

**** Digital Cleanup Day occurs in March annually. The 2026 event includes both Fall 2025 and Winter 2026 INF1600 students.***

5. OUTCOMES AND DISCUSSION

5.1. Quantitative outcomes

Participation data (Table 1) demonstrate consistent engagement across implementation phases. The Winter 2025 launch achieved 68.6% Digital Cleanup participation (157/229 students) and 39.3% article submission rate (90/229), indicating substantial voluntary engagement with optional sustainability activities. These rates remained strong across Fall 2025 (98.6% cleanup, 63.9% articles) and Winter 2026 (72.9% cleanup, 63.8% articles).

The collective environmental impact is tangible (Table 2): institution-wide Digital Cleanup 2025 freed 10,932 GB of storage across 171 participants (157 from INF1600, 8 other students, and 6 employees), equivalent to reducing annual CO_2 emissions by approximately 2,733 kg. While individual contribution varies widely, the aggregate demonstrates measurable environmental benefit beyond pedagogical value. These results represent the inaugural institutional edition, establishing baseline participation primarily from INF1600 students.

The practice demonstrates continuity and expanding reach beyond measured metrics (Table 3). Digital Cleanup Day participation grew year-over-year from 171 (2025) to 268 (2026) participants, with non-INF1600 students increasing from 8 to 30 and employees from 6 to 16. Total data deleted grew from 10,932 GB to 30,184 GB, extending beyond course requirements through enhanced institutional promotion by the Office of Sustainable Development and Communications Office. However, these figures underrepresent actual impact—former students frequently report at information kiosks that they perform annual cleanups without submitting data, viewing the environmental action itself as primary rather than quantification. Annual promotional campaigns thus create lasting behavioral touchpoints beyond measured participation.

Article submissions grew the resource pool to 268 unique contributions spanning peer-reviewed research on AI sustainability, circular economy, digital sobriety practices, device lifecycle analysis, and innovation for environmental impact. This diversity enables rich thematic synthesis and ensures capsule content reflects current scholarship rather than instructor perspective alone.

Beyond exam-based assessment, evidence of competency development emerges through student-initiated actions (e.g., OER creation, advocacy in student media) and informal feedback—several INF1600 students reported that the course influenced their decision to extend device lifespans. More systematic competency assessment tools (pre/post surveys, behavioral tracking) represent an area for future development.

Figure 1 illustrates this institutional expansion trajectory: from course-level activities to campus-wide initiatives (Moodle portal, Digital Cleanup Day) to planned cross-university dissemination through OER formalization in 2026.

5.2. Indicators of Transformative Engagement

Beyond participation metrics, qualitative indicators suggest transformative learning outcomes. In 2025, a student exemplified the progression from individual awareness to empowered collective action. She first explored Digital Cleanup Day 2025 as part of a sustainability project in GCH2730 (Sustainable Development in Engineering), then published an educational article "Digital Sustainability: Guide and Practical Tools" in the student newspaper Le Polyscope, which she subsequently formalized as an Open Educational Resource [16]. She continues to advocate for the initiative by promoting the 2026 Digital Cleanup Day edition in Le Polyscope.

This trajectory exemplifies Mezirow's transformative learning [7][8]—moving from course participant to institutional change agent—and demonstrates the ripple effects documented by Damerell et al. [9], where student-led initiatives influence broader institutional practices. This progression from individual awareness toward collective action enables students to empower themselves and others. This empowerment, sustained by the spiral approach, cultivates students as vectors of sustainable change who extend impact beyond their own coursework and inspire collective action across the institution.

Classroom exchanges during INF3500 capsule presentations revealed student engagement with systemic issues. Through guided discussions, students made connections between the presented material and their technical work. Themes that emerged from these exchanges included: concerns about semiconductor supply chains and geopolitical dependencies, questions about cloud computing's actual environmental impact, observations on the rebound effect where efficiency gains lead to increased consumption, and recognition of greenwashing in tech company sustainability claims. While time constraints limit the depth of in-class debate, these exposures to diverse perspectives from peer research demonstrate what Rodríguez Aboytes and Barth [10] term capacity building: students begin to construct understanding of their role in sustainability transitions rather than passively receiving information.

