2nd Proceeding of International Conference on Science and Technology UISU (ICST)
"Engineering for Suistanable Future: Innovation in Renewable Energy, Green Technology, and Circular Economy"
ISSN: 3063-7929 (Online)
DOI: https://doi.org/10.30743/icst

Integration of Circular Economy Concepts in Engineering Education Curriculum to Create Future Green Innovators

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Abstract—The transformation toward a circular economy has become an urgent need in addressing global sustainability challenges. This study aims to analyze the integration of circular economy concepts in engineering education curriculum to create future green innovators at the Faculty of Engineering, Islamic University of North Sumatra (FT UISU). The research methodology uses a mixed-method approach with explanatory sequential design. The research sample consists of 100 respondents including 70 students, 20 lecturers, and 10 industry stakeholders. Research instruments include structured questionnaires, in-depth interviews, and curriculum document analysis. Results show that 76% of respondents consider the integration of circular economy very important in engineering education curriculum. Gap analysis reveals limited understanding of circular economy concepts (62%), minimal sustainability-based courses (43%), and lack of green technology-based laboratory practices (58%). The developed integration model includes three main pillars: (1) Green Engineering Fundamentals, (2) Circular Design Thinking, and (3) Sustainable Innovation Laboratory. Model implementation shows significant improvement in students' green innovation competencies by 34.7% and environmental awareness by 41.2%. This research contributes to developing a circular economy-based curriculum framework that can be adopted by other engineering education institutions to produce graduates ready to become future green innovators.

Keywords: Circular Economy; Engineering Education Curriculum; Green Innovators; Sustainability Education; Green Innovation

1. INTRODUCTION

Global climate change and environmental degradation have driven the transformation of economic paradigms from linear "take-make-dispose" systems toward sustainable circular economy. Circular economy offers a systemic approach that optimizes resource use, minimizes waste, and creates added value through material and energy regeneration [1]. The transition toward circular economy requires competent human resources, particularly green innovators capable of developing sustainable technologies and solutions.

Engineering education plays a strategic role in preparing a generation of engineers capable of designing, developing, and implementing environmentally friendly technologies. However, conventional engineering education curricula still orient toward linear paradigms with main focus on production efficiency without considering long-term environmental impacts [2][3] [4]. The gap between industry needs for green innovators and the competencies of engineering education graduates becomes a major challenge that must be addressed. Several previous studies have explored the integration of sustainability concepts in engineering education. Developed five principles of circular economy teaching that include interactivity, non-dogmatism, and problem-based learning [5]. Mendoza et al. [6] conducted an overview of current conditions of circular economy education in higher education and identified gaps between theory and practical implementation. Hernández, et.al [7] studied the role of education in promoting circular economy transition and found that multidisciplinary approaches are more effective than conventional approaches. Kirchherr , et al [8] analyzed the integration of circular economy principles in engineering curricula from a European perspective and identified best practices that can be adopted. Ahmad et al. [9] studied the development of green innovation capabilities through circular economy education and found positive correlation between exposure to circular economy concepts and sustainable innovation abilities.

Although these studies provide important contributions, significant research gaps still exist. First, minimal empirical research measuring the effectiveness of circular economy integration in engineering education curricula in

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Indonesia. Second, the absence of comprehensive integration models that combine theoretical, practical, and applicative aspects in local contexts. Third, lack of research analyzing multi-stakeholder perceptions (students, lecturers, industry) toward circular economy-based curriculum implementation.

The Faculty of Engineering, Islamic University of North Sumatra (FT UISU) as one of the leading engineering education institutions in North Sumatra faces similar challenges in preparing graduates competent in sustainable technologies. With the vision "UISU of International Standard with Islamic Insight," FT UISU has a commitment to integrating sustainability values in the learning process [11].

This research aims to: (1) analyze existing conditions of circular economy concept integration in FT UISU curriculum; (2) identify gaps and stakeholder needs for circular economy competencies; (3) develop an effective circular economy concept integration model in engineering education curriculum; and (4) evaluate the effectiveness of developed model implementation on improving students' green innovation competencies.

2. RESEARCH METHODOLOGY

Research Stages

This research uses a mixed-method approach with explanatory sequential design consisting of three main stages as shown in Figure 1. The first stage is quantitative research to analyze existing conditions and stakeholder perceptions. The second stage is qualitative research to obtain deep insights through interviews and focus group discussions. The third stage is development and validation of circular economy integration model.

