INVESTIGATING THE SUSTAINABILITY OF THE DOW CHEMISTRY CLASSROOM KITS AS AN ALTERNATIVE TO TRADITIONAL LABORATORIES

By: Apichai Wejsuwan, Bridhikul Bridhikitti, Connor Tam, Declan Reily, Jirachaya Kaemavichanurat, Tanat Boonratanakornkit, Tathata Youngsuksathaporn, Samyra Guerrier

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Apichai Wejsuwan, Bridhikul Bridhikitti, Connor Tam, Declan Reily, Jirachaya Kaemavichanurat, Samyra Guerrier, Tanat Boonratanakornkit, Tathata Youngsuksathaporn

Submitted to:

Prof. Caitlin A. Neer, Worcester Polytechnic Institute

Prof. Dr. Esther Boucher-Yip, Worcester Polytechnic Institute

Prof. Dr. Supawan Tantayanon, Chulalongkorn University

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Abstract

In this project, we investigated the sustainability and environmental impact of Dow Chemistry Classroom (DCC) kits. The carbon footprint of DCC kits was analyzed and compared with emissions from traditional chemistry experiments. Additionally, we conducted classroom observations and interviews with secondary school teachers, the university's laboratory technicians, and the creators of DCC kits. Through these methodologies, we found that DCC kits produce less waste and have implemented green chemistry principles such as waste prevention, offering a safer alternative to traditional chemistry experiments. Moreover, through the Life Cycle Assessment (LCA) and other methodologies, we have found that without good practices, the DCC kits' emissions will be greater than those of their traditional counterparts. However, with good waste management and green chemistry principles, the kits' emissions are less than those of traditional experiments. Finally, we recommended further LCA of the DCC kits, improvements on DCC kits, and suggestions for future research.

Executive Summary

The Problem

In chemistry education, laboratory experiments help learners and students understand important theoretical concepts, gain hands-on laboratory experience, develop problem-solving skills, and practice critical thinking. Chemicals in laboratories require vast quantities of reagents, solvents, and energy for various experiments and processes. Many of these chemicals are synthesized using resource-intensive procedures, contributing to carbon emissions and environmental degradation (Sevian & Talanquer, 2014). To address this issue, Dow Thailand collaborated with the Chemical Society of Thailand and launched the project Dow Chemistry Classroom (DCC), promoting small-scale chemistry experiments in education and raising awareness of climate change (Dow Thailand Group, 2021).

Goal & Objectives

The goal of this project was to investigate the sustainability of the Dow Chemistry Classroom kits (DCC) as an alternative to traditional chemistry experiments. With this goal in mind, we were able to obtain a deeper insight not only into the kit's educational aspect but also into its environmental impact. To examine the sustainability of these kits, we developed three objectives to aid us in assessing our goal:

1. Quantify the environmental impact of traditional and small-scale chemistry experiments.
2. Compare the environmental impact of traditional and small-scale chemistry experiments.
3. Recommend ways that Dow Chemistry Classroom kits can improve in regard to sustainability to further promote its use in schools.

Methodology

To evaluate our first objective, we interviewed two experts on carbon footprint analysis and conducted two life cycle assessments (LCA) focusing on acid-base titration; an LCA on a traditional chemistry laboratory and another LCA on a DCC small-scale kit. We evaluated 3 cases based on interviews and participant observations: replacing the whole DCC kit, replacing only chemicals used in the kits, and replacing chemicals and essential plastics.

To evaluate our second objective, we analyzed and compared results from our LCAs to quantify the kit's environmental impact with the traditional experiment. Furthermore, we analyzed and provided a comparison in waste management procedures and integration of green chemistry principles between the chemistry experiments at Prachinratsadorm-Amroong School and Chulalongkorn University.

To evaluate our third objective, we developed recommendations using our results from the first two objectives to ensure long-term sustainability, scalability, and promotion of the DCC kits.

Key Findings

1. **Tissue usage has a higher environmental impact than chemicals.**

   Tissue usage used in the clean-up process for any spills results in a much higher emission factor compared to chemicals due to the high energy-intensive procedures required for the production of tissue papers.

2. **DCC kits generate higher carbon emissions in the production phase but lower emissions in the end-of-life phase.**

   The carbon-intensive nature of producing plastic results in the DCC kit emitting more carbon, but traditional experiments produce more waste and emissions during disposal, assuming only chemicals and essential plastics are replaced in the DCC kit.

3. **The carbon emissions of DCC kits outperform the traditional experiments in some cases.**

   When replaced entirely after 20 uses, the DCC kit emits roughly twice as much carbon as traditional experiments. However, when replacing only consumables, emissions are lower.

4. **Chemical waste disposal varies between small-scale and traditional experiments.**

   Our observations at Prachinratsadorm-Amroong School indicated that small-scale kit users dilute chemicals and dispose of waste and chemicals in general bins, while traditional experiments categorize and manage waste more systematically through designated containers.

5. **Green chemistry principles are partially integrated at Prachinratsadorm-Amroong School.**

   We observed significantly less waste production, less chemical usage, and reused materials in the small-scale chemistry kits used at Prachinratsadorm-Amroong School.

Recommendations

1. **Consider using alternative materials for the containers.**

   We recommend using alternative materials, such as recycled plastics, or optimizing the design of these kits to reduce the carbon footprint of small-scale chemistry kits.

2. **Consider the use of natural indicators and more implementation of green chemistry in experiments.**

   We recommend further incorporation of the Safer Solvents and Auxiliaries principle into the DCC kit.

