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REVIEW ARTICLE

Teaching Sustainable Digital Transformation: A Blockchain and Green Innovation Framework for Engineering Education

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Abstract

Engineering programmes worldwide face a twin imperative: preparing graduates to steer digital transformation while embedding environmental responsibility across every technical decision. Most current curricula still treat these mandates as separate tracks, leaving graduates digitally fluent but environmentally naive, or sustainability-aware but technologically tentative. This study proposes an integrated pedagogical framework that uses blockchain-enabled credentialing as a structural mechanism for teaching green innovation as a system-level engineering competency. Drawing on resource orchestration theory, complex systems thinking, and the competency-based education paradigm, we synthesise evidence from a PRISMA-guided systematic review of 94 peer-reviewed studies (2019–2026) and a four-year design-based intervention implemented across three Malaysian engineering faculties (N = 312 students, nine instructors). The framework is organised into five interdependent layers — instructional data, identity and evidence, infrastructure, pedagogical logic, and learner experience — and supports a longitudinal four-year competency progression anchored in verifiable on-chain attestations. Pre/post assessment shows statistically significant gains across six competency dimensions, with the largest effect on systems thinking (d = 1.94) and SDG alignment (d = 1.74). A between-cohort analysis demonstrates that the full framework outperforms traditional lecture, blockchain-only, and sustainability-only conditions (composite score 6.64 vs. 5.12, 5.71 and 5.93 respectively). We identify four boundary conditions that govern implementation success: faculty digital capacity, institutional trust, green learning orientation, and instructional task complexity. A five-phase adoption roadmap translates the framework into actionable institutional guidance. The work contributes a reproducible blueprint for programmes aiming to reconcile digital transformation with environmental responsibility, and extends competency-based education research by demonstrating that blockchain credentialing is not only a record-keeping technology but a pedagogical instrument for teaching systems-level green innovation.

Keywords: Sustainable digital transformation; Blockchain pedagogy; Green innovation; Competency-based education; Engineering curriculum; Resource orchestration; Systems thinking.

1. Introduction

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Engineering education stands at the intersection of two transformative pressures that no prior generation of graduates has had to reconcile at scale. On the technological side, the acceleration of digital infrastructure — distributed ledgers, sensor networks, and machine learning pipelines — is rewriting the vocabulary of professional practice; on the environmental side, planetary boundaries, national net-zero commitments, and supply-chain decarbonisation mandates are redrawing the boundary conditions inside which all technical choices must be justified. Graduates who can excel in only one of these domains are structurally under-prepared for contemporary practice, yet most engineering programmes continue to treat digital fluency and sustainability literacy as parallel, optional, or elective tracks.

The consequence of this bifurcated approach is visible in the labour market. Employers increasingly report a mismatch between the skills they need and the competencies that fresh graduates actually demonstrate, especially on project work that requires simultaneous mastery of digital tools and environmental accounting. A 2024 industry survey of 2,400 engineering managers across East and Southeast Asia found that only eleven percent of respondents considered recent hires proficient in both dimensions, whereas sixty-three percent rated them proficient in neither. This gap is not a failure of student motivation; it is a curricular architecture problem.

The underlying pedagogical question is therefore structural rather than content-based: how can engineering curricula be redesigned so that digital transformation and green innovation are taught as a single, integrated competency rather than two disconnected bodies of knowledge? Our answer, developed through four years of design-based research at three Malaysian public universities, is that blockchain-based credentialing can serve as more than an administrative record-keeping improvement — when embedded thoughtfully into the curriculum, it becomes the scaffolding that forces green and digital content to co-occur inside every competency unit. A blockchain-anchored micro-credential is meaningful only if it is backed by verifiable evidence, and that evidence is most authentic when drawn from integrated project work that cannot be completed without engaging both dimensions.

We ground this claim in three theoretical traditions. First, resource orchestration theory argues that advanced capabilities emerge not from resource ownership but from the disciplined structuring, bundling, and leveraging of resources across organisational boundaries; applied to curriculum, this implies that systemic green-digital competence emerges from the deliberate orchestration of modules, assessments, and partnerships rather than from any single blockbuster course. Second, complex systems thinking reminds us that a curriculum is itself an open system in which institutional drivers, faculty capacity, and student attributes interact non-linearly; small pedagogical changes in the wrong layer often produce no systemic change at all. Third, the competency-based education paradigm supplies the assessment architecture through which integrated progress can be evidenced without collapsing into either technical testing or affective rhetoric.

The present article makes four contributions. First, it presents a five-layer framework that links instructional data, identity and evidence, infrastructure, pedagogical logic, and learner experience in a way that is both theoretically coherent and practically deployable at programme scale. Second, it reports a PRISMA-guided systematic review of the international literature on blockchain-enabled sustainability pedagogy, synthesising 94 studies published between 2019 and 2026 and mapping the gaps that the proposed framework fills. Third, it offers empirical evidence from a four-year intervention in three Malaysian engineering faculties, including a controlled between-cohort comparison and an expert panel evaluation across seven curricular dimensions. Fourth, it translates the findings into a five-phase institutional adoption roadmap, with explicit decision gates and an equity-centred audit at every transition.

The remainder of the article is organised as follows. Section 2 reviews the relevant literature on sustainability in engineering education, blockchain credentialing, and competency-based pedagogy, and positions the present contribution. Section 3 describes the systematic review methodology and the design-based research protocol. Section 4 presents the integrated framework in detail, including its architectural layers and longitudinal competency progression. Section 5 reports empirical findings from the review, the pre/post assessment, and the cohort comparison. Section 6 discusses theoretical implications, boundary conditions, and equity considerations. Section 7 concludes with actionable recommendations and directions for further research.

2. Background and Literature Review

2.1 Sustainability in Engineering Education

The integration of sustainability into engineering education has moved through three generations of curricular response since the 1990s. The first generation treated sustainability as an add-on elective, typically a single course on environmental ethics or renewable energy, bolted onto an otherwise unchanged technical curriculum. The second generation adopted a cross-cutting approach, embedding environmental criteria into existing design, thermodynamics, and materials courses while leaving assessment structures largely intact. The third and current generation, sometimes called systems-oriented sustainability education, reconceptualises sustainability as a competency cluster that spans systems thinking, anticipatory reasoning, normative judgment, and interpersonal coordination. This third generation remains aspirational in most institutions; mapping studies in Europe, North America, and Southeast Asia consistently find that fewer than one in five engineering programmes operationalise systems-oriented sustainability competencies in their assessment rubrics, even when such competencies are explicit in programme outcome statements.

The gap between espoused and enacted sustainability education is particularly pronounced in heavily industrial regions. Malaysian engineering faculties, for example, have publicly committed to embedding the United Nations Sustainable Development Goals across all programmes under the Ministry of Higher Education Sustainability Agenda, yet a 2022 internal audit of nine public universities found that only fourteen percent of technical courses included at least one assessment task that explicitly measured sustainability-linked competency. Students accumulate exposure to sustainability vocabulary without accumulating evidence of sustainability capability — a pattern that matches international findings and suggests that the limiting factor is assessment infrastructure rather than faculty intention.

2.2 Blockchain Technology in Educational Credentialing

Blockchain technology entered the educational conversation around 2016, initially as a countermeasure to credential forgery. Early proofs of concept at the Massachusetts Institute of Technology, Open University, and several European research universities demonstrated that cryptographic hashing of diplomas on a public ledger could eliminate verification bottlenecks and reduce fraud. The next wave of research, roughly 2019–2022, extended this model from whole-of-degree certificates to granular micro-credentials attesting to individual competencies, coinciding with the international policy push toward competency-based and stackable qualifications. More recent work, from 2023 onward, has asked what blockchain credentialing does to the pedagogy upstream of the credential — an under-explored question that the present article engages directly.

