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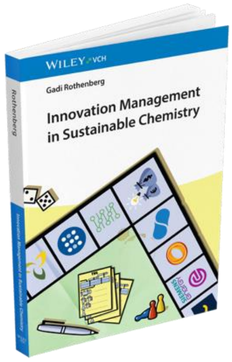
Innovation Management in Sustainable Chemistry, First Edition. Gadi Rothenberg.

Solutions for selected exercises from the textbook

Innovation Management in Sustainable Chemistry

(Wiley-VCH, 2026, 352 pp. ISBN 9783527354511)



Answer to Q1.4

The first option would be the best, but it is naïve to think that people will change their habits so easily. For this to happen, there has to be a large external stimulus, e.g. what has happened during the COVID-19 pandemic. People will not stop using fossil fuels without a large external incentive.

CCS is available technology, and so for the time being it is a viable short-term solution for reducing carbon emissions. However, it has two main drawbacks: First, it treats CO_2 as garbage, which it is not. Second, it does not provide any incentive for people and for companies to change their ways, and therefore does not promote a long-term sustainable solution. So long as there is something that works, many companies and societies will continue with "business as usual". This is especially true for so-called "cash cows", processes and factories that have already depreciated and are now a simple source of cash for the company.

CCU is a much more sustainable option, since it does not treat CO_2 as garbage but rather as a resource. This is the key to sustainability and to a circular economy – no waste. However, CCU faces three serious challenges: First, capturing carbon from the air is costly, and there is little incentive to do this, so long as the alternative cost of CO_2 emissions is low. Second, CO_2 is a thermodynamic sink, which means that you must invest much energy to convert it to anything. You cannot burn it further down in energy. **Let's look at the numbers**: even on paper, you need about 7 GJ to convert one ton of CO_2 back to carbon. If this energy comes from fossil fuels, the whole process does not make sense. Finally, even if you can convert CO_2 back to some useful chemicals, you run into the problem of size. This is where another **quantitative argument** comes in: If CO_2 emissions are 35 Gton per year, it means 9.45 Gton of carbon per year (because CO2 contains 27% carbon). What are you going to make from this? The entire plastics industry accounts for 350 Mton per year, that's not even 3%…

The only viable product on that scale is fuel itself, and hopefully the demand for that will decrease as more renewable energy becomes available.

Answer to Q1.6

The balanced reaction:

$Br-C_6H_4-C(=O)CH_3 + C_6H_5B(OH)_2 \rightarrow C_6H_5-C_6H_4-C(=O)CH_3 + HBr + HBO_2$

(another acceptable answer is where the HBr is neutralised with the base).

E-factor = $kg_{waste}/kg_{product}$. If we start from 1 mole of bromoacetophenone and 1 mole of phenylboronic acid, and if we assume 100% yield, we will get 1 mole of 4-phenylacetophenone. This is our product. The waste is 1 mole HBr and 1 mole HBO_2. Therefore: Mass of product = 196 grams and total mass of waste = 125 grams, and the E-factor = 125/196 = 0.63.

Atom Economy = # atoms in the desired product / total # atoms in the reactants.

In this case: 27/33 = 0.81 or 81%.

The **Environmental Quotient** depends on the type of waste. In this case it is HBr (or NaBr) and HBO_2, both are relatively non-toxic and contain no heavy metals, so the EQ would be low to medium.

Method 1: Switch from -Br to Cl.

Advantages: Less waste; reagent is cheaper per weight; reagent is cheaper per unit.

Disadvantages: C–Cl bond is less reactive; Cl is not a good leaving group; reaction requires better (and possibly more expensive) catalyst.

Method 2: Recycle the side products in other processes/applications.

Advantages: Generates income from side-products, these are not “waste” anymore.

Disadvantages: New offset and markets required, these might not fit with the current business unit.

Company A (Drug Synthesis for Rare Disease Treatment):

1. Safety and Purity of Reagents: Company A will prioritize using high-purity reagents. They may opt for pharmaceutical-grade starting materials to minimize the risk of impurities.
2. Biocompatibility: Company A will carefully select reagents and solvents that are unlikely to introduce toxic or harmful residues.
3. Scalability and Cost: Considering the limited market for drugs treating rare diseases, Company A will prioritize getting quickly to market over process optimisation.

Company B (Pesticide Synthesis for Banana Pest Control):

1. Efficacy Against Target Pest: Company B's primary consideration will be the effectiveness of the pesticide against the specific insect pest targeting bananas. They will select reagents and catalysts known to facilitate the synthesis of active ingredients with potent insecticidal properties.
2. Environmental Impact: Company B will also consider the environmental impact of the pesticide. They want to minimize the use of hazardous or environmentally persistent reagents.
3. Regulatory Compliance: Company B must adhere to regulatory requirements governing the use of pesticides in agriculture.
4. Cost-Effectiveness: Given the large-scale agricultural application of the pesticide, Company B will prioritize cost-effective synthesis routes to ensure market competitiveness.