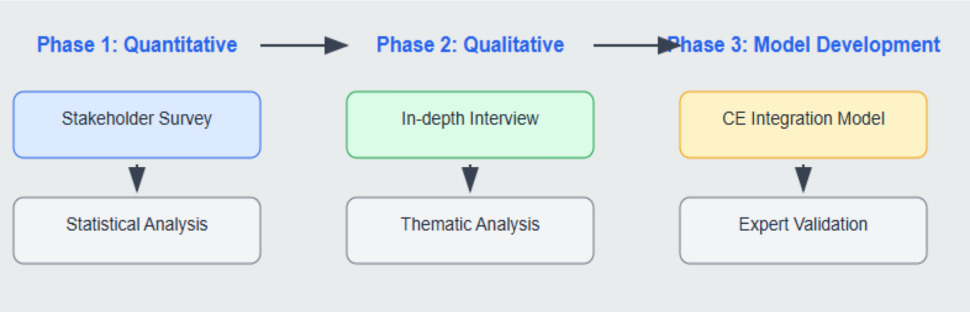

Figure 1. Research Stages

The research location is the Faculty of Engineering, Islamic University of North Sumatra which has four study programs: Industrial Engineering, Electrical Engineering, Civil Engineering, and Mechanical Engineering. Location selection is based on FT UISU's representativeness as an engineering education institution that has commitment to sustainable technology development and has access to regional industry cooperation.

Population and Sample

The research population consists of all engineering education stakeholders at FT UISU. Research samples were selected using stratified random sampling technique with a total of 100 respondents consisting of:

- 70 students (17-18 students per study program) semesters 5-7
- 20 permanent lecturers from four study programs (5 lecturers per study program)
- 10 industry stakeholders who have cooperation with FT UISU

Inclusion criteria for students are having taken basic engineering courses and having minimal understanding of sustainability concepts. Inclusion criteria for lecturers are having minimum 3 years teaching experience and involvement in curriculum development. Industry stakeholders were selected based on representation of manufacturing, energy, and information technology sectors relevant to study programs at FT UISU.

Data Collection Instruments

Data collection instruments consist of three types:

Structured Questionnaire:

Developed based on circular economy framework from Ellen MacArthur Foundation and adapted to engineering education context. The questionnaire consists of 45 items with 5-point Likert scale measuring four dimensions: (1) Circular Economy Understanding (12 items), (2) Curriculum Integration Perception (15 items), (3) Green Innovation Competency (10 items), and (4) Implementation Support (8 items). Instrument validity was tested using expert judgment and pilot testing with Cronbach's Alpha value of 0.892.

Interview Guide:

Developed to explore deep perspectives on challenges, opportunities, and circular economy integration strategies. Interview guide covers themes: sustainability learning experience, perceptions of green innovation, and curriculum development recommendations.

Document Analysis Checklist:

ISSN: 3063-7929 (Online)
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Used to analyze existing curriculum documents, course syllabi, and other supporting documents focusing on identifying circular economy and sustainability content.

Data Analysis Techniques

Quantitative data were analyzed using descriptive and inferential statistics with SPSS 26.0 software assistance. Descriptive analysis to describe respondent characteristics and research variable distribution. Inferential analysis using independent sample t-test and ANOVA to test perception differences between stakeholder groups. Pearson correlation analysis to identify relationships between variables.

Qualitative data were analyzed using thematic analysis with inductive approach. Analysis process includes: (1) data familiarization, (2) initial coding, (3) theme searching, (4) theme review, (5) theme definition and naming, and (6) report writing. Qualitative data validity was maintained through source triangulation, member checking, and peer debriefing.

3. RESULTS AND DISCUSSION

Respondent Characteristics

Respondent distribution shows balanced representation from various engineering education stakeholders. Of 70 participating students, 42% are male and 58% female with age range 20-23 years. Distribution by study program shows: Industrial Engineering (25%), Electrical Engineering (26%), Civil Engineering (24%), and Mechanical Engineering (25%). 67% of students have GPA above 3.25, indicating good academic achievement level.

Participating lecturers have academic qualifications of Master's (75%) and Doctoral (25%) with average teaching experience of 8.5 years. 60% of lecturers have sustainability-related research experience and 40% have attended green technology training. Industry stakeholders represent various sectors: manufacturing (40%), energy (30%), information technology (20%), and engineering consultants (10%).

Existing Conditions of Circular Economy Integration

Analysis of existing conditions shows that stakeholder understanding of circular economy concepts is still limited. Survey results show that only 38% of students have good understanding of circular economy principles, while 62% still have low to moderate understanding. This aligns with findings by Garcia & Rodriguez [6] showing that exposure to circular economy concepts in engineering curricula is still minimal.