3. **Reduce tissue usage.**

   We suggest minimizing tissue usage to one tissue or none to reduce carbon emissions from the DCC kits.

4. **Obtain university endorsements to enhance the DCC kits in the curriculum.**

   We recommend obtaining academic adoption proposals and reaching out to universities for endorsement and approval support to promote the DCC kits' cost-effectiveness, efficiency, and sustainability.

5. **Obtain carbon footprint certification for DCC kits.**

   To enhance the use of the DCC kits in the chemistry curriculum, we recommend the Dow Chemistry Classroom program to reach out to Thailand Greenhouse Gas Management Organization (TGO) to obtain certification.

Recommendations for Future Study

1. **Recommendations for LCA calculation:**

   We recommend collecting primary data at each stage in the life cycle to ensure an accurate cradle-to-grave LCA. We also recommend performing other comparisons of the DCC Kits and traditional chemistry experiments.

2. **Participant interviews**

   We recommend interviewing chemical waste management experts, designers of the DCC kits, and sustainable material experts to obtain information on the DCC kits.

3. **Visiting various schools with DCC**

   We recommend visiting schools to ensure that future researchers can gather the most comprehensive information from these teachers who are truly experts in DCC kits and large-scale experiments.

Conclusions

To promote a more sustainable future for both Thailand and educators, Dow Chemical Thailand should continue to integrate green chemistry and waste management principles into its training for teachers while also iterating on the materials used in the production of the kits. Although we found that the DCC kits may lack green chemistry and waste management aspects, we believe the kits emit far less carbon emissions, save cost and time, and the infrastructure required to bring the kits to schools that lack the resources for traditional chemistry experiments.

Further iteration and promotion of small-scale kits can both be environmentally friendly while providing a highly accessible solution to garner students' interest in science education and help foster the next generation of scientists in the industry. The DCC kits serve as a case study in Thailand for small-scale laboratory kits as a whole; once the DCC kits iterate regarding green principles, they can serve as a comprehensive reference to be further promoted internationally.

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Authorship

Chapter & Section	Primary Author(s)	Primary Editor(s)
Abstract	Bridhikul	Apichai
Executive Summary	Samyra, Apichai	Tanat
Chapter 1: Introduction	Bridhikul, Tathata, Jirachaya	Tanat, Connor
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List of Acronyms

Abbreviation	Meaning
BAU	Business-as-usual
CAT	Climate Action Tracker
CFA	Carbon Footprint Analysis
DCC	Dow Chemistry Classroom
DSC	Doing Science Co., Ltd.
EIU	Economic Intelligence Unit
GHG	Greenhouse Gases
GLAD	Global LCA Data Access
HCl	Hydrochloric acid
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
NaOH	Sodium Hydroxide
NDC	Nationally Determined Contributions
SDG	Sustainable Development Goals
SHECU	Center for Safety, Health and Environment of Chulalongkorn University
TGO	Thailand Greenhouse Gas Management Organization
TNLD	Thai National LCI Database

UNDP	United Nations Development Programme
UNESCO	The United Nations Educational, Scientific, and Cultural Organization

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1. Introduction

In chemistry education, students can understand important theoretical concepts, experience using traditional chemistry instruments, develop problem-solving skills, and practice critical thinking through hands-on chemistry experiments. To conduct these experiments, chemistry laboratories require vast quantities of reagents, solvents, and energy for various experiments and processes. Many of these chemicals are synthesized using resource-intensive procedures, contributing to carbon emissions and environmental degradation (Sevian & Talanquer, 2014). For instance, organic solvents such as dichloromethane and chloroform, commonly used in chemical extractions and chromatography, have high toxicity levels and contribute to air pollution (Anastas & Warner, 1998). Additionally, laboratory instruments and equipment consume significant amounts of energy, heightening the carbon footprint associated with research and development activities (Farooq et al., 2021). Laboratory instruments significantly contribute to global carbon emissions due to their consumption of energy and the carbon footprint associated with research and development (Hopkinson et al., 2011). Traditional laboratories in schools have been generating carbon emissions through the large number of chemicals used in experiments, chemical reactions they facilitate, waste they generate, and even disposal of chemical waste (École Polytechnique fédérale de Lausanne, 2022).

In recent years, climate change has been posing significant negative impacts in Thailand. Since the 1950s, researchers have noted that the temperature of the country has increased by 0.8°C per century (The World Bank Group, 2021). One of the main factors that causes raised temperatures in Thailand is carbon emissions–the release of greenhouse gases (GHG) and carbon dioxide (CO_2) into the atmosphere due to burning fossil fuel, deforestation, and transportation

(Tangkitvanich, 2023). In 2016, Thailand signed the Paris Agreement; they committed to reduce carbon emissions from greenhouse gases by 30% from the projected business-as-usual (BAU) level by 2030, accomplish the long-term goal of carbon neutrality by 2050, and achieve net-zero GHG emission by 2065 (United Nations Framework Convention on Climate Change, 2022).

To address this issue, Dow Thailand collaborated with the Chemical Society of Thailand to launch the Dow Chemistry Classroom (DCC). They promoted small-scale chemistry experiments in education, raising awareness of climate change while making hands-on learning accessible without the need for expensive laboratories (Dow Thailand Group, 2021). This program aims to bridge the gap in science education by providing affordable experimental chemistry opportunities to rural Thai government high schools (Vailikhit et al., 2013). Through the program, teachers receive training in sustainability and green chemistry, which allows them to educate and inspire their students (Dow Thailand Group, 2022).