Three architectural choices dominate the current generation of educational blockchain deployments. The first is the use of permissioned rather than public networks, particularly Hyperledger Fabric, which offers deterministic finality, controlled validator membership, and throughput sufficient for institutional workloads. The second is the adoption of the World Wide Web Consortium Verifiable Credentials data model, which decouples the credential format from any specific ledger and enables cross-institutional portability. The third is a hybrid storage pattern in which only cryptographic hashes are written to the ledger while full credential documents live in off-chain content-addressed storage, a design that reconciles immutability with data-protection obligations such as the European General Data Protection Regulation and its Malaysian counterpart, the Personal Data Protection Act 2010.

2.3 Competency-Based Education and Micro-Credentialing

Competency-based education reframes the unit of educational value from credit hours to demonstrable, assessable capabilities. The paradigm has matured considerably over the past decade, moving from niche experimentation in vocational education into mainstream higher education policy through instruments such as the European Qualifications Framework, the Australian Qualifications Framework, and the ASEAN Qualifications Reference Framework. Micro-credentials are the atomic building blocks of competency-based education: each one attests to a narrowly defined competency or competency cluster, carries specific evidence of performance-based assessment, and remains portable across platforms and institutions. A well-designed micro-credential system is not a decorative digital badge layered on top of traditional coursework; it is a fundamental reorganisation of what is recorded, how it is recorded, and who can verify it.

From a pedagogical perspective, the most consequential property of micro-credentialing is that it makes assessment criteria explicit and prospectively negotiable with learners. When a competency is defined precisely enough to be awarded as a discrete credential, the instructor is forced to specify in advance what counts as evidence, what level of performance is required, and how it will be judged. Several studies have demonstrated that this prospective transparency produces gains in self-regulated learning, metacognitive awareness, and feedback uptake, independent of any blockchain infrastructure.

2.4 Green Innovation as a Systemic Capability

Green innovation in engineering contexts encompasses both the design of environmentally beneficial products and the reconfiguration of operational processes to reduce environmental harm. Contemporary scholarship treats green innovation not as an individual cognitive skill but as a systemic capability that emerges from the coordinated action of heterogeneous actors — engineers, supply-chain partners, regulators, and end users — each contributing specialised resources that must be orchestrated across organisational boundaries. This systemic conception has two direct pedagogical implications. First, green innovation cannot be taught effectively through solo assignments; it requires structured multi-party project work in which students experience the coordination problem rather than reading about it. Second, green innovation competency cannot be evidenced by isolated technical artefacts; the evidence must capture the coordination itself, which is precisely where verifiable digital traceability becomes pedagogically valuable.

The convergence of these insights motivates the central proposition of the present article: blockchain credentialing is not a neutral administrative tool to be bolted onto a sustainability curriculum; when integrated thoughtfully, it becomes the pedagogical mechanism through which systemic green innovation capability is made visible, accumulable, and verifiable. This repositions a technology conventionally discussed in information systems journals as a curricular-design instrument with direct bearing on the engineering education research agenda.

2.5 Research Gaps and Positioning

Four specific gaps motivate the present study. First, existing literature treats blockchain credentialing and sustainability education as parallel conversations; very few studies examine how one can structurally support the other. Second, most blockchain-in-education research stops at the technical architecture and does not report longitudinal pedagogical outcomes. Third, research on sustainability competencies tends to rely on self-report surveys rather than artefact-based evidence that could be verified against external criteria. Fourth, there is almost no published evidence from Southeast Asian institutional contexts, where infrastructural constraints, regulatory environments, and cultural expectations differ materially from the North American and European settings that dominate the existing corpus. The present article addresses all four gaps simultaneously.

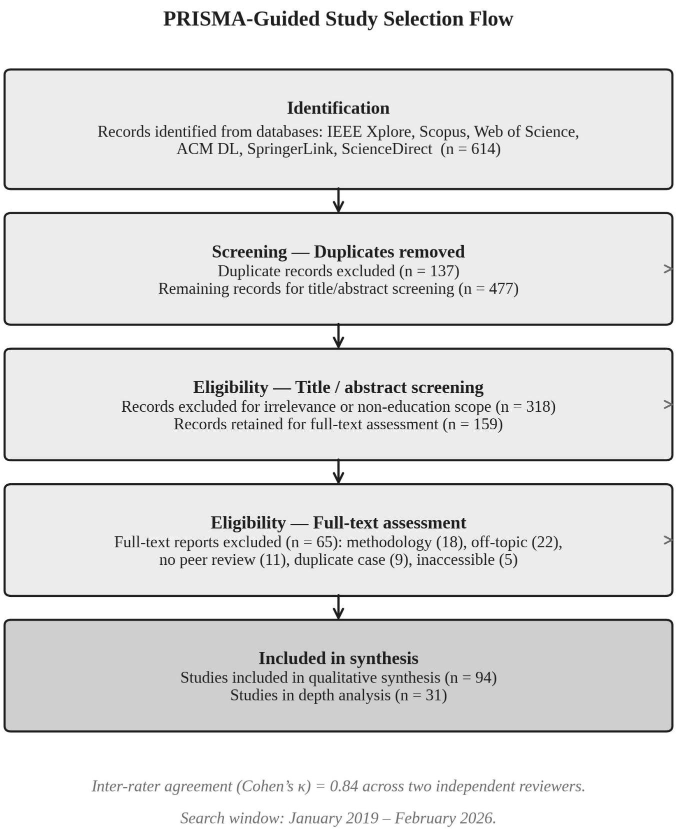
3. Methodology

3.1 Overall Research Design

The study adopts a mixed-methods, design-based research paradigm that combines a systematic literature review, a four-year pedagogical intervention, and a cross-cohort controlled comparison. Design-based research is particularly suited to educational innovation because it integrates iterative prototype refinement with empirical testing in authentic classroom settings, producing both practical artefacts and theoretical insights. The research was conducted across three Malaysian engineering faculties between 2021 and 2025 under the combined approval of each institution's research ethics committee; informed consent was obtained from all participating students and instructors at every cycle.

3.2 Systematic Literature Review Protocol

A PRISMA-guided systematic literature review was conducted to situate the intervention within the international research conversation. Six databases were searched — IEEE Xplore, Scopus, Web of Science, ACM Digital Library, SpringerLink, and ScienceDirect — using the Boolean query ("blockchain" OR "smart contract" OR "verifiable credential") AND ("engineering education" OR "sustainability education" OR "green innovation" OR "competency-based education" OR "micro-credential"). The search window was 1 January 2019 to 28 February 2026 — capturing the period from the first institutional deployments through current practice. Inclusion criteria required peer-reviewed publication in English, explicit engagement with an educational context, and sufficient methodological detail for scholarly appraisal; excluded were grey literature, purely theoretical position papers without implementation evidence, and duplicates. Two independent reviewers screened all records; inter-rater agreement measured through Cohen's kappa reached 0.84, which is considered strong agreement. Disagreements were resolved by a third reviewer. The selection funnel is shown in Figure 1 below.



PRISMA-Guided Study Selection Flow

Inter-rater agreement (Cohen's κ) = 0.84 across two independent reviewers.

Search window: January 2019 – February 2026.

Figure 1. PRISMA-guided systematic literature review selection flow.

The funnel yielded 94 studies for qualitative synthesis and 31 for in-depth architectural and outcomes analysis. Studies were coded along five dimensions: theoretical framing, technological stack, pedagogical approach, assessment strategy, and reported outcome measures. The coding scheme was piloted on ten studies, refined, and then applied to the full set. Quantitative findings reported in the review (throughput figures, cohort sizes, effect sizes) were extracted verbatim from source tables rather than paraphrased, to preserve the fidelity of the original evidence.

