

Integrating Green Manufacturing Concepts into Industrial Engineering Education: A Curriculum Simulation to Strengthen Students' Environmental Literacy

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Abstract

This study designed and simulated an instructional model for integrating green manufacturing concepts into industrial engineering education to strengthen students' environmental literacy. The study responded to the tendency of manufacturing courses to emphasize productivity, cost, and quality while treating environmental considerations as supplementary content. A design-oriented literature synthesis and curriculum simulation were employed. Green manufacturing principles were mapped onto four environmental literacy dimensions: knowledge, cognitive skills, attitudes and values, and action competence. Two eight-week curriculum scenarios were then compared: a conventional lecture-centered model and an integrated model combining material and energy flow analysis, cleaner production, life-cycle thinking, circular economy, contextual industrial cases, collaborative projects, and reflective assessment. A transparent opportunity-to-learn rubric was used to score curriculum coverage; the scores represented design characteristics rather than observed student achievement. The simulation showed that the integrated scenario provided substantially broader and deeper coverage across all environmental literacy dimensions, particularly cognitive application and action competence. The proposed model also linked technical analysis with the spatial and social consequences of industrial activity, enabling students to consider communities, workers, resource users, and other stakeholders in engineering decisions. The study concluded that green manufacturing should be embedded across learning outcomes, content, pedagogy, assessment, and partnerships rather than offered as an isolated topic. A phased implementation involving lecturer preparation, local industry collaboration, project-based assessment, and empirical pilot evaluation was recommended.

Keywords: Circular Economy; Curriculum Simulation; Environmental Literacy; Green Manufacturing; Industrial Engineering Education; Sustainable Production

1. INTRODUCTION

Manufacturing systems generate economic value and employment, but they also shape patterns of energy consumption, material extraction, waste generation, emissions, land use, and community exposure to environmental risk. Sustainable manufacturing therefore requires more than the installation of cleaner equipment (Gutowski et al., 2013). It requires engineers who can understand production as a socio-technical system and evaluate the consequences of technical decisions across the product life cycle. Green manufacturing provides a practical orientation for this purpose because it seeks to reduce environmental impacts while maintaining the economic and operational viability of production systems (Deif, 2011; Garetti & Taisch, 2012). Its scope includes resource efficiency, pollution prevention, cleaner production, environmentally conscious process design, life-cycle assessment, remanufacturing, and circular material flows.

Industrial engineering education is strategically positioned to support this transition (Koch et al., 2025). Industrial engineers design and improve integrated systems involving people, materials, information, equipment, energy, and organizations (Shil, 2023). Decisions about

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facility layout, inventory, quality, work methods, supply chains, and production planning can either reproduce resource-intensive practices or contribute to more responsible production (Haapala et al., 2013).). However, sustainability is often introduced as a separate elective, a short lecture, or a general institutional campaign rather than being embedded in core engineering analysis. When environmental content is separated from technical decision-making, students may recognize environmental problems without being able to incorporate environmental criteria into process design and improvement.

Education for Sustainable Development emphasizes the development of knowledge, skills, values, attitudes, and behavior needed to make responsible decisions for environmental, economic, and social well-being (UNESCO, 2020). This orientation is consistent with environmental literacy, which includes not only knowledge of environmental systems but also competencies for analyzing issues, affective dispositions, and the capacity to participate in responsible action (Hollweg et al., 2011). Environmental literacy is therefore broader than awareness. An environmentally literate industrial engineering student should be able to identify environmental pressures in a production system, interpret material and energy data, compare alternatives, recognize ethical and social trade-offs, communicate with diverse stakeholders, and propose feasible improvement actions.

Sustainability education also requires pedagogies that move beyond the transmission of concepts. Wiek et al. (2011) identified systems thinking, anticipatory, normative, strategic, and interpersonal competencies as central to sustainability problem solving. Brundiers et al. (2021) later reinforced the importance of integrating these competencies into higher education programs. Project-based learning, case studies, problem-based learning, simulations, community engagement, and reflective activities are especially relevant because they allow students to connect knowledge with decisions and action (Lozano et al., 2017). In engineering education, active learning has consistently been associated with deeper engagement than exclusively lecture-based instruction (Prince, 2004). These approaches are compatible with industrial engineering practice, which already relies on process mapping, measurement, optimization, teamwork, and continuous improvement.