The DCC kits, developed by Dow Thailand, provide a more sustainable and cost-effective alternative to traditional chemistry experiments, which mostly require large amounts of hazardous chemicals and breakable glassware (Day et al., 2019). The DCC kits demonstrate the green chemistry principles (12 guidelines aimed at minimizing waste, reducing hazardous substances, improving energy efficiency, and designing safer chemicals and processes to promote environmental sustainability) by minimizing the energy produced from chemical reactions and reducing unnecessary waste. The DCC kits are also designed for safety and efficiency, helping students understand concepts of experiments by conducting experiments in class with limited time and resources, making them an eco-friendlier alternative to traditional laboratory experiments (Dow Thailand Group, 2022). These properties align with the concerns in Sustainable Development Goal 12 (SDG 12), which focuses on ensuring sustainable consumption and production patterns that emphasize the importance of reducing waste generation, promoting efficient resource usage, and minimizing environmental impacts, especially in education (United Nations, 2023).

Moreover, previous research indicates that DCC kits are a good alternative option for traditional chemistry experiments. These kits offer a cost-efficient, time-efficient, and accessible approach while minimizing chemical waste and enhancing student engagement in schools with limited resources. On the other hand, traditional chemistry experiments provide higher accuracy and precision but require more financial and safety resources (Fialli et al., 2020).

However, there is limited research in evaluating how these small-scale kits contribute to reducing their environmental impact. Thus, in our research, we aimed to evaluate the environmental impact of the DCC kits. To achieve this goal, we set out the following objectives:

1. Quantify the environmental impact of traditional and small-scale chemistry laboratories
2. Compare the environmental impact of traditional and small-scale chemistry laboratories
3. Recommend ways that Dow Chemistry Classroom can improve regarding sustainability to further promote its use in schools.

To achieve our goal, we conducted a partial Life Cycle Assessment (LCA) to measure the carbon footprint of the kits. We also conducted interviews to gather deeper insights from teachers, sponsors, and producers and observed chemistry classrooms to obtain first-hand experience about the usage of chemistry kits. By understanding these impacts, we can provide insights and recommendations into how to improve the sustainability of DCC kits.

2. Literature Review

In this section, we begin with a brief overview of decarbonization and climate action plans in Thailand and discuss Dow Thailand's contributions to these efforts. Next, we discuss the green chemistry principles as a sustainable practice in chemistry education. Using these principles, we analyze the sustainability of traditional laboratories and introduce small-scale chemistry kits as an alternative to conventional laboratories. We conclude by discussing our sponsor, Dow Thailand, and its commitment to improving and promoting sustainability in science education.

2.1 Decarbonization and Climate Action Plans

2.1.1 Insufficient Climate Action Plan

Traditional laboratories significantly contribute to global carbon emissions. This negatively impacts our ecosystem and global climate change, causing increased temperatures. Thailand has been proactive in joining global efforts to address the world's climate change. They joined the Kyoto Protocol in 2002, committed to the Paris Agreement in 2016, and submitted a long-term strategy to reduce greenhouse gas emissions in 2021 (Ministry of Natural Resources and Environment, 2022). However, in 2022, the Climate Action Tracker rated their current policies as "critically insufficient" (*Thailand*, 2022), while EIU labeled their policies "modest" at best (Clarke, 2023). Additionally, an analysis conducted in 2008 by Danny Marks highlighted that these policies favored government officials and the private sector rather than providing actionable items for the whole country. Marks also found that these policies were not based on scientific knowledge (Marks, 2011).

These sources both identified key failures, such as inadequate progress in reducing Thailand's dependence on fossil fuels and implementing renewable energy solutions. To achieve these goals, the nation must address its disorganized bureaucracy and reduce its fossil fuel dependency. Additionally, fostering public awareness of climate initiatives, especially the importance of Thailand's Nationally Determined Contributions (NDC) targets, is crucial, as highlighted by a CAT assessment of Thailand's climate change policies (Clarke, 2023). Thailand will need to make massive strides in its bureaucratic organization, reliance on fossil fuels, and continued political will to establish comprehensive policies that fall in line with the rest of the world's leaders in climate action.

Despite the shortcomings in Thailand's policies, both the Economic Intelligence Unit (EIU) and Climate Action Tracker (CAT) have acknowledged Thailand's continued efforts, such as revising its 2021 long-term strategy and establishing goals to become net-zero GHG by 2065 (Clarke, 2023; *Thailand*, 2022).

2.1.2 Dow Thailand's Efforts

Dow Thailand targets two main sustainability goals: reducing carbon emissions and eliminating plastic waste. Dow aims to reduce its net annual carbon emissions by 15 percent by 2030, seeking to convert 3 million metric tons of annual waste into circular and renewable solutions (by selling 100% of Dow products as reusable or recyclable materials by 2035). To achieve carbon neutrality by 2050, Dow has incorporated a variety of strategies, such as product portfolios and manufacturing optimization, to reduce carbon emissions (Dow Thailand Group, 2023). These goals fall in line with the United Nations Development Programme's (UNDP) Sustainable Development Goal (SDG) 12, Responsible Consumption and Production, which pushes for the green management of chemicals and all their byproduct waste throughout their life cycle.