Answer to Q1.8

Calculating the E-Factor and Environmental Quotient

E-factor = $kg_{waste}/kg_{product}$

For the Cumene Process (Eq. 1):

Product: Phenol, C_6H_5OH = 94.11 g/mol; Waste: Acetone, $(CH_3)_2CO$ = 58.08 g/mol

E-Factor = 58.08 / 94.11 = 0.62

For the Toluene Oxidation Process (Eq. 2):

Product: Phenol, C_6H_5OH = 94.11 g/mol; Waste: CO_2 (44.01 g/mol) + H_2O (18.02 g/mol)

E-Factor = 62.03 / 94.11 = 0.66

The Environmental Quotient (EQ) is given by: EQ = E × Q, where Q is a hazard factor. The toluene route generates CO_2, which is a greenhouse gas, but otherwise harmless. The cumene process produces acetone, which is less environmentally harmful than CO_2 emissions, and is a liquid product that can be sold. In both cases, the size of the environmental quotient is low.

Advantages and Disadvantages of Each Process

Cumene Process (Eq. 1)

Advantages:

1. High selectivity, leading to minimal waste generation.
2. Produces acetone as a valuable by-product, which is widely used in industry.

Disadvantages:

1. Requires cumene as a raw material, which is derived from petroleum-based benzene and propylene.
2. Ties your phenol sales also to the acetone market, or requires you to find another use for the acetone.

Toluene Oxidation Process (Eq. 2)

Advantages:

1. Toluene is cheaper and more abundant than cumene.
2. Does not require propylene, reducing dependence on petroleum refining.

Disadvantages:

1. Although the E-factor is similar to eq 1, the products are not worth anything. You're wasting a C atom and two H atoms, which were already bound in the toluene starting material.
2. Produces CO_2, contributing to greenhouse gas emissions.

Despite the potential benefits of the Dow toluene oxidation process, over 95% of global phenol production follows the cumene route. This is due to:

1. The production of acetone as a valuable co-product, making the process economically favorable.
2. The established industrial infrastructure and supply chains that favor the cumene route, making switching to alternative methods costly and impractical.

Answer to Q2.1

Political	***Environmental***
***Solar energy**: Governments are highly in favour, there is immediate benefit to the local and national government due to short installation times, capital investment is relatively low and there is little or no political cost; if the cells are based on rare-earth elements (which are typically mined in China) there is also a political angle to the supply chain.* ***Wind energy**: Governments are partly in favour; there is long-term benefit to the local and national infrastructure, but installation times are long; there is often strong discussion on the pros and cons.*	***Solar energy**: Gives immediate environmental benefit, while the environmental costs (due to production) are typically far away in the producing lands. 100% clean electricity, no by-products.* ***Wind energy**: Production and installation changes the environment considerably, both in sea and on land. Long-term environmental costs due to recycling and disposal of old windmills have to be factored in. A windmill lasts for about 20 years.*
Socio-economic	***Technological***
***Solar energy**: Installation costs are low and the raw material price is zero, both now and in the future. Production costs are decreasing as more panels are produced, and technology improves. Local installation (on residential roofs) enables people to choose for themselves if they want this kind of renewable energy or not; green hi-tech image creates social standing value and a feeling of independence.* ***Wind energy**: Turbines are typically large and must be installed by companies/governments. The raw material price is zero, both now and in the future. Production costs are decreasing as more turbines are produced, and technology improves. Turbines are considered ugly and "pollute" the view, which in turn reduces the value of real estate, which is the main investment of most people worldwide. Since the energy goes to the grid, there is no additional social standing value for specific households.*	***Solar energy**: Current utility of photovoltaic cells 20–25%. New developments will raise this to >30% in the coming years. Cells contain no moving parts and in theory can operate many years with little or no maintenance. Solar energy is available only during datytime, and therefore energy storage/delivery systems are required.* ***Wind energy**: Wind is available in some regions, typically more over sea and on large plains and mountain ridges. Supply is intermittent and therefore energy storage/delivery systems are required. Turbines contain moving parts and typically last ca. 20 years. Large-scale wind farms can deliver substantial amounts of electricity to national grids.*

On the short term, solar energy has the advantages of low installation costs and immediate access to electricity. A main disadvantage is that they only work in the day. For the long term, one must take into account also the scarcity of materials (e.g. rare-earth metals). Wind farms cost more money to install and take longer to build and require more maintenance. However, they can deliver more electricity once set up and can work also at night, as long as the wind blows.