The integration of green manufacturing can also broaden the social and geographical relevance of industrial engineering education (Jawahir et al., 2013). Industrial facilities are located in specific places where environmental burdens and benefits are distributed unevenly (Walker et al., 2005). Water use, waste transport, air emissions, traffic, and land conversion may affect workers and surrounding communities differently. A contextual curriculum can therefore use local industrial areas, small and medium enterprises, campus operations, or community production systems as learning environments. Such contextualization reflects ecopedagogical principles that connect environmental learning with lived social realities and encourage critical responsibility (Misiaszek, 2016). It also aligns with recent IJGSME publications that position universities and contextual environmental learning as important settings for sustainability awareness and action (Pratama et al., 2025; Ramadhani et al., 2026).

Recent evidence further suggests that green manufacturing knowledge is related to engineering students' environmental attitudes and sustainability awareness. Dewiyani et al. (2026) found that environmental attitude played an important role in the relationship between green manufacturing knowledge and sustainability awareness among engineering students. This finding indicates that curriculum design should address cognitive and affective learning

simultaneously. Technical knowledge alone may be insufficient when students do not discuss values, responsibility, uncertainty, or the social consequences of industrial decisions. Conversely, attitude-oriented activities without analytical tools may not enable students to develop technically feasible solutions.

Despite the relevance of these ideas, educators still need an implementable structure showing where green manufacturing concepts can be placed, how learning can be assessed, and how environmental literacy can be developed without replacing the technical identity of industrial engineering. The novelty of this study was the construction of a curriculum simulation that connected green manufacturing content, environmental literacy dimensions, active pedagogies, and contextual industrial problems in one model. The simulation was not intended to claim empirical improvement in student performance. Instead, it examined the opportunity to learn created by alternative curriculum designs and generated recommendations for subsequent classroom implementation.

Accordingly, this study addressed two questions: (1) How can green manufacturing concepts be integrated into an industrial engineering learning module to cover the major dimensions of environmental literacy? and (2) What implementation strategy can be recommended based on a comparison between a conventional curriculum scenario and an integrated green manufacturing scenario?.

2. METHOD

This study used a design-oriented literature synthesis followed by a curriculum simulation. The approach was selected because no primary student data were available and the purpose was to develop an implementable instructional model rather than to estimate an empirical treatment effect. The unit of analysis was an eight-week learning module that could be embedded in courses such as Production Systems, Manufacturing Systems, Facilities Planning, Work System Design, Operations Management, or Sustainable Manufacturing.

The conceptual sources were selected purposively from four groups. The first group concerned green and sustainable manufacturing, including systems models, resource efficiency, process improvement, life-cycle thinking, and circular production. The second group concerned Education for Sustainable Development and sustainability competencies. The third group concerned environmental literacy and ecopedagogy. The fourth group concerned active and experiential pedagogies in higher education. Priority was given to peer-reviewed publications, international frameworks, and studies that offered clear implications for curriculum design. The source base is represented by the works cited in this article.

Curriculum construction was completed in four stages. First, six content domains were identified: environmental impacts of manufacturing; material and energy flow analysis; cleaner production and waste prevention; lean-green process improvement; life-cycle thinking and circular economy; and environmental management with stakeholder responsibility. Second, these domains were mapped to four environmental literacy dimensions adapted from Hollweg et al. (2011): knowledge, cognitive and analytical skills, attitudes and values, and action competence. Third, suitable pedagogical activities and assessments were assigned to each domain. Fourth, the integrated curriculum was compared with a conventional scenario through an opportunity-to-learn scoring rubric.

The conventional scenario was defined as an eight-week module dominated by lectures on productivity, cost, quality, and process efficiency, with one introductory session mentioning environmental impacts and a final written examination. The integrated scenario retained the same industrial engineering foundation but added environmental performance indicators, contextual cases, team investigation, stakeholder analysis, reflective discussion, and an improvement project. Each environmental literacy dimension was evaluated across six curriculum components: learning outcomes, content, pedagogy, assessment, industrial or community context, and reflection or action. A score of 0 indicated absence; 1 indicated brief mention; 2 indicated explicit teaching or assessment; and 3 indicated applied learning through an authentic task and feedback. The maximum score was 18 for each literacy dimension and 72 for the complete scenario.