To achieve these goals, Dow Thailand has implemented programs aimed at (Dow Thailand Group, 2019):

- **Enhancing Teacher Capabilities** by providing professional development to educators to make science teaching more effective and hands-on.
- **Fostering Student Engagement** by encouraging curiosity and critical thinking through innovative learning tools and methods.
- **Promoting Sustainability** by introducing practices like small-scale chemistry kits, which minimize resource usage while maintaining educational impact.

One of Dow Thailand's initiatives, the Dow Chemistry Classroom (DCC), exemplifies this commitment to education and sustainability. The program emphasizes small-scale chemistry kits, which reduce chemical waste and costs while enhancing safety and accessibility for every school.

2.2 Sustainability Practices in Chemistry Education

Green Chemistry, proposed in 1998 by Paul Anastas and John Warner, is a series of principles to create more sustainable chemical processes and products. The principles consist of preventing waste (designing syntheses that leave no waste to treat or clean up), maximizing atom economy (the final product contains the maximum proportion of starting materials), and designing chemical products to degrade after use (Anastas & Warner, 1998). Figure 1 depicts the twelve green chemistry principles. These principles play an important role in addressing urgent global challenges, including climate change, pollution, and the depletion of natural resources (United States Environmental Protection Agency, 2024). Sustainable chemistry expands this focus by incorporating broader considerations like economic feasibility, community benefits, and long-term environmental impacts.

Figure 1: Principles of Green Chemistry

Note. Description of the twelve principles of green chemistry (Brunning, 2015).

Dow Thailand is also very interested in the United Nations Sustainable Development Goals (SDG, a universal framework for achieving a sustainable future), particularly goal 12: Responsible Consumption and Production. This goal aims to manage natural resources and reduce and recycle waste by 2030. In the context of DCC kits, the aforementioned principles of green chemistry can be applied toward this goal as well.

Several case studies have implemented green chemistry practices in classroom experiments; some focus on evaluating and finding alternatives to the reagents and solvents used, whereas others evaluate how solutions are disposed of. For example, a study conducted in a 2nd-year organic chemistry class examined a S_NAr reaction (the process used for tie-dyeing shirts) taught in the course. The researchers found that eight of twelve green chemistry principles were addressed. A few of these include the most applicable principles to consider in the project:

1. **Less hazardous chemical synthesis:** The resulting dyed fabric poses no harm to the person wearing the shirt after being washed
2. **A safer solvent**: The experiment uses water as a reaction medium, which is one of the safest to use
3. **Safe disposal of the dye**: Only 20% of the dye remains unfixed on the t-shirt.

Researchers also found that students were encouraged by the experiment to research viable solutions and alternative chemicals that could remove the dye before being washed down the sink to safely dispose of the dye, thus letting them gain exposure to the "waste prevention" principle of green chemistry (R. V. Listyarini et al., 2019).

In addition to performing analysis of hands-on experiments in classrooms, researchers have also evaluated existing waste management practices. For example, in a study conducted of five undergraduate laboratory courses of the National University of Singapore (NUS) Department of Chemistry, researchers combed through the procedures of various hands-on experiments to determine how effectively waste was disposed of and grouped them into 3 categories.

1. **Source Elimination/Reduction**: Students performed experiments in pairs and shared the materials (materials were bought in bulk to reduce logistics).
2. **Recycling/Reusing:** The same organic compounds were reused in future experiments.
3. **Treatment of Wastes**: Neutralizing resultant products before washing them down the sink.

Going further than analyzing these experiments, the researchers also proposed improvements to classroom practices. These include conducting waste audits, evaporating solvents to recover chemicals as solids, and treating more waste in-house before disposal (Goh et al., 2020).

All of the above research sought to implement green chemistry principles at two levels: the experiment level and the institution level. At the experiment level, researchers suggested swapping out or eliminating chemicals for "greener" alternatives and improving the procedure to save on resources. At the institutional level, researchers suggested standardizing procedures or sharing resources between departments.

Traditional chemistry experiments often come with significant challenges, such as the generation of hazardous waste and high operational costs. These challenges can lead to serious environmental and safety concerns, especially when chemical waste is not properly managed or disposed of, leading to pollution and health risks for both humans and ecosystems (Freese et al., 2024). The Dow Chemistry Classroom project also includes training sessions on how to handle chemical waste responsibly to ensure that the students can understand the importance of proper disposal and reduction of hazardous substances (Dow Thailand Group, 2018).

Dow Chemistry Classroom partners with many local schools in Thailand to provide the topic of waste management and sustainability in the workshop teachers enrolled (Dow Thailand Group, 2022). The use of environmentally friendly materials further supports sustainable practices in educational settings. Using household materials and locally sourced materials can make laboratory work more accessible and affordable for schools, particularly those with limited resources.

2.3 Sustainability Challenges of Traditional Chemistry Laboratories

Students commonly conduct chemistry experiments in a classroom laboratory–a "traditional" laboratory. This type of laboratory uses glassware such as beakers and graduated cylinders, and some are equipped with fume hoods to ensure personal and laboratory safety while conducting experiments. Conventional laboratories provide students with experiential learning opportunities to explore chemistry concepts (Khan, 1996). In these laboratories, students learn chemistry concepts that are examined through acid/base titrations, electrochemistry, and thermodynamics (Steely, 2012).

Although traditional laboratories are essential to students' understanding of chemistry concepts, full-scale laboratories generate substantial waste and reduce the sustainability of these laboratories. An alternative solution to traditional laboratories that allows hands-on experimentation is small-scale chemistry kits. These kits can be used in classrooms, at home, or in any other desired location. It is important to note that there are other alternative options to using traditional laboratories, such as virtual laboratories (Steely, 2012). For this paper, however, we focused on analyzing case studies of small-scale chemistry kits to understand the sustainability of the small-scale chemistry kits.