The intergenerational aspect creates visible continuity. Students who submitted articles in INF1600 see their work synthesized into capsules when taking INF3500 the following session. This recognition that their contribution has lasting value beyond course credit appears to deepen engagement. Anecdotally, several students expressed pride in seeing their research inform subsequent cohorts' learning. Furthermore, since GCH2730 runs concurrently with INF3500 in the fall session, students appear to draw upon both their prior INF1600 exploration and ongoing INF3500 capsule discussions as foundational resources for sustainability assignments in GCH2730, creating synergies across the curriculum.

5.3. Connection to technical learning

Sustainability principles are woven directly into technical instruction rather than presented as external add-ons. In INF1600, discussions of semiconductor manufacturing processes naturally connect to environmental costs: water consumption in chip fabrication, energy-intensive clean rooms, and supply chain vulnerabilities. These real-world constraints reframe abstract hardware concepts as tangible engineering trade-offs.

Beyond conceptual connections, sustainability informs concrete programming practices. When teaching memory management in INF1600, students learn how data structure alignment and class parameter ordering directly impact memory utilization. These compact layouts reduce cache misses and RAM access, lowering energy consumption. Loop restructuring demonstrates how cache-friendly iteration patterns improve performance while reducing hardware demands. In INF3500, optimization techniques emphasize that cleaner, more efficient code requires less computational resources, translating directly to reduced energy footprints in deployed systems.

This pedagogical approach reinforces a core principle: well-engineered solutions are inherently more sustainable. By framing optimization not merely as performance enhancement but as resource stewardship, technical coursework cultivates environmental consciousness as an integral engineering competency rather than an afterthought.

5.4. Challenges and Adaptations

Sustaining student motivation to contribute for future cohorts remains an ongoing challenge. The optional nature of activities means participation is never universal. Some students prioritize other coursework, particularly during high-stress periods. The flexibility that makes activities accessible also limits their reach.

To address this, Digital Cleanup Day's status as annual institutional event creates recurring touchpoints. Students encounter the initiative multiple times throughout their program, not just in INF1600. This repetition reinforces sustainable practices beyond single-course exposure. Additionally, making activities optional but incentivized (replacing lower grades) balances accessibility with motivation; students engage because they see value, not merely obligation. This aligns with adult education principles central to Mezirow's framework [7][8], where learning becomes meaningful when students perceive its relevance and value to their lives and professional development. This respects diverse student contexts while maintaining participation rates.

Developing and continuously updating thematic capsules with insights from 268 student articles requires significant instructor effort. However, this investment produces reusable OER that benefit multiple cohorts and other courses. The summer 2026 formalization as OER will enable other institutions to adapt to the approach, multiplying impact.

The same instructor teaches technical content and synthesizes student articles into capsules—intentionally ensuring authentic connections to course concepts rather than add-ons, while modeling sustained commitment. Though this represents additional workload, engaging with student research and connecting sustainability to evolving technical contexts makes the investment worthwhile.

Transferability across instructors was validated when a second lecturer successfully implemented the capsule discussions in Winter 2026 INF3500, demonstrating that the practice does not depend on a single instructor's expertise or personality. Clear documentation and structured materials enable scalability.

Large language models present challenges across the entire assignment workflow. However, the pedagogical goal (exposing students to sustainability literature beyond social media) is achieved even if AI assists. Egregious plagiarism (unedited AI text with visible prompts) receives zero credit. Future iterations may include exam questions on submitted articles to verify engagement.

5.5. Broader Implications

This practice offers a scalable model for addressing persistent gaps in engineering sustainability education [2][3][15]. The institutional expansion trajectory illustrated in Figure 1 demonstrates that sustainability integration can extend beyond individual courses to become systemic institutional infrastructure. By embedding sustainability within existing technical courses rather than creating separate modules, it avoids marginalization while demonstrating feasibility without curriculum overhaul.