On the whole, solar energy is more sustainable, mainly thanks to lower maintenance and to the possibility of small-scale and large-scale applications. However, each case should be looked at specifically, e.g. in places where there is lots of wind and little sunlight, wind energy is preferred. You can argue that in the Netherlands, where there is much wind year-round and less sunlight during the autumn and winter months, wind energy is preferable. Similarly, in Africa, where the electrical grid is not always that reliable (or even non-existent) and there is lots of sunlight, off-grid photovoltaic installations would be the better choice.

Answer to Q2.5

Digital Learning Platforms

Strengths: *Environmentally Friendly: Reduces paper waste and conserves natural resources.* *Accessibility: Allows students to access learning materials from anywhere with internet access.* *Interactivity: Offers multimedia content and interactive features that enhance engagement and learning.* *Cost Savings: Eliminates the need for purchasing physical textbooks, potentially reducing expenses for the school.*	*Weaknesses:* *Digital Divide: Some students may lack access to technology or reliable internet.* *High Initial Investment: Setting up digital learning platforms requires investment in technology infrastructure and staff training.* *Technical Issues: Connectivity problems or software glitches may disrupt learning and require technical support.*
Opportunities: *Innovation: Provides opportunities for integrating new educational technologies and teaching methods.* *Customization: Allows for personalized learning experiences tailored to individual student needs.* *Collaboration: Facilitate collaboration among students and teachers through online platforms and forums.*	*Threats:* *Resistance to Change: Some teachers, students, or parents may resist the transition from traditional textbooks to digital learning platforms.* *Security Concerns: Risks of data breaches or privacy violations.* *Dependency on Technology: Vulnerability to disruptions in technology infrastructure or cyberattacks.*

Textbook Reuse and Exchange

Strengths: *Cost Savings: Reduces expenses for purchasing new textbooks, benefiting both the school and students.* *Sustainability: Promotes environmental sustainability by extending the lifespan of textbooks and reducing waste.* *Community Building: Fosters a sense of community and among students through sharing and exchanging.* *Equity: Ensures access to learning materials for students who may not have access to reliable internet.*	*Weaknesses:* *Limited Availability: Availability of textbooks for reuse may vary, especially for specialized or updated editions.* *Quality Control: Ensuring the quality and condition of reused textbooks may be challenging.* *Logistics: Managing the logistics of textbook collection, distribution, and exchange requires coordination and resources.*
Opportunities: *Partnerships: Collaborating with other schools or educational institutions can expand access to a wider range of textbooks for reuse.* *Education on Sustainability: Promotes awareness and education on sustainable practices and environmental stewardship among students.*	*Threats:* *Disruption: Disruptions in the supply chain or logistics may impact the availability and distribution of textbooks.* *Loss or Damage: Risk of loss or damage to textbooks may reduce the effectiveness of the reuse and exchange program.*

More sustainable: The textbook reuse and exchange solution is more sustainable overall. While digital learning platforms have environmental benefits in reducing paper waste, they also come with challenges such as the digital divide and electronic waste generation. On the other hand, textbook reuse and exchange contribute to resource conservation, promote social equity, and foster community engagement – all key aspects of sustainability.

More effective: Although it might seem that the all-digital solution is more effective, this is not the case. Many studies have shown that textbooks and notebooks have a sort of tactile added value. The interaction that students have with the paper and the "permanence" of the textbooks creates long-term anchors in student's memories and helps them learn.

Answer to Q2.7

Value Proposition: "We transform tomato crop waste into valuable chemicals, offering farmers an innovative solution to reduce waste and generate additional revenue streams. By utilizing advanced bioconversion processes, we extract high-quality chemicals from tomato waste, creating sustainable products with various industrial applications. Our approach fosters a circular economy and promotes a sustainable agriculture."

Key Points:

1. Waste Reduction and Valorization: We offer farmers a sustainable solution to minimize tomato crop waste by converting it into valuable chemicals, reducing environmental impact and promoting efficient resource utilization.
2. Revenue Generation: By extracting chemicals from tomato waste, farmers can generate additional income streams from their agricultural operations, improving profitability and sustainability.
3. Environmental Benefits: Our process contributes to environmental conservation by reducing greenhouse gas emissions associated with agricultural waste decomposition and minimizing landfill usage.
4. Community Engagement: Our initiative fosters collaboration and engagement within the agricultural community, offering farmers an opportunity to participate in sustainable practices and contribute to environmental stewardship.

Chemicals and Applications:

1. Lycopene: Extracted from tomato skins, lycopene is a potent antioxidant with applications in pharmaceuticals, nutraceuticals, and cosmetics. It offers health benefits such as cancer prevention and cardiovascular support.
2. Pectin: Derived from tomato peels, pectin is a natural polysaccharide used as a gelling agent, stabilizer, and thickener in food, pharmaceutical, and cosmetic industries.
3. Organic Acids: Fermented from tomato pulp, organic acids such as citric acid and malic acid have diverse applications in food preservation, flavor enhancement, and industrial processes.
4. Biofuels: Tomato waste can be converted into biofuels such as ethanol or bio-oil through biochemical or thermochemical processes, offering renewable alternatives to fossil fuels.