2.3.1 Limitations of Traditional Laboratories

Traditional laboratories offer students essential chemistry skills; however, there are many barriers to implementing them in schools with limited resources. One limitation is the cost of installing laboratories (Du Toit & Du Toit, 2024; Khan, 1996). A case study in Northwest, South Africa, emphasized its inability to install traditional laboratories in schools due to underfunding and untrained science teachers (Du Toit & Du Toit, 2024). Properly trained teachers in both laboratories and safety procedures are required to run a laboratory. Furthermore, Glasgow University, located in Scotland, faced budget issues in maintaining its laboratories due to the expensive cost of disposing of organic and inorganic chemical waste (Khan, 1996).

Another limitation of experiments conducted in traditional laboratories is their consumption of time. A case study from the University of Kebangsaan Malaysia reported that experiments take as long as three hours to complete in traditional laboratories. This may disengage and tire students from the tedious procedures of conducting chemistry experiments. Additionally, conventional laboratories also consume a lot of energy and water (Zakaria et al., 2012). Finally, a case study at the University of Groningen, located in the Netherlands, studied the sustainability of laboratory practices by focusing on waste generation in traditional labs. The study reported that their conventional laboratories consume energy, waste significant amounts of water, and produce a substantial amount of chemical waste (Freese et al., 2024). We used these limitations of traditional laboratories to analyze the sustainability of small-scale chemistry kits as an alternative to conventional laboratories and provide recommendations.

2.3.2 Waste Generation

Waste generation significantly impacts the sustainability of conventional laboratories. The University of Groningen found that their laboratories account for 60-65% of the heating and electricity consumption and 60% of the water consumption of the university (Freese et al., 2024). Based on these statistics, we can deduce that these laboratories account for more than half of their university's energy and water utilities. To address this issue, universities have implemented small-scale chemistry kits as an alternative to traditional laboratories with goals that include reducing waste generation. The University Kebangsaan Malaysia case study reported a decrease in greenhouse gas emissions, chemical waste, and water and energy consumption after implementing small-scale chemistry kits. During experimentation, instead of discarding water after one use, water was recycled and then reused (Zakaria et al., 2012). This minimizes and repurposes the usage of water in these experiments. Further, a water pump controls water flow during a reflux process, lessening water usage from 50 L to 500 mL (Zakaria et al., 2012). The decrease in water consumption is sustainable and reduces the cost of water utilities universities pay. Since these experiments were conducted on a smaller scale, the chemical waste produced from these experiments was significantly smaller than the chemical waste produced using conventional laboratories. Flasks used in these small-scale kits ranged from 5-25 mL (Zakaria et al., 2012). These small-scale chemistry kits align with the Green Chemistry principle of waste prevention because students conduct chemistry experiments with minimal waste. While there was insufficient information regarding reduced energy consumption, we can infer a decrease in energy consumption since the small-scale chemistry kits use smaller apparatuses and are smaller in size. Overall, it seems that small-scale chemistry kits are a good alternative because they are more eco-friendly and budget-friendly in this case study. These examples qualitatively prove the effect of small-scale chemistry kits on the environment.

2.4 Small-Scale Chemistry Kits as a Solution

The implementation of small-scale chemistry kits bridges the educational disparity between urban and rural schools. In the North West province, South Africa case study, schools in underfunded rural areas lacked funding for science laboratories. With no access to laboratories, students were unable to learn chemistry via hands-on experiments. By introducing small-scale chemistry kits to classrooms, students received proper training in chemistry techniques, helping to bridge the science gap between rural and urban schools (Du Toit & Du Toit, 2024). Through chemistry experimentation, students can develop their investigation, critical thinking, and analysis skills in science.

As previously mentioned, funding for traditional laboratories is costly and requires increased safety measures. Like Scotland, one of the many reasons for implementing the DCC kits in Thailand was because it was budget-friendly and produced less chemical waste (Figure 2, 3) (Dow Thailand Group, 2018). The DCC kits are also implemented for the same reasons stated above. In addition, the DCC kits minimize education inequality between urban and rural schools by allowing students to have hands-on experience in chemistry (Dow Thailand Group, 2018). Although both urban and rural schools face obstacles in science education, it is more likely for rural schools to be impacted. Rural schools tend to lack qualified teachers, which in turn affects the curriculum learned in the schools (Fialli et al., 2020).

Figure 2: Dow Chemistry Classroom Kit

Note: An image of the Dow Chemistry Classroom kit.

Figure 3: Dow Chemistry Classroom Kit

Note. An image of materials in the Dow Chemistry kit (Fialli et al., 2020).

2.5 Limitations & Gaps

2.5.1 Limitations of Small-Scale Chemistry Kits

Despite their potential to enhance learning and provide cost-effective alternatives to the traditional laboratory, small-scale chemistry kits face challenges in scalability and standardization. Another limitation is the potential inaccuracy from working with minute quantities of substances. When using microscale burettes, measuring volume differences is difficult because the quantities are small (Kimel et al., 1998). Students at Glasgow University reported that while using their organic chemistry kits, they had trouble examining the results of the organic reactions because the experiments were small-scale (Khan, 1996). While these small-scale chemistry kits are efficient in helping students understand the basic concepts of each experiment, they lack practical experience and knowledge of operating real instruments in a real laboratory. For example, at the university level of education, titrations with small-scale kits are used to teach students basic knowledge. In this version of titration, the lesson uses plastic Pasteur pipettes, which are significantly different from the glassware pipettes used in the laboratory. As a result, they tend to be more suitable for demonstrating theoretical knowledge rather than preparing students for practical, hands-on application within the university-level curriculum.