The scores were generated from the documented characteristics of the two curriculum scenarios. They were design outputs, not measurements of actual students. Their purpose was to make assumptions explicit and to compare the relative breadth of learning opportunities. The interpretation emphasized curricular coverage rather than causal impact. Figure 1 summarizes the conceptual pathway used in the model.

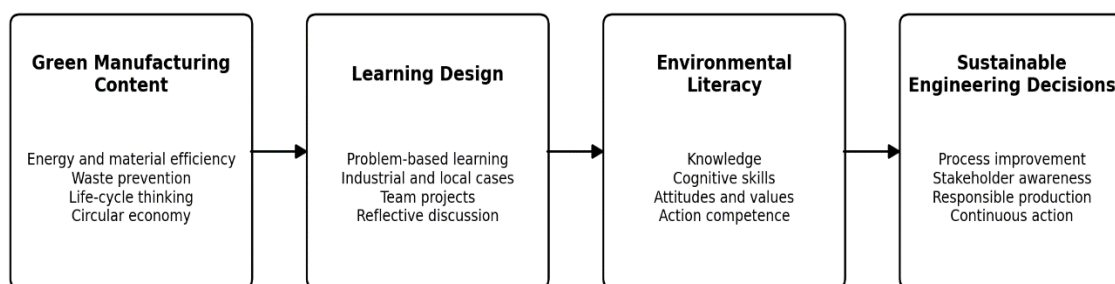


Figure 1. Conceptual pathway for integrating green manufacturing into industrial engineering education.

3. RESULTS AND DISCUSSION

3.1. Proposed Curriculum Integration

The curriculum design produced an eight-week sequence in which environmental literacy was developed through progressively more complex industrial engineering tasks. The sequence began with system boundaries and environmental pressures, continued with quantitative analysis of material and energy flows, and ended with a team-based improvement proposal. The model did not remove conventional concerns such as productivity, quality, time, and cost. Instead, it expanded the criteria used to define process performance.

Table 1 shows the proposed integration. Knowledge was developed through concepts and indicators; cognitive skills were developed through mapping, calculation, comparison, and evaluation; attitudes and values were addressed through discussion of responsibility and trade-offs; and action competence was developed through improvement planning and communication. The inclusion of local and spatial context was important because environmental effects are experienced in specific communities and ecosystems rather than only in abstract global indicators.

Table 1. Proposed eight-week green manufacturing integration module

Week	Core topic	Learning activity	Environmental literacy emphasis	Main output
1	Manufacturing–environment relationships	Map system boundaries and identify environmental pressures in a local production case.	Knowledge; systems thinking	Impact map
2	Material and energy flow analysis	Construct a simplified material-flow and energy balance.	Knowledge; analytical skills	Flow diagram and indicators
3	Cleaner production and waste prevention	Apply the waste hierarchy and identify source-reduction options.	Analytical skills; responsibility	Waste prevention proposal
4	Lean-green process improvement	Compare productivity and environmental waste using value-stream analysis.	Analytical and strategic skills	Lean-green improvement map
5	Life-cycle thinking	Compare alternatives using simplified life-cycle criteria and carbon implications.	Anticipatory and evaluative skills	Alternative comparison matrix
6	Circular economy and eco-design	Redesign a product, packaging, or process for reuse, repair, remanufacturing, or recycling.	Creativity; values; action competence	Circular design concept
7	Stakeholders, place, and environmental responsibility	Analyze effects on workers, communities, suppliers, and local resources.	Attitudes; interpersonal competence	Stakeholder dialogue brief
8	Integrated improvement project	Present a feasible technical, environmental, economic, and social improvement plan.	All dimensions	Team presentation and action plan

3.2. Curriculum Simulation Results

The opportunity-to-learn simulation indicated a marked difference between the two curriculum scenarios. The conventional scenario generated limited coverage because environmental content was mentioned but was not consistently expressed in learning outcomes, assessed through authentic tasks, or connected with action. The integrated scenario generated high coverage because the same concepts were reinforced across multiple curriculum components.