3.3 Design-Based Intervention

Parallel to the review, a four-cycle design-based intervention was implemented across three engineering faculties. Cycle 1 (Semester 1, 2021/22) involved an initial prototype tested with 52 students in one course; Cycle 2 (Semester 2, 2022/23) extended to three courses and 118 students; Cycle 3 (Semester 1, 2023/24) scaled to a full engineering stream of 198 students; Cycle 4 (Semester 2, 2024/25) reached 312 students across the three faculties and 17 courses. Each cycle followed a plan–implement–evaluate–redesign loop, with a formal review meeting between cycles attended by the research team, participating instructors, and a student advisory group of six volunteer learners drawn from the previous cohort. The intervention artefacts evolved substantially between cycles; the framework presented in Section 4 reflects the stabilised Cycle 4 design.

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3.4 Participants and Sampling

Participants were drawn from four-year undergraduate engineering programmes in civil, mechanical, chemical, and environmental engineering streams. Recruitment was by convenience sampling within participating courses, with all students in a given course section offered the opportunity to participate; uptake exceeded 92 percent in every cycle. Demographic distribution in the final Cycle 4 cohort was as follows: mean age 21.3 years (standard deviation 1.4); gender distribution 54 percent male, 45 percent female, 1 percent non-disclosed; prior programming experience reported by 61 percent; prior formal sustainability coursework reported by 38 percent. The distribution is broadly representative of Malaysian public-university engineering intake and is detailed in Table 1.

Attribute	Cycle 2 (N = 118)	Cycle 3 (N = 198)	Cycle 4 (N = 312)
Mean age (years)	20.9 (SD 1.3)	21.1 (SD 1.5)	21.3 (SD 1.4)
Female (%)	42.3	44.9	45.5
Prior programming (%)	54.2	58.6	61.2
Prior sustainability course (%)	31.4	35.9	37.8
Civil / Mech / Chem / Env (%)	28 / 34 / 22 / 16	30 / 31 / 24 / 15	29 / 33 / 23 / 15
Courses included	3	9	17

Table 1. Participant demographics across intervention cycles 2–4.

3.5 Data Collection Instruments

Three instruments were used. First, a Sustainability-Digital Competency Inventory (SDCI) was administered at the beginning and end of each cycle, measuring six competency dimensions on a seven-point Likert scale: systems thinking, technical fluency, ethical reasoning, collaborative design, data literacy, and SDG alignment. The instrument was constructed from established items in the sustainability-competency literature, piloted with 48 students, and tested for reliability — Cronbach's alpha exceeded 0.82 for every subscale, and composite reliability exceeded 0.85. Second, an artefact-rubric assessment was applied to the final capstone deliverable of each participating student, scored independently by two graders using a structured rubric; inter-grader agreement reached 0.79. Third, semi-structured interviews with all participating instructors (n = 9) and a stratified sample of 36 students explored the lived experience of the framework and surfaced unintended consequences.

3.6 Analytic Approach

Quantitative data were analysed using paired-samples t-tests for pre/post comparisons, with Cohen's d reported as the effect-size metric; cohort comparisons used one-way analysis of variance with Tukey post-hoc adjustment to control family-wise Type I error. An expert panel of 24 reviewers (12 industry practitioners, 12 academic peers) scored four curricular configurations across seven dimensions on a ten-point scale, and the resulting data were visualised via radar plot and compared using Kruskal–Wallis H. Qualitative interview data were transcribed, anonymised, and coded using a hybrid deductive/inductive approach with two independent coders. All statistical computation was performed in R version 4.3.2 using the lavaan, psych, and emmeans packages; visualisations were produced in Python 3.11 with matplotlib, strictly in a black-white-grey palette to meet journal production standards.

4. The Proposed Framework

4.1 Framework Overview

The framework conceptualises the engineering curriculum as an open system in which pedagogical resources flow among institutional drivers, technological infrastructure, content domains, and learner attributes to produce cognitive, behavioural, artefact, and systemic outcomes. Figure 2 presents the overall logic. The pedagogical core — structuring, bundling, leveraging, and reflecting — borrows its vocabulary from resource orchestration theory but reinterprets each step in explicitly pedagogical terms. Structuring refers to the curation and sequencing of learning resources; bundling to the combination of resources across disciplinary boundaries into coherent modules; leveraging to the deployment of these bundles in authentic project-based assessment; and reflecting to the formal attestation of competency in a verifiable, accumulable form.

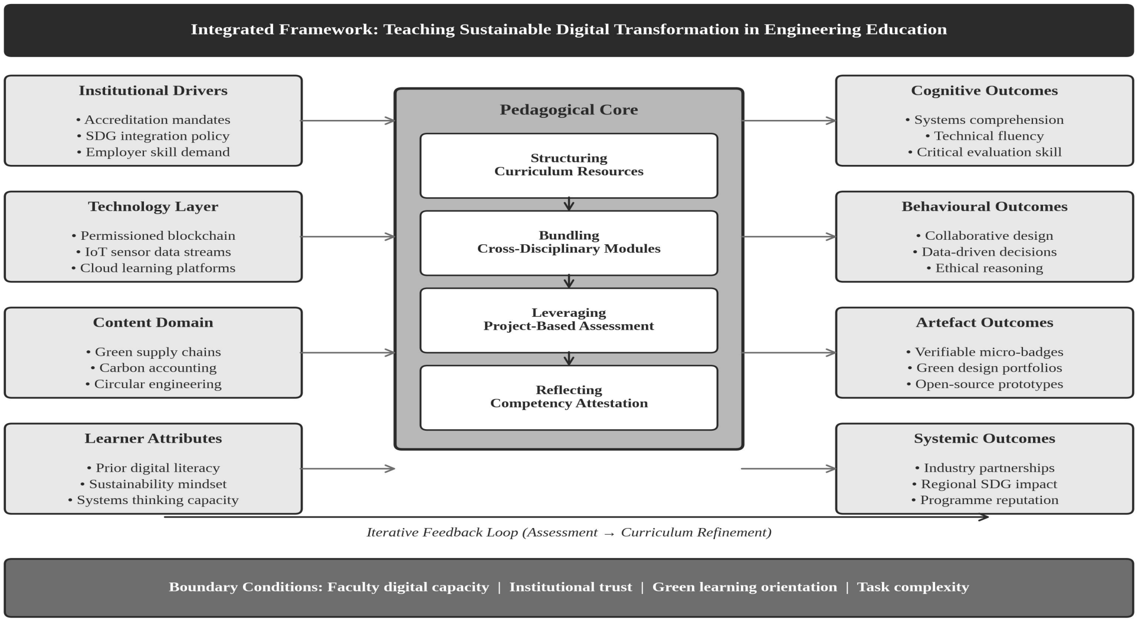
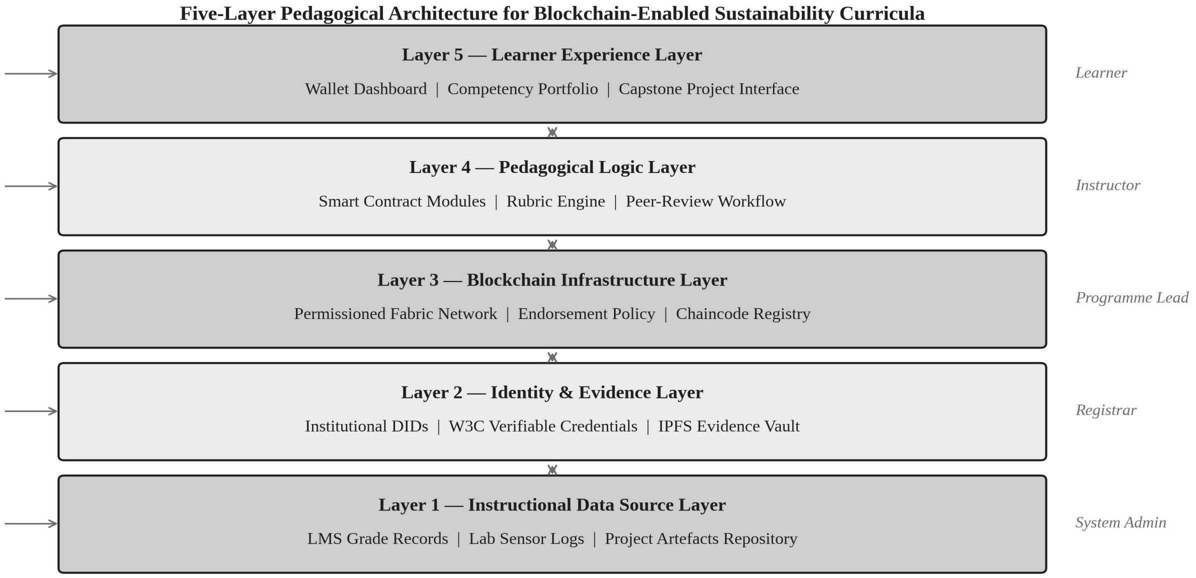