2.5.2 Gaps in Sustainability Research of Small-Scale Chemistry Kits

While DCC kits are a viable option to replace traditional chemistry experiments, we find gaps in the environmental impact of small-scale chemistry kits. During our research stage, we found that there is limited research regarding the CFA of small-scale chemistry kits. These assessments can further demonstrate the sustainability of small-scale chemistry kits. Additionally, there is a lack of research regarding waste management practices and a lack of incorporation of green chemistry in small-scale chemistry kits. We aim to fill these gaps in our research by conducting an LCA and collecting qualitative data on waste generation and the usage of green chemistry in both small-scale chemistry kits and conventional laboratories.

2.6 Quantifying Carbon Footprint with a Life Cycle Assessment

According to *Carbon Footprint Analysis* published by Taylor and Francis Group, "a life cycle assessment (LCA, also known as life cycle analysis, eco-- balance, and cradle-- to-- grave analysis) is the investigation and evaluation of the environmental impacts of a given product or service caused or necessitated by its existence." (Franchetti, 2012). It follows a widely agreed-upon set of standards to evaluate all aspects of a product's lifecycle.

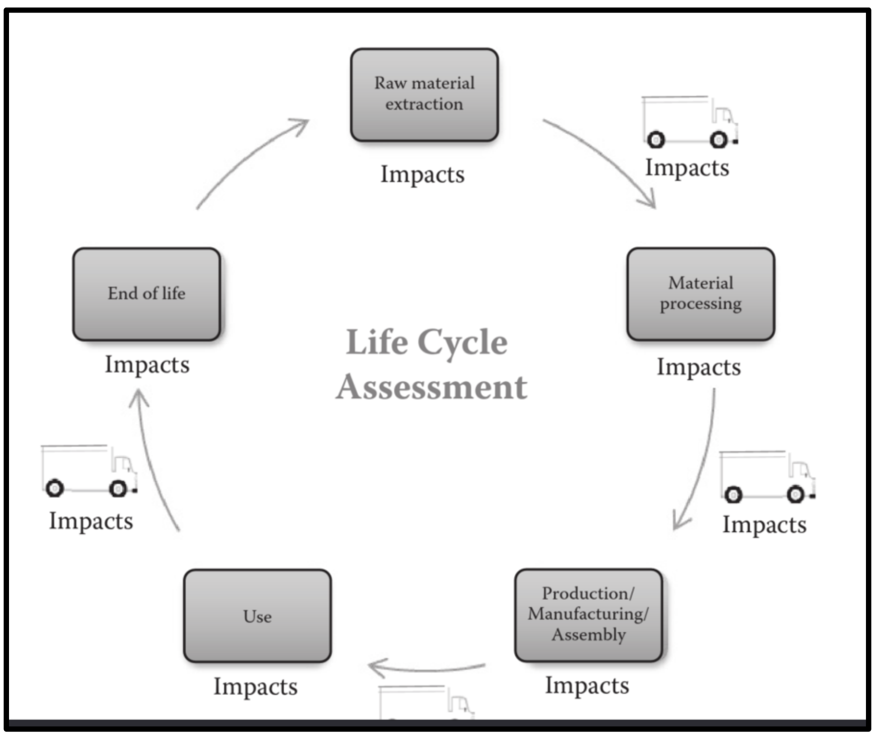

Figure 4: Life Cycle Circle

Note. An infographic showing the different avenues of a life cycle assessment (Franchetti, 2012).

Figure 4 above highlights the key stages considered in an LCA. LCA accounts for environmental impacts across the entire life cycle of a product or service, including transportation, manufacturing, usage, and end-of-life management. For the end of a product's life, we can analyze the impact of whether a product can be recycled or disposed of in a landfill. The policy implementations of these assessments are crucial. *Environmental Carbon Footprints: An Industrial Case Study* discusses how many laws only address a portion of the LCA (Franchetti, 2012). For example, banning plastic waste imports only addresses the end-of-life phase of certain products (United Nations Thailand, 2023).

Note that an LCA analyzes the inputs and outputs of each stage in a product's lifecycle qualitatively. However, to quantify an LCA, researchers use a Carbon Footprint Assessment, which estimates the carbon emissions produced by a product. Carbon footprint is the measurement of a company's GHG emissions that are released into the atmosphere, with a larger index indicating a more negative impact on global warming and climate change. An accurate and reliable assessment of carbon footprint is required for all businesses for companies to meet climate disclosure regulations, such as the Paris Agreement, and showcase their commitment to sustainability (Alp E., 2024).

For this project, we calculated the carbon footprint of both DCC kits and traditional chemistry experiments. We collected data from chemistry experiments, following manuals from DCC kits and Chulalongkorn University's GEN CHEM laboratory manuals. A comparison will be made between the two methods to determine which one is the more sustainable alternative.

To further strengthen this analysis and quantitatively assess the actual effect of a small-scale chemistry kit versus a traditional laboratory and its impact on sustainability, we propose conducting a Carbon Footprint Analysis (CFA).