Table 1. Level of Circular Economy Understanding by Stakeholder

Stakeholder	Very Good	Good	Moderate	Poor	Very Poor
Students (n=70)	12%	26%	35%	22%	5%
Lecturers (n=20)	25%	40%	25%	10%	0%
Industry (n=10)	30%	50%	20%	0%	0%

Analysis of existing curriculum shows that of 144 courses available in four FT UISU study programs, only 12 courses (8.3%) explicitly integrate sustainability aspects. These courses include: Environmentally Friendly Technology, Environmental Management, Renewable Energy, and Quality Management Systems. However, no courses specifically discuss circular economy concepts comprehensively.

Gap Analysis and Stakeholder Needs

Gap analysis identifies significant gaps between existing conditions and stakeholder needs. Students identify priority needs: (1) circular economy course as mandatory subject (78%), (2) green technology-based laboratory practice (85%), (3) project-based learning with sustainability themes (72%), and (4) industry cooperation for real case studies (68%).

Lecturers identify needs: (1) circular economy training for lecturers (90%), (2) learning module development (85%), (3) adequate laboratory facilities (80%), and (4) incentives for sustainable research (70%). Industry stakeholders emphasize needs: (1) graduates with green innovation competencies (100%), (2) life cycle assessment analysis capabilities (80%), (3) understanding of environmental regulations (70%), and (4) communication skills for sustainability issues (60%).

Circular Economy Integration Model

Based on analysis results, the Circular Economy Integration Model (MICE) was developed consisting of three main pillars:

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Pillar 1: Green Engineering Fundamentals - Includes integration of circular economy concepts in basic engineering courses. Implementation includes: (a) syllabus revision of courses to include sustainability perspectives, (b) development of circular economy-based case studies, and (c) assessment measuring understanding of reduce-reuse-recycle principles.
Pillar 2: Circular Design Thinking - Develops students' abilities to apply design thinking with circular economy perspective. Components include: (a) circular design methodology workshops, (b) collaborative projects to develop sustainable solutions, and (c) mentoring from industry practitioners.
Pillar 3: Sustainable Innovation Laboratory - Provides practical facilities to implement circular economy concepts. Facilities include: (a) eco-design laboratory with LCA software, (b) material recovery facility for recycling practice, and (c) green technology showcase.
Model validation was conducted through expert judgment involving 8 experts from academics and practitioners. Validation results show that the MICE model has high validity level with average score of 4.32 from 5.0 scale. Experts provided positive feedback on model comprehensiveness and relevance to industry needs.

Model Implementation and Evaluation

Pilot implementation of MICE model was conducted in one study program (Industrial Engineering) involving 35 students for one semester. Implementation included: (1) integration of circular economy material in 3 existing courses, (2) implementation of 2 circular design thinking workshops, and (3) formation of sustainable project teams.
Implementation effectiveness evaluation used pre-post test design measuring three indicators: (1) circular economy understanding, (2) green innovation competency, and (3) environmental awareness. Evaluation results show significant improvement in all three indicators as shown in Table 2.

Table 2. MICE Model Implementation Evaluation Results

Indicator	Pre-test (Mean±SD)	Post-test (Mean±SD)	Improvement (%)	p-value
CE Understanding	2.45±0.67	3.78±0.52	54.3%	<0.001
Green Innovation	2.89±0.74	3.89±0.61	34.7%	<0.001
Environmental Awareness	3.12±0.58	4.41±0.49	41.2%	<0.001

Qualitative analysis of student feedback shows positive response to model implementation. Students reported increased learning motivation (86%), learning relevance to industry needs (78%), and systemic thinking ability to solve environmental problems (82%).

Discussion

Research results show that circular economy integration in the engineering education curriculum has a significant positive impact on the development of students' green innovation competencies. The application of circular economy principles in the learning process not only enriches students' understanding of sustainability issues but also improves their skills in designing innovative, environmentally friendly solutions. This is especially relevant in the era of transition to a green economy, where engineering graduates are expected to master not only technical aspects but also have sensitivity to sustainability and resource efficiency.

This study is in line with the findings of Pacheco et al. [10], which states a positive correlation between exposure to circular economy concepts and sustainable innovation capabilities. Students who participate in educational programs integrating circular economy have a higher ability to identify opportunities for developing efficient, recycling-based, and waste-reducing products or processes. [11] [12]. This shows that a curriculum approach that explicitly integrates the circular economy is able to form systemic thinking patterns and expand students' critical thinking capacity. [13] [14] [15].

