SUPPLEMENTARY INFORMATION

Revision of Manuscript [SU-ART-06-2025-000545]

Greener Chemistry for a Sustainable Future: An Interdisciplinary Course based on Systems Thinking

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UNIT 1: GREEN CHEMISTRY IN EVERYDAY LIFE

Learning Goals:

1. Make connections between sustainable chemistry and household/personal care products used in everyday life
2. Investigate a traditional commercially available product and compare it to a more environmentally friendly equivalent
3. Determine the short- and long-term impacts of greener products on the environment, health, safety, and economics
4. Identify advantages and barriers associated with the production and marketing of greener products

Deliverable

Students design a concise case study (approximately 3-5 pages) including:

1. **Introduction** (3 pts): Brief introduction of the product selected and the company/manufacturer involved
2. **Rationale** (2 pts): Explanation of why this product was chosen
3. **Chemistry** (3 pts): Comparison of chemical composition and properties of traditional vs. greener alternative
4. **Immediate Impacts** (3 pts): Effects on environment, health, safety, and economics
5. **Long-term Significance** (2 pts): Broader implications for sustainability
6. **Barriers** (3 pts): Challenges related to production and marketing (cost, public perception, regulatory constraints)
7. **Conclusions** (2 pts)
8. **References** (2 pts)

Total Points: 20

Example Topics

- Biodegradable fishing line ("TUF-line")

- Eco-friendly all-purpose cleaner ("Green Llama")
- Natural indigo dye in textile industry ("Indigo Rit")

UNIT 2: SYSTEMS THINKING AND SOCME MAPPING

Learning Goals:

1. Connect chemistry to systems thinking using the System-Oriented Concept Map Extension (SOCME) visualization tool
2. Apply green chemistry principles and life cycle analysis to a chemical element and its use in reactions
3. Evaluate environmental, economic, health, and social impacts using a cradle-to-cradle approach

Deliverable

Students create a digital SOCME (PowerPoint, Canva, or equivalent) mapping the life cycle of a chosen chemical element.

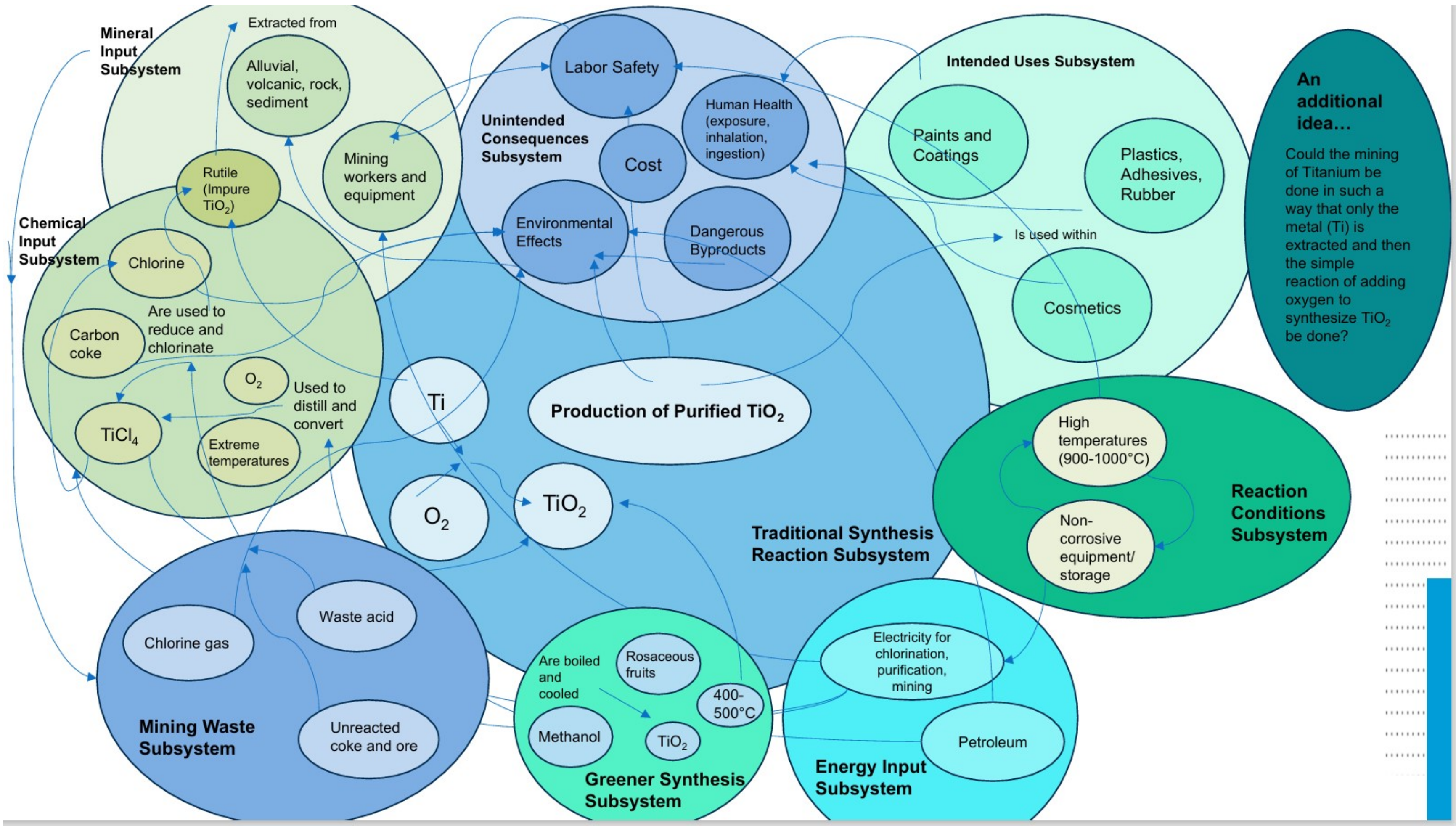
Assessment Rubric (40 points total)