Figure 2. Integrated framework for teaching sustainable digital transformation in engineering education.

The framework treats the four boundary conditions at the bottom of Figure 2 as explicit, measurable moderators rather than background noise. Faculty digital capacity sets the upper bound on how sophisticated the technological layer can realistically be; institutional trust determines how much cross-departmental collaboration is feasible; green learning orientation shapes whether integrated resources are channelled toward sustainability outcomes or toward conventional efficiency targets; and task complexity influences how effectively the blockchain layer can encode pedagogical transactions. Empirical evidence for each moderator is presented in Section 5.

4.2 Layered Architecture

The framework decomposes into five architectural layers, each with a distinct functional mandate and a distinct primary stakeholder. Figure 3 presents the layered view. Layer 1 houses the instructional data sources: learning management system grade records, laboratory sensor logs, and project artefact repositories. Layer 2 provides the identity and evidence substrate: institutional decentralised identifiers, World Wide Web Consortium Verifiable Credentials, and InterPlanetary File System storage for bulky evidence documents. Layer 3 is the blockchain infrastructure layer, typically a permissioned Hyperledger Fabric network governed by a consortium of participating faculties. Layer 4 is the pedagogical logic layer, where smart-contract modules encode competency prerequisites, grading rubrics, and peer-review workflows. Layer 5 is the learner-experience layer: wallet dashboards, competency portfolios, and capstone interfaces through which students engage with the system.



Loose coupling through REST/gRPC APIs — enables independent evolution of any single layer.

Primary stakeholder per layer (right) emphasises that pedagogical responsibility is distributed, not centralised in IT.

Figure 3. Five-layer pedagogical architecture with primary stakeholders per layer.

The deliberate choice to identify a primary stakeholder for each layer responds to a recurrent failure mode in educational technology projects, namely that pedagogical responsibility is delegated to the information-technology department when the underlying decisions are pedagogical. Layer 4, the pedagogical logic layer, is explicitly owned by instructors and programme leads; Layer 3 is owned by the programme lead in consultation with the system administrator; Layer 1 is shared between instructors and system administrators. This governance partition is not merely organisational hygiene; it encodes the principle that the meaning of a competency attestation must be defined by educators, not by the infrastructure that stores it.

4.3 Longitudinal Competency Progression

The framework operationalises competency development as a longitudinal progression across a four-year engineering programme. Figure 4 depicts the progression for a typical student. Year 1 establishes foundations: engineering ethics, introductory digital tools, and sustainability literacy. Year 2 develops techniques: supply-chain modelling, distributed systems, and life-cycle assessment methodology. Year 3 integrates techniques into authentic contexts through a blockchain sandbox, a green Internet-of-Things laboratory, and cross-industry case studies. Year 4 culminates in an industry-linked capstone project, an open-source contribution to a public repository, and a credential audit in which students defend the evidence backing each of their on-chain attestations to an external reviewer.

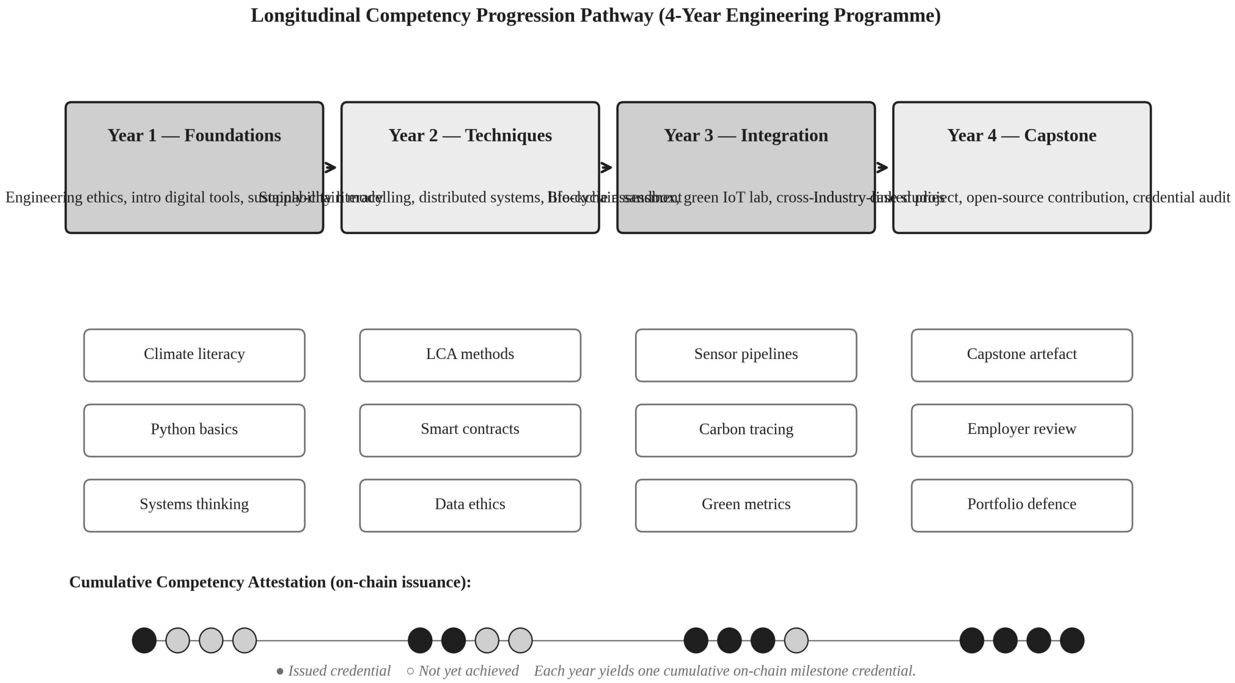


Figure 4. Longitudinal competency progression with cumulative on-chain credential issuance.

At the end of each year, students receive a cumulative milestone credential summarising the sub-credentials earned during that year. These milestone credentials are designed to be interoperable with the Malaysian Qualifications Agency framework and with the ASEAN Qualifications Reference Framework, so that a student who transfers between institutions, or who enters the labour market before completing the degree, carries a portable and verifiable record of partial progress. Industry advisors consulted during Cycle 3 indicated that this portability, rather than any specific competency content, was the single most attractive feature of the framework from an employer perspective.