The spiral framework's discipline-agnostic sequence enables adaptation across programs using field-specific sustainability topics and appropriate hands-on activities. This transferability positions the model as broadly applicable beyond computer engineering.

Grounding the practice in transformative learning positions sustainability integration as capacity building rather than knowledge transmission. This directly addresses Wals and Dillon's [5] critique that traditional approaches fail to cultivate agency. By positioning students as knowledge co-creators whose work benefits future cohorts, the approach fosters the critical consciousness necessary for engineers to drive sustainable transformation in professional practice.

5.6. Recommendations for Future Success

Based on implementation experience across five course offerings over three sessions, the following recommendations support sustained success in this spiral approach:

Institutional Integration. Secure official status for initiatives like Digital Cleanup Day ensures continuity beyond individual instructor efforts. Central coordination, communication support, and recurring calendar placement reduce organizational burden while increasing visibility and legitimacy.

Flexible Assessment Structure. Making sustainability activities optional but incentivized (replacing lower grades) balances accessibility with motivation. Students engage because they see value, not obligation. This respects diverse student contexts while maintaining participation rates.

Resource Formalization. Converting student-generated content into Open Educational Resources ensures long-term availability and institutional memory. Clear licensing (CC BY 4.0), professional formatting, and central repository placement enable reuse across courses and institutions.

Cross-Instructor Transferability. Document capsule facilitation approaches, discussion prompts, and assessment rubrics to enable multiple instructors to implement consistently. As demonstrated with the second INF3500 instructor, well-structured materials support scalability without requiring specialized expertise.

Student Recognition. Explicitly acknowledge students' contributions to future cohorts' learning. Showing students that their work has lasting value beyond course credit deepens engagement and models professional knowledge sharing practices.

Iterative Refinement. Update capsule content annually with new student articles to maintain currency and relevance. Archive previous versions to track evolution of sustainability discourse in the field. Solicit student feedback on discussion quality and adjust facilitation accordingly.

Deepen Critical Engagement. Future iterations could enhance article submissions by requiring personal reflection components where students explicitly connect findings to their emerging engineering identity and professional responsibilities. This addition would strengthen the transformative learning dimension by prompting students to articulate how research challenges or shifts their assumptions about technology's role in sustainability.

6. CONCLUSIONS

This spiral approach to sustainable development integration demonstrates that engineering education can cultivate both technical competence and environmental consciousness without sacrificing either. Implementation across five course offerings shows consistent student engagement with voluntary sustainability activities, measurable environmental impact through Digital Cleanup Day, and qualitative evidence of transformative learning through student-initiated civic engagement.

The practice's strength lies in its progressive structure: students move from personal action to scholarly engagement to collective exposure, with each stage building on the previous. This creates an intergenerational learning cycle where students co-create Open Educational Resources that benefit future cohorts while developing their own capacity as vectors of sustainable change.

Key success factors include institutional support through Digital Cleanup Day infrastructure and sustainable development portal, instructor curation of thematic capsules that synthesize student contributions with facilitation that provides structure while respecting student autonomy and building trust to sustain engagement, and optional-incentivized activities respecting diverse student needs. Additionally, the approach transforms student work into lasting institutional resources while grounding practice in transformative learning theory to foster agency rather than merely transmit information.

The approach is scalable and transferable. A second instructor successfully implemented capsule discussions, demonstrating independence from original designer. The spiral framework applies across disciplines—any program can adapt using discipline-specific sustainability topics and appropriate hands-on activities. Formalization as OER in summer 2026 will enable broader institutional adoption.

Future work will track longitudinal outcomes: Do students maintain sustainable practices after graduation? How do graduates' professional decisions reflect environmental consciousness cultivated through this approach? Additionally, expanding to other course sequences and disciplines will test generalizability and identify necessary adaptations.

This practice demonstrates that sustainability integration need not burden technical education but rather enhance it. By planting seeds today through personal action to scholarly engagement to collective exposure, we cultivate tomorrow's engineers as informed, critical, and committed vectors of sustainable development.

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