As shown in Table 2, the largest difference occurred in action competence. This result followed directly from the design assumptions. A lecture-and-examination model could introduce environmental terminology, but it offered few opportunities for students to investigate a process, negotiate trade-offs, and formulate an implementable improvement. The integrated design required students to move from identifying impacts to producing an action plan. This progression is consistent with ESD, which connects knowledge with responsible action (UNESCO, 2020), and with environmental literacy frameworks that include competencies, dispositions, and participation rather than knowledge alone (Hollweg et al.,

2011).

Table 2. Simulated opportunity-to-learn coverage by environmental literacy dimension

Environmental literacy dimension	Conventional scenario (0–18)	Integrated scenario (0–18)	Interpretation of difference
Environmental knowledge	5	16	Concepts were systematically connected to manufacturing indicators and decisions.
Cognitive and analytical skills	4	17	Students repeatedly mapped, calculated, compared, and evaluated alternatives.
Attitudes and values	1	16	Reflection and stakeholder analysis made responsibility and trade-offs explicit.
Action competence	0	16	The project required a feasible improvement plan, communication, and follow-up indicators.
Total	10/72	65/72	The integrated scenario created broader curriculum coverage; it did not represent observed student achievement.

The simulated improvement in cognitive coverage was also important. Green manufacturing should not be reduced to slogans such as saving energy or reducing waste. Industrial engineering students need analytical instruments that allow them to diagnose where resources are lost and why. Material flow diagrams, energy intensity, waste ratios, process yield, environmental value-stream mapping, and simplified life-cycle comparisons can be incorporated into familiar industrial engineering tasks. Deif (2011) emphasized the systemic character of green manufacturing, while Garetti and Taisch (2012) highlighted the need to connect manufacturing performance with broader sustainability challenges. The proposed module translated these principles into learning activities that could be completed with modest data and software requirements (Von Hippel, 2021).

The high simulated coverage of attitudes and values resulted from adding social and contextual dimensions to technical analysis. Students were asked to examine who benefited from an industrial activity, who experienced environmental burdens, and how improvement alternatives affected workers, communities, suppliers, and local resources. This did not transform the course into a purely social science subject. Rather, it made explicit the stakeholder conditions within which engineering solutions are implemented. Misiaszek (2016) argued that ecopedagogy should connect environmental issues with critical citizenship and local-global relationships. In the proposed model, a local case made abstract sustainability concepts visible and encouraged students to understand production as part of a place-based social system.

The curriculum also addressed the relationship between knowledge and environmental attitude. Dewiyan et al. (2026) showed that environmental attitude contributed to the relationship between green manufacturing knowledge and sustainability awareness. The implication for teaching is that students need opportunities to interpret and discuss evidence, not only receive it. Reflective prompts can ask students to explain the values embedded in a

process decision, identify acceptable and unacceptable trade-offs, and consider professional responsibility. Group work involving students with different regional, cultural, and disciplinary experiences can further enrich the discussion, provided that participation is structured and respectful.

The model was compatible with sustainability competency frameworks. Systems thinking was developed through boundary definition and flow mapping; anticipatory competence through life-cycle comparisons and future scenarios; normative competence through discussion of values and responsibility; strategic competence through improvement planning; and interpersonal competence through teamwork and stakeholder communication (Wiek et al., 2011). The combination of case studies, project work, problem-based learning, and reflection was also consistent with the pedagogical framework proposed by Lozano et al. (2017). These pedagogies are more likely to develop integrated competence than a single instructional method used in isolation.

3.3. Design

Assessment was designed to align technical performance with environmental literacy. A student should not receive a high score merely for expressing a positive environmental opinion, nor should a technically efficient proposal be considered complete when it transfers pollution to another process, place, or stakeholder. The assessment structure therefore combined conceptual knowledge, quantitative analysis, design quality, justification of trade-offs, teamwork, and reflective responsibility.