Through this analysis, we examined a previous case study conducted at Western Washington University, which conducted and compared a carbon footprint analysis on traditional laboratories and a carbon footprint analysis on a small-scale chemistry kit. A CFA is typically used to understand the environmental impact of a subject or object. In this context, a CFA was conducted to compare traditional laboratories to small-scale chemistry kits. Many factors were taken into consideration, such as printer and heater usage, lighting, computers, and analytical balances. It is important to note, however, that other factors were not taken into account, such as water usage. The results found that the traditional laboratories had much higher carbon emissions than the small-scale chemistry kits (Steely, 2012). This study concluded that traditional laboratories negatively contribute to carbon emissions.

2.7 Dow Thailand's Commitment to Science Education

2.7.1 Introduction of Dow Thailand

Dow Thailand, a subsidiary of the Dow Chemical Company, was established in 1967 as a materials science company that values using sustainable materials (Dow Thailand Group, n.d.). Composed of Dow Chemical Thailand with the SCG-Dow Group, Dow Thailand has since become a leader in petrochemicals and specialty chemicals in Southeast Asia (Dow Thailand Group, 2020). With a strong emphasis on sustainability, Dow Thailand has committed to its company's global mission of innovating for a better future. One of Dow Thailand Group's initiatives is "Thailand PPP Plastics," which aims to build a circular plastic economy. The goal of the circular plastic economy initiative is to reduce plastic waste by promoting recycling and waste segregation (Dow

Thailand Group, 2023). Dow Thailand partners with educators to build science, technology, engineering, and mathematics (STEM) teaching and leadership skills and works to stimulate and prepare students in the STEM field through employee engagement and strategic partnerships (Dow Thailand Group, 2020). The foundation of Dow Thailand’s educational and sustainability initiatives lies in its goal to improve science education and the environment by making it more accessible, engaging, and sustainable (Dow Thailand Group, 2021). The company recognizes that science is critical for addressing global challenges such as climate change, resource management, and innovation for a sustainable future.

2.7.2 Dow Chemistry Classroom

Dow Thailand is committed to enhancing science education among young students. In collaboration with the Chemical Society of Thailand under the Royal Patronage of Professor Dr. Her Royal Highness Princess Chulabhorn Krom Phra Srisavangavadhana, the company launched the "Dow Chemistry Classroom" initiative. This program aims to improve chemistry education by incorporating small-scale experimental equipment that is safer, requires minimal chemical usage, shortens experiment time, and reduces waste disposal. Unlike traditional methods where students primarily learn through lectures, this initiative ensures hands-on participation, allowing every student to conduct experiments themselves (Dow Thailand Group, 2022).

The "Dow Chemistry Classroom" program focuses on advancing science education, particularly in chemistry experiments, by enhancing the skills and experiences of both teachers and students. It employs “Small-Scale Chemistry Laboratory” techniques, which are internationally recognized by UNESCO for their efficiency and high safety standards. These small-scale chemistry laboratory techniques have been widely adopted in various countries, including the UK, Germany, Austria, Mexico, the Philippines, Japan, China, Myanmar, Cambodia, Indonesia, and Vietnam. This initiative marks the first time that a private-sector organization has systematically introduced this educational model into Thailand’s school system (Dow Thailand Group, 2022).

2.8 Chapter in Review

To summarize, small-scale chemistry kits have been introduced to classrooms for many reasons. These reasons include cost-friendliness of the small-scale chemistry kits, reduction of laboratory disparities between rural and urban schools, decrease in chemical waste, shorter time duration for preparation and experimentation, and better understanding of chemistry concepts. Even though traditional chemistry experiments have their benefits, they generate a large amount of waste and are expensive to conduct. Schools might prefer to implement small-scale chemistry kits because of their economic benefits and similar conceptual outcomes to traditional laboratories. Through this project, chemistry education evolves into a platform for promoting environmental responsibility. By teaching students to prioritize sustainability and apply eco-conscious methods, initiatives like the Dow Chemistry Classroom play an important role in shaping a more sustainable future for both education and the broader scientific community.

3. Methodology

To evaluate the environmental impact of the Dow Chemistry Classroom (DCC) small-scale chemistry kits, our research integrates both quantitative and qualitative data approaches. We proposed the following objectives to guide our research toward our goal:

1. Quantify the environmental impact of traditional and small-scale chemistry laboratories
2. Compare the environmental impact of traditional and small-scale chemistry laboratories
3. Recommend ways that the Dow Chemistry Classroom can improve regarding sustainability to further promote its use in schools

We addressed the first objective by estimating the carbon emissions of a small-scale experiment (DCC acid-base titration experiment) and a traditional laboratory (Chulalongkorn University laboratory experiment) based on the material composition and weight of the equipment used for each experiment, along with the amount of chemicals used. We wanted to identify the most carbon-intensive phases in the experiment's lifecycle (Figure 4) and in their materials.

For the second objective, we compared traditional chemistry laboratories at Chulalongkorn and small-scale laboratories at Prachinratsadorn-Amroong School in three ways: comparing carbon emissions, addressing waste management protocols, and adhering to green chemistry.

Finally, we recommend actionable items based on our findings from the first two objectives to further improve sustainability and to further promote the use of DCC kits in schools.

To achieve these objectives, we performed and collected data on a Chulalongkorn University titration experiment and DCC kit, observed a General Chemistry class at Chulalongkorn University, performed participant observation, interviewed six teachers of various laboratories utilizing small-scale chemistry at Prachinratsadorn-Amroong School, and interviewed laboratory technicians to investigate waste management procedures at Chulalongkorn University.