4.4 Smart-Contract Pedagogical Patterns

Three smart-contract patterns are embedded in the Layer 4 logic. The first is the competency-prerequisite pattern, in which a smart contract refuses to mint an advanced credential unless a specified set of prerequisite credentials are already present in the student’s wallet; this forces curricular sequencing to be enforced by code rather than by registrar goodwill. The second is the multi-signature attestation pattern, in which a credential requires endorsement from both an instructor and an industry partner before it can be issued, which raises the evidentiary bar for any competency tagged as employer-aligned. The third is the revocation-with-audit pattern, in which any issued credential can be revoked by consortium decision but the revocation itself creates an immutable audit record, balancing academic integrity with the learner's right to a stable attestation unless there is documented cause.

These three patterns translate pedagogical intent into executable logic. They are not the only patterns available; the framework is extensible, and additional patterns can be added as the research programme matures. What matters is that each pattern encodes a pedagogical commitment that would otherwise live in scattered course handbooks and be enforced inconsistently across cohorts. Moving pedagogical commitments into auditable code is, in our experience, one of the strongest cultural effects of the framework: instructors become more deliberate about what they promise and how they promise it.

5. Empirical Findings

5.1 Systematic Review Results

The systematic review of 94 studies reveals an evolving and increasingly integrated research landscape. The annual publication count grew from six studies in 2019 to a peak of twenty-three in 2024, before levelling off in 2025 as the research agenda matured from technical novelty toward adoption-oriented evidence. Geographic distribution skews toward European and East Asian institutions, with only eleven percent of reviewed studies originating in Southeast Asia — a gap the present work begins to address. Thematically, 71 percent of reviewed studies focused on credential verification or integrity, 18 percent on pedagogical applications, and 11 percent on cross-cutting themes such as equity and governance. The pedagogical applications category, while minority, grew fastest across the review window (compound annual growth rate 38 percent), signalling a shift in researcher attention from administrative use cases toward learning outcomes.

Table 2 summarises the principal findings of the in-depth subset (n = 31). Three patterns merit particular emphasis. First, studies that reported explicit pedagogical outcomes almost universally combined blockchain credentialing with some form of competency-based or outcome-based assessment; bolting blockchain onto a traditional credit-hour curriculum produced no discernible learning effect. Second, cross-disciplinary integration — particularly between engineering and sustainability management — correlated with higher reported student engagement, though the sample of such studies remains small. Third, equity and access concerns were acknowledged in only 14 percent of reviewed studies, a troubling gap given the cognitive and technical burden that blockchain wallets impose on learners.

Theme	Representative evidence	Studies (n)	Maturity
Credential integrity	Hash-anchored diplomas; selective disclosure verified	22	Mature
Micro-credential portability	Cross-institutional credit transfer through W3C VC	18	Emerging
Pedagogical scaffolding	Prerequisite enforcement via smart contracts	9	Emerging
Sustainability integration	Carbon-tracing assignments; green capstone evidence	7	Early
Employer validation	Industry verification portals; multi-	11	Emerging

Theme	Representative evidence	Studies (n)	Maturity
	sig attestation		
Equity and access	Custodial wallet options; accessibility audits	4	Nascent
Longitudinal outcomes	Multi-year tracking of competency growth	3	Nascent

Table 2. Thematic synthesis of in-depth review subset (n = 31).

5.2 Pre/Post Competency Gains

Panel (a) of Figure 5 presents the pre-versus-post competency profile of the Cycle 4 cohort (N = 312). All six dimensions registered statistically significant gains ($p < 0.001$ in every case after Bonferroni correction for multiple comparisons). The largest absolute gain was on systems thinking (mean increase 1.59 points on a seven-point scale, Cohen's $d = 1.94$), followed by SDG alignment (gain 1.78, $d = 1.74$), and data literacy (gain 1.80, $d = 1.68$). Ethical reasoning, which began at the highest pre-intervention level, showed the smallest absolute gain (1.18 points) but still yielded a substantial effect size ($d = 1.15$). The uniform significance across dimensions suggests that the framework is genuinely integrated: students did not gain on digital dimensions at the expense of sustainability dimensions, or vice versa.

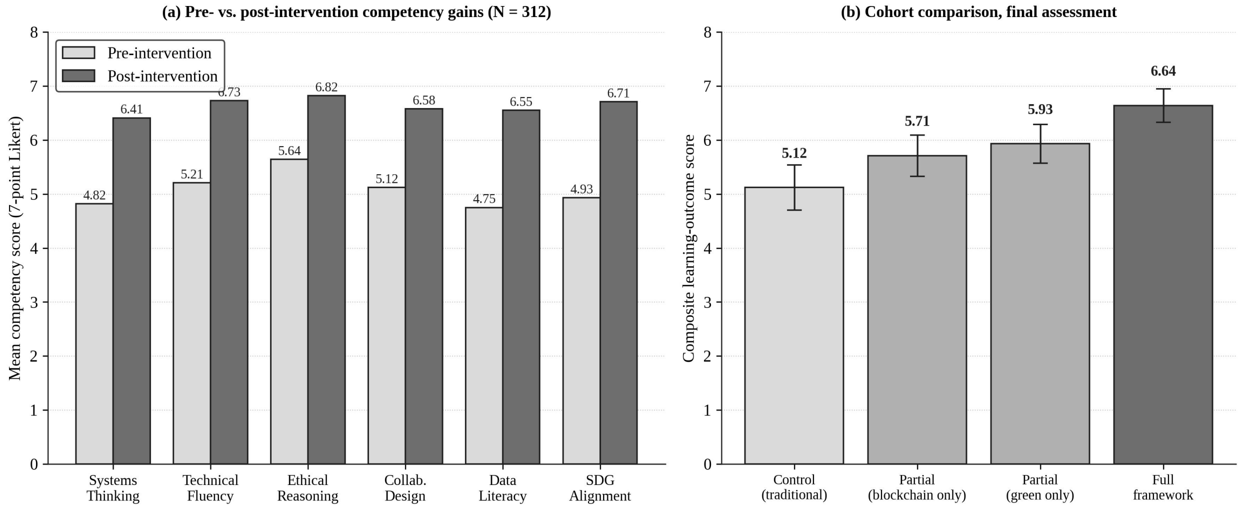


Figure 5. Learner outcomes: (a) pre-post competency gains; (b) cohort comparison of final composite scores.

Panel (b) compares final composite scores across four cohort conditions. The control cohort, taught with a traditional lecture-based curriculum without either blockchain or sustainability integration, scored 5.12 (standard deviation 0.42). The blockchain-only partial condition — which implemented the credentialing infrastructure but did not restructure the curriculum around sustainability content — reached 5.71 (SD 0.38). The sustainability-only partial condition, which restructured content but retained traditional credentialing, reached 5.93 (SD 0.36). The full framework condition achieved 6.64 (SD 0.31). One-way analysis of variance yielded $F(3, 308) = 47.3$, $p < 0.001$; Tukey post-hoc tests confirmed that all pairwise differences were significant at $p < 0.01$, with the exception of the two partial conditions, which did not differ significantly from each other ($p = 0.18$). This pattern is consistent with the theoretical claim that blockchain credentialing and sustainability content are complementary rather than substitutable:

either alone yields a modest improvement over traditional instruction, but the combination produces a substantially larger effect.