Explanation:

Lycopene is a valuable antioxidant known for its health benefits, making it a lucrative product for pharmaceutical and nutraceutical industries. Pectin serves as a versatile ingredient in food products, cosmetics, and pharmaceuticals, offering thickening, gelling, and stabilizing properties. Organic acids find applications in various industries, including food and beverage, pharmaceuticals, and agriculture, where they serve as preservatives, flavor enhancers, and chelating agents. Biofuels derived from tomato waste offer renewable alternatives to fossil fuels, contributing to energy sustainability and reducing dependence on non-renewable resources.

Two main drawbacks of the business case:

1. **Seasonal Availability**: Tomato crop waste is only available seasonally, leading to inconsistent feedstock supply and production fluctuations.
2. **Processing Costs**: Converting tomato waste into chemicals involves processing costs, including equipment, labor, and energy expenses.

How these drawbacks can be turned into opportunities:

1. **Seasonal Availability Turned Opportunity:**
   - Diversification of Feedstock: Explore opportunities to utilize other agricultural waste streams or complementary feedstocks to supplement tomato crop waste during off-season periods. This diversification ensures continuous feedstock availability and operational stability.
   - Product Development: Develop a portfolio of products that can be produced year-round using different agricultural waste sources. This approach expands the business's product range and mitigates the impact of seasonal variations in feedstock availability.
   - Strategic Partnerships: Collaborate with multiple farms or agricultural cooperatives across different regions to access a steady supply of tomato waste throughout the year. Establishing long-term partnerships ensures consistent feedstock availability and strengthens market presence.
2. **Processing Costs Turned Opportunity:**
   - Value-Added Products: Focus on developing high-value chemicals or specialty products with premium pricing to offset processing costs and increase profit margins. Target niche markets where customers are willing to pay a premium for sustainable, eco-friendly products derived from agricultural waste.

Resource Efficiency: Implement sustainable practices such as waste heat recovery, water recycling, and by-product utilization to minimize resource consumption and waste generation.

Answer to Q2.15

PEST Analysis for Neodymium Wind Turbine Magnets

Factor	Analysis
Political	Dependence on rare-earth elements from China, which controls ~70% of global supply. Geopolitical tensions and export restrictions could disrupt supply chains. Government incentives for sustainable materials and green energy policies.
Economic	High costs due to limited supply of REEs. Price volatility affects production costs and profitability of wind energy projects. Recycling of REEs is expensive and inefficient, adding to long-term costs. New mines require a large investment and are only viable if there's long-term market stability.
Social	Public concerns about unethical mining practices, including human rights and environmental damage. Growing demand for sustainable energy solutions pressures industries to find alternatives – uncertain future for the Neodymium market.
Technological	Advances in magnet recycling could improve supply sustainability. Research into alternative materials to reduce reliance on rare-earth magnets. Another technology (e.g. better photovoltaic cells) could disrupt the wind energy market.

Challenges in the Neodymium Magnet Market:

Supply Chain Risks: Heavy reliance on China creates vulnerability to supply disruptions.

Environmental Impact: Mining and processing rare-earth elements cause soil and water contamination.

High Costs & Price Volatility: Fluctuating market prices impact production costs and economic feasibility.

Ethical Concerns: Some mining practices involve human rights violations and hazardous labor conditions.

Once a technology is chosen, then it is used. The barrier for change is high because the risk of changing technology is high. To be economically successful, a wind turbine should operate for 15–20 years. This means that investors prefer backing known and trusted technologies.

Alternative Materials or Approaches

Alternative	Chemical Formula	Advantages	Challenges
Ferrite Magnets	$BaFe_{12}O_{19}$ or $SrFe_{12}O_{19}$	Made from abundant and inexpensive iron oxide. Non-toxic and environmentally friendly.	Lower magnetic strength than NdFeB magnets. Larger size required for the same efficiency. Does this larger size (and higher weight!) make sense when building wind turbines?
High-Temperature Superconductors (HTS)	$YBa_2Cu_3O_7$ (YBCO)	Extremely high efficiency with minimal energy loss. No reliance on rare-earth metals.	Requires cooling with liquid nitrogen or helium, increasing complexity and cost. Still in early-stage development.

Environmental Benefits of Using Alternatives

Reduced Mining Impact: Avoids the harmful environmental effects of rare-earth element extraction, such as radioactive waste and heavy metal pollution.

Lower Carbon Footprint: Ferrite magnets require less energy to produce compared to rare-earth magnets.

Sustainability: Alternatives are more abundant and reduce reliance on geopolitically sensitive supply chains.

Recyclability: Ferrite and superconducting materials can be recycled more efficiently than rare-earth magnets, further reducing environmental impact.