Component	Points
Traditional synthesis reaction subsystem	4
Mineral input subsystem	3
Chemical input subsystem	3
Energy input subsystem	3
Reaction conditions subsystem	3
Mining waste subsystem	3
Intended uses subsystem	3
Unintended consequences subsystem	3
Greener synthesis alternative	4
Identification of green chemistry principles	4
Benefits of greener synthesis	3
Additional sustainability considerations	2
References with links	2

Example Elements Studied:

- Titanium (Ti) in purified TiO_2 production
- Copper (Cu) in copper chloride formation
- Magnesium (Mg) in MgO production

Example of SOCME for Titanium:



Mineral Input Subsystem
Extracted from
Alluvial, volcanic, rock, sediment
Mining workers and equipment
Rutile (Impure TiO2)
Chemical Input Subsystem
Chlorine
Are used to reduce and chlorinate
Carbon coke
O2
Used to distill and convert
TiCl4
Extreme temperatures
Unintended Consequences Subsystem
Labor Safety
Human Health (exposure, inhalation, ingestion)
Cost
Environmental Effects
Dangerous Byproducts
Intended Uses Subsystem
Paints and Coatings
Plastics, Adhesives, Rubber
Is used within
Cosmetics
An additional idea…
Could the mining of Titanium be done in such a way that only the metal (Ti) is extracted and then the simple reaction of adding oxygen to synthesize TiO2 be done?
Ti
Production of Purified TiO2
O2
TiO2
Traditional Synthesis Reaction Subsystem
High temperatures (900-1000°C)
Non-corrosive equipment/ storage
Reaction Conditions Subsystem
Chlorine gas
Waste acid
Unreacted coke and ore
Mining Waste Subsystem
Are boiled and cooled
Rosaceous fruits
400-500°C
Methanol
TiO2
Greener Synthesis Subsystem
Electricity for chlorination, purification, mining
Petroleum
Energy Input Subsystem

UNIT 3: AI AND MACHINE LEARNING IN SUSTAINABLE CHEMISTRY

Learning Goals:

1. Familiarize yourself with how AI/machine learning can enhance greener and sustainable chemistry practices
2. Critically analyze peer-reviewed literature at the intersection of AI and green chemistry
3. Communicate research findings and ethical implications to diverse audiences

Deliverable

Teams of 2-3 students create and deliver a 20-minute presentation (30 minutes for teams of 3) on a recent peer-reviewed article (published within past 5 years) where AI/machine learning or computer-aided design drives innovation in sustainable chemistry.