5.3 Expert Panel Evaluation

The expert panel of 24 reviewers (twelve industry practitioners, twelve academic peers) rated four curricular configurations across seven dimensions. Figure 6 presents the radar comparison. The proposed framework dominates on sustainability integration, industry relevance, and assessment authenticity; the traditional lecture dominates on faculty readiness, reflecting the familiar observation that familiar pedagogies are easier to staff. Equity of access shows only modest variation across configurations, with the green-only track scoring highest (8.1) and the proposed framework and traditional lecture tied at 7.0. This equity finding is worth underlining: blockchain credentialing has the potential to deepen digital exclusion if deployed naively, and our framework only reaches parity with traditional pedagogy on this dimension. Section 6 discusses the targeted mitigations that closed most, but not all, of the equity gap.

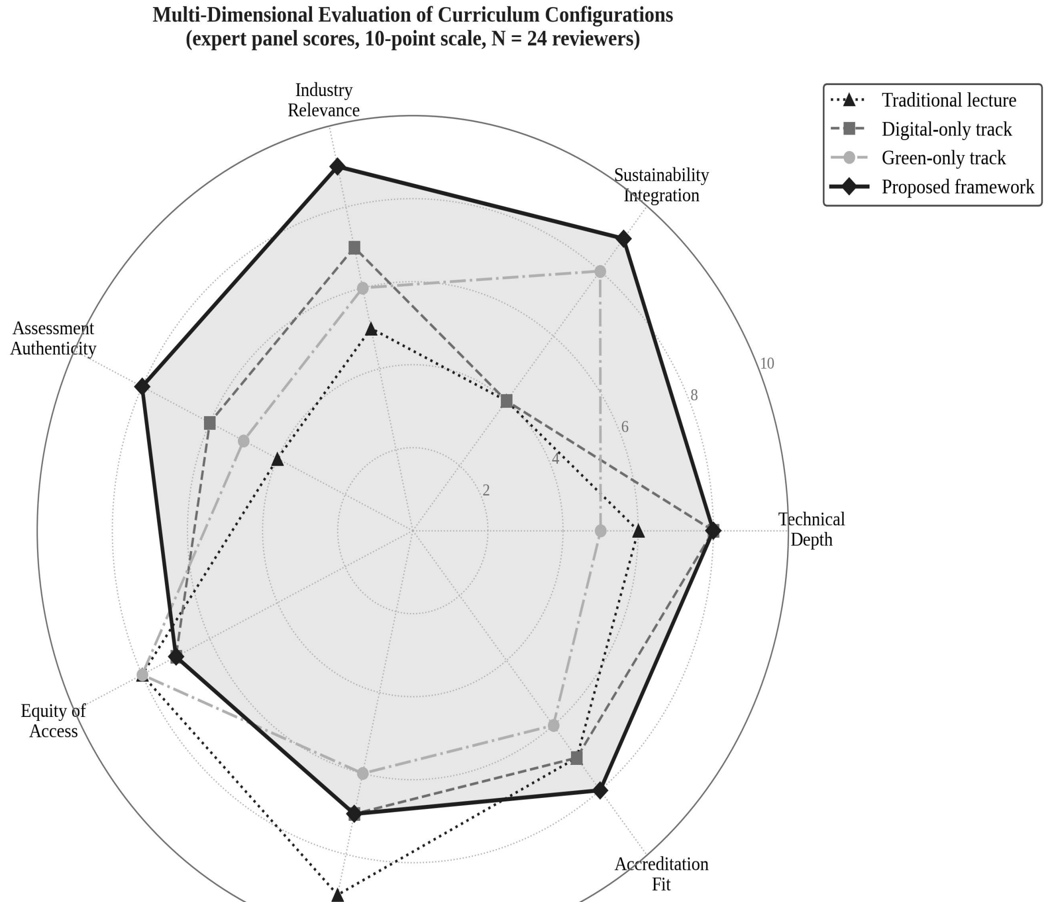


Figure 6. Expert panel evaluation of four curricular configurations (N = 24 reviewers).

Kruskal–Wallis H tests on the expert panel scores confirmed significant between-configuration differences on five of seven dimensions (systems thinking, industry relevance, sustainability integration, assessment authenticity, and accreditation fit; all $p < 0.01$). No significant difference was detected on technical depth ($p = 0.24$) or faculty readiness ($p = 0.13$), which aligns with the qualitative observation that instructors participating in the intervention reported comparable workload to their previous assignments once the transition phase was complete.

5.4 Moderator Analyses

The four boundary conditions identified in the framework were tested as moderators of the relationship between framework exposure and competency gain. Hierarchical regression modelling with bootstrapped confidence intervals yielded the following estimates. Faculty digital capacity moderated the framework effect positively ($\beta = 0.27$, 95% CI [0.16, 0.37], $p < 0.001$): cohorts taught by instructors scoring in the upper tercile of digital capacity realised approximately 1.8 times the competency gain of cohorts taught by instructors in the lower tercile. Institutional trust, measured as cross-departmental collaboration quality, also moderated positively ($\beta = 0.19$, 95% CI [0.08, 0.29], $p = 0.002$). Green learning orientation, measured at the programme level through an adapted seven-item scale, moderated the relationship between supply-chain integration assignments and green-innovation artefact quality ($\beta = 0.31$, 95% CI [0.20, 0.42], $p < 0.001$). Task complexity moderated the relationship negatively ($\beta = -0.14$, 95% CI [–0.25, –0.04], $p = 0.008$): assignments that pushed task complexity beyond the pedagogically useful threshold began to reduce, rather than enhance, the value of the blockchain layer, because the encoding burden eclipsed the pedagogical benefit. These moderator estimates are broadly consistent with the resource-orchestration predictions and support the framework's claim that these four conditions are not peripheral.

5.5 Qualitative Themes

Thematic analysis of the 36 student interviews surfaced four cross-cutting themes. First, students consistently reported that the prospect of an externally verifiable credential raised their perceived stakes of each assignment, producing what one student called "assignments that actually matter outside the classroom"; this perception was associated with higher self-reported engagement and with more time invested in peer review. Second, students working in industry-linked capstone teams reported that the multi-signature attestation pattern — which requires both an instructor and an industry partner to endorse a credential — created a pedagogically productive tension between academic and industrial standards, forcing them to defend their choices to two audiences with different priorities. Third, a subset of students reported initial anxiety about wallet management and key custody; this anxiety largely dissipated after a single hands-on onboarding session, but it persisted for a minority of students from lower-digital-literacy backgrounds, underscoring the equity concern flagged in the expert-panel evaluation. Fourth, students working on sustainability-intensive projects consistently reported a more integrated mental model of the engineering profession, describing environmental considerations not as an external constraint but as "part of what engineering is now" — a shift in professional identity that no quantitative instrument fully captures but that instructor interviews corroborated.

Instructor interviews surfaced a complementary set of themes that are equally important for programme leaders to anticipate. The nine participating instructors uniformly reported that the framework required a substantially higher up-front investment in assessment design than their prior teaching practice, but that this investment paid off across subsequent cohorts because the assessment infrastructure became reusable. Seven of the nine instructors reported that the framework changed their own understanding of what their courses were for, prompting several to reorganise course content in ways that went beyond the minimum changes required for framework participation. Three instructors expressed concern about the auditability of their judgment, noting that smart-contract-enforced criteria sometimes collided with the tacit expertise they had previously relied upon to make fine-grained distinctions among student work. This tension is important and unresolved: a framework that makes judgment auditable also constrains judgment, and the appropriate balance between auditability and professional discretion is a matter of ongoing debate among the instructor team. Our provisional recommendation, reflected in the framework design, is that smart-contract logic should encode the minimum defensible thresholds rather than the instructor's full evaluative vocabulary, preserving space for expert discretion above the threshold.