Table 3. Recommended assessment structure for the integrated module

Assessment component	Weight	Evidence of learning	Primary literacy dimensions
Concept quiz and short explanations	15%	Understanding of green manufacturing, environmental indicators, and life-cycle concepts.	Knowledge
Material and energy flow assignment	20%	Accurate mapping, calculations, interpretation, and identification of losses.	Knowledge; cognitive skills
Contextual industrial case audit	25%	Problem diagnosis, stakeholder analysis, and comparison of improvement alternatives.	Cognitive skills; attitudes
Integrated team improvement project	30%	Feasible proposal balancing technical, economic, environmental, and social criteria.	Cognitive skills; action competence
Individual reflection and action commitment	10%	Professional responsibility, lessons learned, and realistic follow-up action.	Attitudes; action competence

Recommended Implementation Strategy

The first recommendation is to begin with curriculum mapping rather than immediately creating a new course. Lecturers can identify where green manufacturing already appears implicitly in existing courses and convert those points into explicit learning outcomes and assessments. For example, a facilities planning assignment can add energy and community-access criteria; a quality course can examine environmental defects and material loss; a production planning case can include energy peaks, waste constraints, or reverse flows; and a

supply chain task can include traceability and end-of-life recovery. This approach reduces curriculum overload and demonstrates that sustainability is part of engineering quality rather than an additional topic.

The second recommendation is to implement a small pilot. One class, one local case, and one integrated project are sufficient for the first cycle. The pilot should collect baseline and post-module evidence using a validated environmental literacy instrument, performance rubrics, student reflections, and lecturer observations. Where feasible, a comparison class or a repeated-measures design can be added. Because the present simulation did not involve actual learners, empirical evaluation is essential before claiming effectiveness.

The third recommendation is to strengthen lecturer and partner readiness. Lecturers may need short training in life-cycle thinking, environmental indicators, facilitation of value-based discussion, and project assessment. Partnerships with local industries, small enterprises, campus facility managers, environmental agencies, or communities can provide authentic problems and data. The UNEP (2021) Sustainable University Framework emphasizes that teaching and research should be connected with campus operations, people, society, and governance. A campus production unit, laboratory, canteen, workshop, or waste system may therefore serve as an accessible first case when industrial data are confidential.

The fourth recommendation is to establish clear boundaries for student projects. Projects should focus on educational analysis and low-risk recommendations rather than unauthorized environmental audits or public accusations. Data confidentiality, occupational safety, and respectful community engagement must be addressed. Students should be taught to distinguish measured evidence from assumptions and to communicate uncertainty. This practice strengthens both professional ethics and the credibility of environmental recommendations.

The fifth recommendation is to monitor implementation using multiple indicators. Suggested indicators include achievement of environmental literacy outcomes, quality of project proposals, student participation, partner feedback, continuity of recommended actions, and the extent to which sustainability criteria are used in later courses. Continuous improvement should be applied to the curriculum itself: plan the integration, implement the pilot, evaluate evidence, and revise content and assessment. In this way, the green manufacturing module becomes a learning system rather than a one-time campaign.

3.4. Limitations

The principal limitation was the absence of empirical student data. The opportunity-to-learn scores reflected the structure of two constructed scenarios and were useful for design comparison, but they could not demonstrate changes in knowledge, attitude, behavior, or academic performance. The literature selection was purposive rather than a systematic review, and the model was not evaluated by an external expert panel. Institutional differences in course credits, facilities, lecturer expertise, student background, and access to industry data may also affect implementation. Future research should pilot the module, validate the assessment instruments, compare learning outcomes across cohorts, and examine whether students transfer green manufacturing reasoning to internships and final projects.

4. CONCLUSION

This study developed a curriculum simulation for integrating green manufacturing concepts into industrial engineering education. The model embedded environmental considerations in learning outcomes, technical content, active pedagogy, assessment, contextual cases, reflection, and action. The simulation indicated that an integrated design created substantially greater opportunities to develop environmental knowledge, analytical competence, attitudes and values, and action competence than a conventional lecture-centered scenario. The model also strengthened the social and geographical relevance of industrial engineering by asking students to consider how manufacturing decisions affect workers, communities, and local resources.

The main practical implication is that green manufacturing should not be confined to an isolated lecture or elective subject. It can be incorporated into existing industrial engineering courses through material and energy analysis, cleaner production, lean-green improvement, life-cycle thinking, circular design, and stakeholder-based projects. Implementation should begin with curriculum mapping and a limited pilot supported by lecturer preparation and local partnerships. Because the results were produced through curriculum simulation rather than student observation, the next step is empirical classroom testing using validated environmental literacy measures and performance-based assessment.

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