Presentation Content:

1. Understanding the Research

- Primary research question
- Connection to previous research
- Methodologies and rationale
- Key findings

2. Implications and Impacts

- Practical implications
- Contribution to existing knowledge
- Beneficial populations/contexts

3. Critical Analysis

- Strengths and limitations
- Effect of limitations on conclusions
- Potential biases

4. Broader Context

- Relation to current trends
- Ethical considerations
- Policy/practice implications

- Future research directions

Presentation Rubric (32 points total)

Criteria	Exceeds (4)	Meets (3)	Approaching (2)	Not Yet (1)
Content Understanding	Thorough understanding of article, methods, findings	Good grasp with minor gaps	Basic understanding; some key points missed	Little understanding; misinterpretations
Organization	Well-structured; clear intro, body, conclusion	Mostly organized; logical flow	Some organization; scattered ideas	Disorganized; difficult to follow
Visual Aids	Excellent use; enhances understanding	Good visuals; minor issues	Present but poorly designed	No visuals or irrelevant
Delivery	Confident, clear; excellent eye contact	Clear; mostly confident	Hesitant; inconsistent eye contact	Difficult to understand
Critical Thinking	Insightful analysis; broader connections	Some analysis; relevant connections	Limited analysis; mostly summary	No analysis; purely descriptive
Q&A Session	Confident, thoughtful responses	Adequate answers; shows understanding	Struggles; vague responses	Unable to address questions
Time Management	Within allotted time	Slightly over/under	Rushed or underdeveloped	Too rushed/incomplete
Team Interaction	Seamless collaboration; mutual support	Good teamwork; occasional awkward transitions	Uneven contributions	Lack of teamwork; dominated

Grading: Final grade = (1/3) peer average + (2/3) instructor grade

Weight: 10% of final course grade

Example Research Topics

- AI-driven waste segregation and biodegradation of plastics

- Machine learning for pesticide detection and degradation
- Autonomous platforms for ocean biogeochemistry assessment
- Predictive modeling of particulate matter toxicity

UNIT 4: GREEN CHEMISTRY AND UN SUSTAINABLE DEVELOPMENT GOALS

Learning Goals:

1. Inform the public about global challenges highlighted in the UN SDGs
2. Gain global perspective including developed and developing country contexts
3. Investigate green chemistry contributions to UN SDGs using systems thinking
4. Develop original solutions and suggest future directions

Deliverable

Each student creates an informative website demonstrating how green chemistry contributes to achieving one of the 17 UN Sustainable Development Goals.

Website Requirements:

Content:

- Structured arguments showing application of 12 green chemistry principles
- Clear demonstration of chemistry knowledge
- Synthesis of published information
- Original conclusions and future work suggestions
- Qualitative and quantitative information
- Relevant references and links

Design:

- Attractive, organized, easy to navigate
- Evidence-based position
- Clear author identification
- Relevant, functional links
- Multimedia and graphical elements
- Correct grammar and spelling

Website Rubric (40 points total)

Authority/Credibility (10 points)

- Author clearly identified
- Contact information provided
- Purpose clearly stated

Content (10 points)

- Accurate, reliable information
- Meaningful and useful content
- Relevant chemistry presented
- Original information included
- Qualitative and quantitative data
- Absence of bias
- Original conclusions and future work
- Links to substantive resources
- Current, functional links
- Effective multimedia elements
- Correct grammar/spelling

Design and Technical Features (10 points)

- Logical organization
- Attractive appearance
- Readable text
- Uncluttered pages with headings
- Appropriate icons
- Consistent design

Navigation (10 points)

- Easy movement around site
- Functional external/internal links

- Clear link descriptions
- Easy return to home page

Grading Scale: 1-10 for each criterion (1 = below expectations, 10 = exceeds expectations)
Weight: 10% of final course grade

Example SDG Topics

- **Goal #2:** Climate-Smart Agriculture
- **Goal #6:** Water pollution prevention through greener herbicides
- **Goal #7:** Bio-based technologies (crab-zinc batteries)
- **Goal #9:** Adaptable infrastructure with minimal environmental impact
- **Goal #12:** Edible food packaging to reduce plastic waste
- **Goal #15:** Alternatives to paper making

UNIT 5: COMMUNITY-BASED INNOVATION PROJECT

Learning Goals:

1. Apply green chemistry, systems thinking, and sustainable development to local challenges
2. Design chemistry-based solutions for campus/community issues
3. Engage stakeholders and communicate proposals effectively
4. Integrate at least 3 green chemistry principles and 3 UN SDGs

Deliverables

This culminating project has three components:

1. Team Proposal (15% of final grade)

Format: Maximum 5 double-spaced pages (excluding cover page, references, appendices)