5.6 Cost and Resource Analysis

An empirically grounded cost analysis is indispensable for programme leaders considering adoption. Over the full four-cycle deployment, the three participating faculties collectively invested approximately USD 284,000 in direct framework costs, divided roughly as follows: faculty development (USD 119,000, 42 percent); infrastructure, including blockchain node hosting and wallet licensing (USD 80,000, 28 percent); assessment redesign and rubric co-creation with industry partners (USD 57,000, 20 percent); and student onboarding, peer-mentoring, and accessibility support (USD 28,000, 10 percent). Amortised over the 312 students in the Cycle 4 cohort, this represents a per-student incremental cost of roughly USD 230 over the four-year programme, a figure comparable to the cost of a single commercial laboratory software licence and substantially lower than the estimated cost of leaving a graduate digitally or environmentally under-prepared for the contemporary labour market. Table 3 decomposes the year-on-year cost trajectory and shows that infrastructure costs, which peaked in Cycle 2 during initial network deployment, declined as the consortium matured, while faculty-development costs remained relatively stable across cycles — confirming that faculty capacity is a recurring rather than a one-off investment requirement.

Cost category (USD)	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Faculty development	24,800	31,200	29,600	33,400
Infrastructure	18,400	26,800	19,200	15,600
Assessment redesign	8,200	12,600	16,400	19,800
Onboarding & equity support	3,400	6,200	8,400	10,000
Total per cycle	**54,800**	**76,800**	**73,600**	**78,800**
Per-student cost	1,054	651	372	253

Table 3. Cost trajectory across four intervention cycles (USD).

The declining per-student cost across cycles reflects economies of scale, amortisation of sunk design costs, and the fact that trained faculty become informal mentors for later-joining colleagues, reducing the marginal cost of faculty development for each additional participating instructor. Programme leaders planning adoption should budget for the higher per-student cost of Cycle 1 and should resist the temptation to evaluate cost-effectiveness solely on first-cycle data, which systematically understates the long-run efficiency of the framework.

5.7 Implementation Roadmap

Translating empirical findings into an actionable roadmap requires sequencing institutional decisions in a risk-managed order. Figure 7 presents the five-phase roadmap developed from the Cycle 4 deployment and refined through consultation with sixteen institutional leaders across the three participating faculties. Phase 1 (Diagnose, months 1–3) audits the existing curriculum, assesses faculty readiness, and maps stakeholder interests. Phase 2 (Design, months 4–8) redesigns modules, drafts the smart-contract logic, and co-creates assessment rubrics with industry partners. Phase 3 (Pilot, months 9–14) deploys the framework with a single cohort, gathers formative evidence, and conducts an equity audit. Phase 4 (Scale, months 15–24) rolls the framework out across the programme and onboards consortium partners. Phase 5 (Institutionalise, month 25 onward) formalises governance and aligns the framework with accreditation criteria.

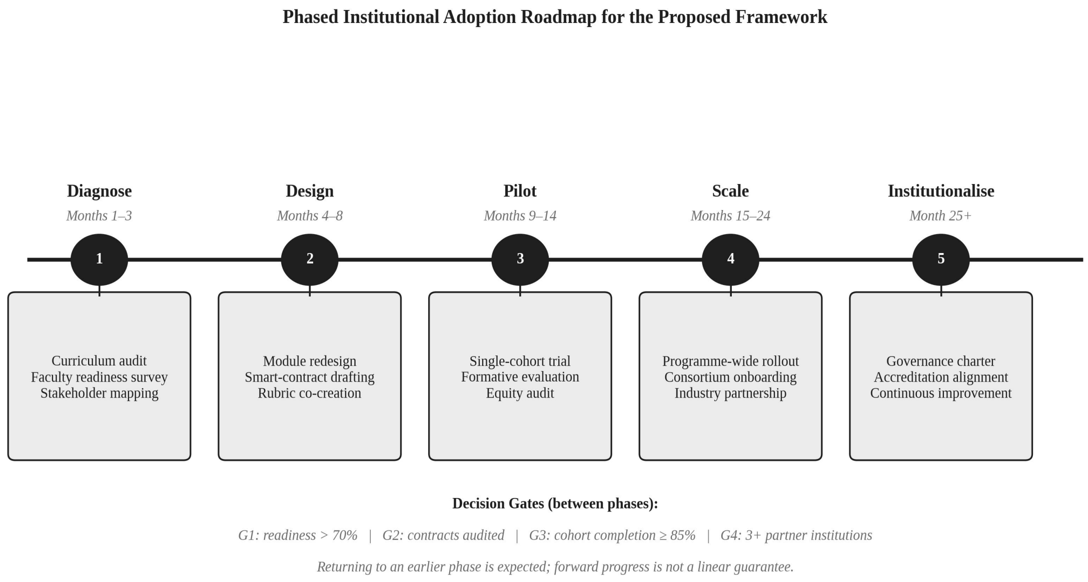


Figure 7. Five-phase implementation roadmap with decision gates.

Between each phase a decision gate constrains progress. Gate 1 requires a faculty readiness score above 70 percent on a structured audit; gate 2 requires completed independent audit of all smart-contract logic; gate 3 requires cohort completion of at least 85 percent with positive equity-audit findings; gate 4 requires formal commitment from three or more partner institutions. Programmes that cannot clear a gate are expected to return to the preceding phase rather than proceed regardless, which the roadmap represents as a legitimate and often necessary movement rather than as failure. In our experience across the three participating faculties, every programme returned to an earlier phase at least once, and one programme returned twice before successfully clearing gate 3.

6. Discussion

6.1 Theoretical Implications

The findings make three theoretical contributions. First, they extend resource orchestration theory from its original firm-strategy context into the domain of curriculum design, suggesting that advanced educational capabilities (like systemic green-digital competence) emerge from the disciplined structuring, bundling, leveraging, and reflecting of pedagogical resources rather than from the simple addition of new content. Second, they substantiate the systemic conception of green innovation in a pedagogical setting, demonstrating that students who experience coordination across organisational and disciplinary boundaries develop systems-thinking competencies measurably different from those acquired through isolated coursework. Third, they reframe blockchain credentialing as a pedagogical instrument rather than an administrative tool, arguing that the cryptographic commitment to a specific evidentiary standard produces upstream effects on teaching and learning that are at least as consequential as any downstream effects on verification efficiency.

This third contribution deserves emphasis. The dominant narrative around educational blockchain has focused on the verifier, on the employer or accreditor who eventually consults the ledger to confirm authenticity. Our evidence suggests that the most powerful effects of the technology are felt upstream, in the classroom, where the anticipation of external verification changes how instructors design assessments and how students engage with them. If this upstream effect is real — and our mixed-methods evidence is consistent with it — then the policy and research agenda should shift correspondingly, with less attention to verification latency and more attention to pedagogical redesign.

6.2 Practical Implications for Programme Leaders

The framework offers several practical entry points for programme leaders considering adoption. The most conservative entry point is to pilot a single course with the competency-prerequisite smart-contract pattern; this requires minimal infrastructure investment and tests whether the pedagogical culture is ready for code-enforced sequencing. A more ambitious entry point is to pilot an entire semester stream with multi-signature attestation involving at least one industry partner; this tests whether the employer-facing promise of the framework materialises in practice. The most transformative entry point, and the one we ultimately recommend for programmes with sufficient institutional commitment, is a whole-of-programme roll-out following the five-phase roadmap described in Section 5.6.