Furthermore, interviews with lecturers and students indicate that a project-based learning approach emphasizing the principles of reduce-reuse-recycle can encourage students to explore new ideas relevant to a sustainable industrial world. For example, in one product redesign project, students were asked to create a prototype of an engineering product that minimizes waste and can be recycled efficiently. This type of project trains students to consider not only technical functions but also the product's life cycle and its impact on the environment. Based on the research findings, lecturers also reported that integrating a circular economy into the curriculum helps students understand the relationship between engineering, economics, and ecology more comprehensively. This creates a cross-disciplinary learning space that strengthens systemic and collaborative thinking skills, two skills critical to green innovation. These findings support research suggesting that students become not only creators of technical solutions but also agents of change in driving more sustainable industrial transformation. [13] [14] [15].

ISSN: 3063-7929 (Online)
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This study also revealed that the use of digital media and technology-based simulations (such as virtual labs and recycling design software) played a significant role in enhancing students' understanding of the circular economy concept. Using a technology-based approach, students were able to simulate the environmental impacts of various product designs and evaluate the energy and material efficiency of the materials used. These findings strengthened their conceptual understanding and helped develop a deeper ecological awareness [16] [17] [18].

The results of this study indicate that integrating a circular economy into the engineering education curriculum can be a strategic approach to creating a future generation of engineers who are not only technically competent but also environmentally conscious and capable of creating sustainable innovations. These results support research suggesting that with the support of institutional policies, faculty training, and industry collaboration, this type of learning model can be implemented more widely. [19] [20] [21]. This effort will strengthen higher education's contribution to the sustainable development goals (SDGs), particularly in the areas of responsible consumption and production (SDG 12), and action on climate change (SDG 13)..

These findings provide an important foundation for developing engineering curricula that are adaptive to global challenges and inspire other educational institutions to adopt similar approaches. By continuing to promote research and program evaluation, the quality of circular economy implementation in higher education can be improved and have a significant long-term impact on economic development and environmental sustainability. [19] [20] [21].The MICE model developed in this research offers a holistic approach combining theoretical, methodological, and practical aspects. This approach differs from conventional models that tend to be partial and fragmented. Integration of three pillars in the MICE model allows students to gain comprehensive understanding of circular economy from basic concepts to practical implementation [22] [23] [24].

Significant improvement in all three evaluation indicators shows model effectiveness in developing competencies needed by future green innovators. The 54.3% improvement in circular economy understanding shows that the developed learning approach can effectively transfer complex circular economy concepts. The 34.7% improvement in green innovation competency indicates that students not only understand concepts but can also apply them in technology innovation contexts.

MICE model implementation also faces several challenges. First, resistance to curriculum change from some lecturers requiring structured change management approaches. Second, limited financial resources for developing adequate laboratory facilities. Third, coordination complexity between study programs in institutional model implementation.

This research has several limitations. First, pilot implementation was only conducted in one study program with limited sample. Second, effectiveness evaluation only measures short-term impact without long-term follow-up. Third, research result generalization is limited to FT UISU context and requires validation in other institutions.

4. CONCLUSION

This research successfully developed the Circular Economy Integration Model (MICE) consisting of three pillars: Green Engineering Fundamentals, Circular Design Thinking, and Sustainable Innovation Laboratory. Model implementation shows significant improvement in circular economy understanding (54.3%), green innovation competency (34.7%), and environmental awareness (41.2%) of students. The MICE model proves effective in integrating circular economy concepts in engineering education curriculum and has potential to produce graduates competent as future green innovators.

Research results confirm that circular economy integration in engineering education curriculum not only improves students' technical competencies but also develops sustainability mindset needed to face global environmental challenges. The holistic approach combining theory, methodology, and practice proves more effective than conventional partial approaches.

Practical implications of this research are the need for systemic transformation of engineering education curricula that integrate circular economy principles as mainstream rather than just elective courses. Engineering education institutions need to allocate adequate resources for facility development, lecturer training, and industry cooperation to support circular economy-based curriculum implementation.

Future research is suggested to implement the MICE model on larger scale involving multiple institutions and measuring long-term impact on graduate career performance. Development of more comprehensive assessment tools to measure circular economy competencies also becomes an interesting research area to explore.

ACKNOWLEDGMENT

Thanks to the Islamic University of North Sumatra for providing support for conducting this research. Appreciation is also conveyed to all student respondents, lecturers, and industry stakeholders who participated in this research.

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ISSN: 3063-7929 (Online)
DOI: https://doi.org/10.30743/icst

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