Required Sections:

Cover Page (2 pts)

- Title: "Applying Green and Sustainable Chemistry to Address [Local Challenge]"
- Infographic (see Component 2)

Introduction (5 pts)

- *Background:* Explain local challenge with relevant statistics/anecdotes

- *Significance:* Discuss broader implications (health risks, economic costs)

Objectives (5 pts)

- *Primary Goal:* Clear statement of achievement
- *Specific Aims:* Measurable objectives

Proposed Solution (5 pts)

- *Green Chemistry Approach:* Innovative processes/products minimizing waste, energy, harmful byproducts
- *Implementation Plan:* Timeline with phases, milestones, responsibilities

Community Engagement (5 pts)

- *Stakeholder Involvement:* Identify key parties
- *Education and Outreach:* Workshops, materials, collaborations

Expected Outcomes (5 pts)

- *Environmental Benefits:* Improved metrics
- *Economic Benefits:* Potential savings
- *Social Benefits:* Health/quality of life improvements

Evaluation and Monitoring (5 pts)

- *Assessment Plan:* Metrics and methods
- *Adjustments:* Feedback collection and iterative improvements

Budget and Funding (5 pts)

- *Budget Overview:* Categories (materials, labor, education)
- *Funding Sources:* Grants, partnerships, government programs

Conclusion (5 pts)

- Transformative potential summary

References (3 pts)

- Well-formatted academic sources

Total: 50 points

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2. Infographic (5% of final grade)

Purpose: Visual overview of the initiative for stakeholders

Required Elements (20 points total):

Element	Points
Clear, engaging title	2
Key points/data (digestible chunks, statistics)	3
Visual elements (graphics, icons, charts)	3
Organized sections/categories	2
Cohesive color scheme	2
Clear fonts/typography with hierarchy	2
Call to action	2
Sources and citations	2
Contact information	2

Total: 20 points

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3. Pitch Presentation (10% of final grade)

Format: 10-minute presentation (15 minutes for teams of 3) + 5-minute Q&A

Grading: 50% peer evaluation + 50% instructor evaluation

Presentation Rubric (35 points total)

Criteria	Excellent (5)	Good (4)	Satisfactory (3)	Needs Improvement (2)	Unsatisfactory (1)
Content	Thoroughly addresses all key points with detail	Covers most points adequately	Some points; lacks depth	Minimal coverage; vague	Fails to address key points
Organization	Logical structure; smooth flow	Mostly organized; minor lapses	Some organization; hard to follow	Poorly organized	Disorganized
Engagement	Captivates; interactive	Engages; some interaction	Limited engagement	Little engagement	No engagement
Visual Aids	High-quality;	Good; supports	Some visuals;	Minimal; poor	No/ineffective

Criteria	Excellent (5)	Good (4)	Satisfactory (3)	Needs Improvement (2)	Unsatisfactory (1)
	enhances understanding	content	limited value	quality	visuals
Delivery	Confident, clear, expressive	Clear; mostly confident	Adequate; lacks energy	Unclear; nervous	Very poor; difficult
Q&A Handling	Confident, thorough responses	Handles well; knowledgeable	Answers; lacks depth	Struggles; limited understanding	Unable to answer
Overall Impact	Strong impression; inspires action	Good impression; encourages interest	Average; doesn't motivate	Weak impression	No impact

Total: 35 points

Example Student Proposals

1. **Nitrogen-fixing plants** to reduce fertilizer use on campus green spaces
2. **On-campus wind turbines** for renewable energy generation
3. **Solar and kinetic energy capture** to power vending machines
4. **EcoShine:** Greener cleaning alternative synthesis
5. **Bio-based materials** to replace traditional asphalt in parking lots (See **Example of an infographic on the next page)**


BIO-BASED
ASPHALT
Join our community to raise $30,000 for replacing Washington College's traditional asphalt parking lots with bio-based alternatives. Let's go green together!
U.S. roads are made of:
94% Asphalt
6% Concrete
Asphalt produces 2500 tons of VOC (volatile organic compounds) per year
Skyrockets by 70% for every 20°C increase in temperature
WHY BIO-BASED?
Reduces CO2 emission by 6.4 gigatons
Lowers VOC emission by 50%; improves health
Decreases cost from $750 per ton to $164 per ton
Greener, cleaner, and more sustainable campus
FUNDRAISING $30,000 DETAILS:
02.13.2025
04.00PM UNTIL 7.00PM
300 WASHINGTON AVENUE,
CHESTERTOWN, MD 21620
Learn more at:
https://www.washcoll.edu/sustainability/
Scan to view our sources:

COURSE STRUCTURE OVERVIEW

Unit Delivery Methods

Unit	Primary Delivery Methods	Assessment Type
1	Online discussion, interactive lecture	Individual case study
2	In-class group discussion, lecture, brainstorming activity	Individual SOCME map
3	Online discussion, in-class discussion, team presentations	Team presentation
4	In-class activity, video analysis, website design	Individual website
5	Guest speaker, group work, pitch event	Team proposal + infographic + presentation

Overall Assessment Weight Distribution

Component	Percentage
Unit 1: Case Study	10%
Unit 2: SOCME Map	10%
Unit 3: AI Presentation	10%
Unit 4: SDG Website	10%
Unit 5: Proposal	15%
Unit 5: Infographic	5%
Unit 5: Pitch Presentation	10%
In-class Activities & Discussions	15%
Attendance & Participation	15%
Total	**100%**

SUPPLEMENTARY RESOURCES

Key References for Instructors

Systems Thinking:

- Talanquer, V. & Szozda, A. R. (2024). An Educational Framework for Teaching Chemistry Using a Systems Thinking Approach. *J. Chem. Educ.*, 101, 1785-1792.
- Mahaffy, P., Matlin, S. A., Holme, T., & MacKellar, J. (2019). Systems thinking for education about the molecular basis of sustainability. *Nature Sustainability*, 2, 362-370.

SOCME Tool:

- Matlin, S. A. (2020). Introducing the SOCME tool for systems thinking in chemistry. *Technical Resource, International Organization for Chemical Sciences in Development*, Namur.

Green Chemistry:

- Anastas, P. T. & Warner, J. C. (1998). *Green Chemistry: Theory and Practice*. Oxford University Press.
- American Chemical Society. *The 12 Principles of Green Chemistry*.

UN Sustainable Development Goals:

- United Nations. *Sustainable Development Goals*. https://www.un.org/sustainabledevelopment/sustainable-development-goals/

AI Ethics (Additional Resources):

- Benjamin, R. (2019). *Race after technology: Abolitionist tools for the New Jim Code*. Polity Press
- Buolamwini, J., & Gebru, T. (2018). Gender shades: Intersectional accuracy disparities in commercial gender classification. In *Proceedings of the 1st Conference on Fairness, Accountability and Transparency* (PMLR, Vol. 81, pp. **77–91**).
- Bender, E. M., Gebru, T., McMillan-Major, A., & Shmitchell, S. (2021). On the dangers of stochastic parrots: Can language models be too big? In *Proceedings of the 2021 ACM Conference on Fairness, Accountability, and Transparency (FAccT '21)* (pp. **610–623**). ACM.

NOTES FOR INSTRUCTORS

Implementation Tips

1. **Scaffolding:** The course is designed to progress from reductionist to systems thinking. Ensure students master foundational concepts before advancing to complex interdisciplinary applications.
2. **Element (from periodic table) Selection (Unit 2):** Approve student element choices early to avoid duplication. Encourage diverse selections across the periodic table.

3. **Article Approval (Unit 3):** Review and approve peer-reviewed articles before students begin presentations to ensure quality and relevance.
4. **Community Partnerships (Unit 5):** Establish relationships with campus sustainability offices or local organizations early in the semester to provide authentic audiences for final pitches.
5. **Technology Support:** Provide workshops or tutorials on website building platforms (Wix, Squarespace) and infographic design tools (Canva, Piktochart).
6. **AI Policy:** Clearly communicate expectations about AI tool usage. Allow AI for design assistance but require original critical thinking and proper citation.

Assessment Strategies

- **Peer Evaluation:** Use anonymous peer assessment for team projects to ensure accountability and equal participation.
- **Formative Feedback:** Provide mid-point check-ins for major projects (especially SOCME maps and proposals).
- **Rubric Transparency:** Share rubrics with students early on to clarify expectations.

Adaptability

This course framework can be adapted for:

- Different institutional contexts (research universities, community colleges)
- Varied class sizes (adjust team sizes and presentation formats)
- Online or hybrid delivery (convert in-class activities to synchronous online sessions)
- Discipline-specific applications (engineering, environmental science, policy)

For questions or additional materials, please contact the corresponding author.