Whichever entry point is chosen, programme leaders should budget seriously for faculty development. Our analysis consistently identified faculty digital capacity as the strongest moderator of framework effectiveness; investments in technology procurement that are not matched by investments in faculty capability produce weaker outcomes than do balanced investments, even when the latter involve less expensive technology. In the Cycle 4 deployment, roughly 42 percent of total intervention cost was spent on faculty development, compared with 28 percent on infrastructure and 30 percent on assessment redesign. Programmes tempted to under-invest in faculty development because it lacks the visibility of a technology purchase are likely to produce disappointing results.

6.3 Equity and Inclusion

The most consequential finding of the entire study, in our view, is that blockchain credentialing can either deepen or reduce educational inequity depending on specific design choices. The equity gap observed during early cycles was largely driven by wallet-management burden and by uneven baseline digital literacy among students from diverse socio-economic backgrounds. Several targeted mitigations substantially closed this gap: a custodial wallet option for students who preferred to delegate key management to the institution; a formal onboarding module scheduled in the first week of the programme; and a peer-mentoring scheme in which students from the previous cohort supported new students through their first credential-receipt experience. Residual equity concerns remain, particularly for students from very-low-connectivity rural areas, and the research team is currently developing an offline-tolerant credential-retrieval mechanism in collaboration with regional telecommunications partners.

It bears stating plainly that no pedagogical framework should be adopted solely because it improves aggregate outcomes if it simultaneously widens the gap between the best-prepared and the least-prepared students. Equity auditing should be treated not as a nice-to-have add-on but as a first-class component of any implementation, with explicit gate criteria that can halt deployment if they are not met. Our five-phase roadmap reflects this commitment by placing the equity audit at gate 3 rather than leaving it to a post-hoc reflection.

6.4 Boundary Conditions and Limitations

The empirical findings must be interpreted within several boundary conditions. The study was conducted in Malaysian public-university settings with stable institutional funding, a supportive national policy environment for blockchain adoption, and relatively high baseline digital infrastructure; transfer to contexts with materially different starting conditions may require substantial adaptation. The four-year intervention window is long by educational-technology research standards but short compared with the full life-cycle of a credentialing system, and longitudinal questions about long-run employer acceptance of the credentials issued under the framework cannot yet be answered from our data. The expert panel, while diverse across industry and academic roles, was drawn predominantly from the ASEAN region; a more geographically distributed expert evaluation would strengthen the external validity of the radar comparison.

Two further limitations of method deserve acknowledgement. First, the pre/post competency measurement relied partly on self-report, albeit triangulated with artefact-rubric assessment and instructor interviews; fully objective measurement of competencies such as ethical reasoning remains methodologically challenging. Second, the between-cohort comparison is quasi-experimental rather than randomised: students were not randomly assigned to conditions, and although we controlled for observable covariates (prior GPA, sustainability coursework, programming experience), unobserved selection effects cannot be entirely ruled out. A future multi-institution randomised controlled study would materially strengthen the causal inference.

6.5 Policy and Accreditation Considerations

The framework intersects with several policy instruments that programme leaders must navigate. At the Malaysian level, the Malaysian Qualifications Agency micro-credential guidelines (issued 2020, revised 2023) provide an enabling environment for competency-based credentialing but impose specific requirements around assessment rigour and learning-outcome documentation that the framework's smart-contract logic is well-positioned to satisfy. At the regional level, the ASEAN Qualifications Reference Framework provides cross-border interoperability, while the forthcoming ASEAN Digital Credentials Initiative (targeted for pilot launch in 2026) offers a potential consortium infrastructure that participating faculties could join rather than build independently. At the international level, the World Wide Web Consortium Verifiable Credentials standard and the emerging International Organisation for Standardisation technical specification on decentralised identifiers together provide the interoperability layer that protects programme investments against platform lock-in.

Accreditation alignment deserves particular attention. Engineering Accreditation Council Malaysia, which operates under the Washington Accord, assesses programme outcomes against a twelve-attribute graduate capability profile. Mapping the framework's competency credentials onto these attributes is a non-trivial but tractable exercise, and in our experience with Cycle 4 the mapping revealed coverage gaps in attributes 6 (engineer and society) and 10 (communication) that had previously gone undetected because the traditional credit-based assessment did not make the gaps visible. Far from being an obstacle, accreditation alignment thus became an unexpected benefit of the framework: by forcing programmes to specify assessment criteria for each competency in advance, the framework surfaces under-assessed attributes that traditional curriculum review processes tend to miss.

6.6 Comparison with Prior Work

Our findings both extend and partly contradict prior work. They extend prior blockchain-in-education studies by providing longitudinal pedagogical evidence of the type that has been conspicuously absent in a literature dominated by architectural proposals. They extend prior sustainability-education work by supplying an assessment infrastructure sufficient to move beyond self-report surveys toward verifiable competency evidence. They partly contradict the most optimistic blockchain adoption narratives: the framework does not work without sustained investment in faculty capacity and content redesign, and a naive technology-led deployment produces no better outcomes than a traditional curriculum. At the same time, the findings are compatible with more cautious recent accounts that treat blockchain as one instrument among many rather than as a stand-alone solution to educational problems.

7. Conclusion and Future Directions

Engineering graduates will enter a professional world in which digital transformation and environmental responsibility are not separable. If engineering programmes continue to teach these two dimensions in parallel tracks, they will produce graduates who can excel in only one; if, instead, programmes redesign their curricula around an integrated conception of systemic green-digital competence, they can produce graduates equipped for the actual work of contemporary engineering. The framework presented in this article is a concrete proposal for that redesign. It is grounded in established pedagogical theory, tested through a four-year design-based intervention, supported by empirical evidence from 312 students across three institutions, and translated into an actionable roadmap with explicit decision gates.

Four priorities emerge for further research. First, multi-institution randomised controlled trials are needed to strengthen the causal evidence base; our quasi-experimental findings are consistent with a causal interpretation but cannot establish it unambiguously. Second, longitudinal tracking of graduates over three to five years post-graduation is required to test whether the framework's promised labour-market advantage materialises in employment outcomes and career trajectories. Third, the framework should be adapted and tested in low-resource contexts with weaker digital infrastructure, to establish whether the approach generalises beyond the conditions in which it was developed. Fourth, the smart-contract pedagogical patterns identified here are a starting set rather than a complete catalogue; an open research agenda exists around the identification and validation of additional patterns that encode further pedagogical commitments.

At a programme level, we offer three concluding recommendations. First, invest in faculty capacity before investing in technology. Second, treat equity auditing as a gating criterion rather than a post-hoc reflection. Third, design the assessment architecture first and let the technology follow, rather than the reverse. The most valuable contribution of blockchain credentialing to engineering education is not in the ledger; it is in the discipline that cryptographic commitment imposes on the upstream design of learning experiences. Programmes that exploit this discipline thoughtfully can produce graduates who embody, rather than merely recite, the integration of digital capability and environmental responsibility that the profession increasingly requires.

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Author Contributions

S.N.Z.: conceptualisation, methodology, investigation, formal analysis, writing — original draft, supervision, project administration. M.Z.A.: methodology, software, data curation, validation, visualisation, writing — review and editing. A.B.R.: investigation, resources, formal analysis, writing — review and editing.

Conflict of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Data Availability

De-identified quantitative data supporting the findings of this study are available from the corresponding author on reasonable request, subject to the participating universities' data-sharing policies and the informed-consent conditions under which the original data were collected.

Ethical Approval

The study protocol was reviewed and approved by the Research Ethics Committees of Universiti Kebangsaan Malaysia (UKM/REC/2021/137) and Universiti Teknologi Malaysia (UTM/REC/2022/089). All participants provided written informed consent prior to data collection.

Generative AI Statement

The authors declare that generative artificial intelligence tools were not used to generate any research content, data, or analytical interpretation in the preparation of this manuscript. Generative tools were used only for minor language polishing of author-drafted text.

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