By utilizing these varied methods, we hoped to establish a more comprehensive overview of the DCC kits' environmental impacts on stakeholders. The following sections present our methodology for accomplishing the aforementioned objectives.

3.1 Quantify the Environmental Impact of Traditional and Small-Scale Chemistry Laboratories

To achieve this objective, we calculated carbon emissions produced by small-scale laboratories and traditional chemistry experiments. We sought to answer the following research questions:

1. "What materials in both DCC kits and traditional chemistry experiments contribute the most carbon emissions?"
2. "How comparable are DCC kits and traditional chemistry experiments in terms of carbon emissions, especially given the emissions of plastics versus glass?"

We chose to collect real-world data on acid-base titration in the context of traditional, and small scale. We chose titration because we suspect it may be one of the most environmentally impactful experiments since…

1. It utilizes strong acids and bases.
2. Students have to perform multiple trials that use and leave excess chemicals.
3. It provides a great comparison point between the DCC kit and traditional laboratories since the equipment in each experiment contains materials that can be directly related to each other (plastic pipettes versus glass pipettes, for example).

4. Chulalongkorn University conducted chemistry laboratories during our timeframe and had both the necessary solutions and equipment readily available, making it convenient for our research.

We took the following steps to gather data about the traditional and small-scale acid-base titration experiment:

1. Acquire a physical kit and equipment
2. Acquire procedures and manuals for acid-base titration
3. Perform the experiment to gather data on the amount of each chemical used and any extra waste generated (such as water)
4. Separate the individual components of each piece of equipment and weigh them
5. Determine the material composition of each component (i.e., plastic boxes, pipettes, and chemicals)

We summarized the specific outcomes from each step we took for the DCC kit and the traditional laboratory in Table 1 below:

Step	Small-Scale	Traditional
1. Acquire equipment	Dow Chemistry Kit Box #301 obtained from Doing Sciences Co., Ltd	Chulalongkorn's Chemistry Laboratory
2. Obtain procedures	Included with the kit	The procedure students use in Gen Chem Class
3. Perform the experiment	Conducted multiple trials and averaged the results Determined mass of chemicals used via calibration step	Collected 4 titration experiments in parallel in pairs Followed the same data collection procedure between pairs
4. Separate and weigh equipment	Considered scissors as 20% stainless steel and 80% ABS plastic Weighed using a digital scale	Separated rubber stopper from glass burette Weighed using a digital scale
5. Determine material composition	Looked at plastic recycling information on equipment Consulted online supplier databases that manufacture common chemistry equipment (as mentioned by the producer of the DCC kit)	Consulted online supplier databases that manufacture common plastic chemistry equipment

Table 1: Breakdown and comparison of steps taken for both types of laboratories

See Appendix B11 for a full list of equipment we considered for this experiment.

To collect data on the materials used in the small-scale chemistry kits and to evaluate their usage, we contacted Doing Sciences Co., Ltd. (DSC)–the manufacturer–who provided us with Kit #301 for acid-base titration, including all of its procedures and equipment. DSC also informed us that they source their materials from various common supplies within the Bangkok area. To address the lack of data, we looked towards the underside of each plastic equipment itself (i.e., 30ml plastic containers) to determine the specific type of plastic used. If the plastic symbol was missing, we decided to turn to online databases to find similar materials and base the composition on the product listing. To determine how much of each material was used, we used an analytical balance to record the mass of each item.

To collect data on the materials used in the traditional setting, Dr. Panawan Vanaphuti, who teaches a General Chemistry class, liaised with laboratory staff to gain us access to a chemistry laboratory running titration experiments at the school. We utilized pre-mixed 0.1M NaOH and 0.1M HCl solutions to experiment. We additionally split up into four groups of two to perform multiple trials of the same experiment, collect more data points to construct a better representation, and average the results. For equipment such as a burette that contains multiple parts (the glass burette, rubber stopper, and Teflon valve), we separated the components and weighed them separately.

Additionally, since students are required to wash the equipment before and after the chemistry laboratory, we considered a case where they use a “minimum” amount of water to thoroughly wash the equipment since the water used by students varies greatly. Thus, we collected the amount of water we used in a 500 mL beaker and averaged the results.

Using our collected data, we later performed a Carbon Footprint Analysis based on an LCA to quantify both types of experiments.

3.2 Compare the Environmental Impact of Traditional and Small-Scale Chemistry Laboratories

3.2.1 Compare Waste Management Practices in Chulalongkorn University and Prachinratsadorn-Amroong School

To assess whether both teachers and students from Chulalongkorn University and Prachinratsadorn adhere to waste protocols and promote reusability, we asked the following questions:

1. "What are the safety protocols for handling the chemicals in both small-scale and traditional chemistry laboratories?"
2. "What are the differences in waste management in both equipment and procedures between small-scale and traditional-scale laboratories, and what can they learn from each other?"

We answered these questions by performing participant observation and recording notes of teachers and students as they taught and used the chemistry kits. We observed five chemistry laboratory classes at Prachinratsadornamroong School: electrolytic cell, metal ion reaction, diffusion of gas, oxygen properties, and electrochemistry.

These experiments lasted one to two hours each during the school day, sometimes overlapping with each other. We split our team into two groups of four to observe each lecture thoroughly. Within these groups, two members focused on observing the small-scale experiment while the other two observed a larger-scale experiment. This approach helped us remain focused on the potential challenges and dynamics of a classroom containing over 30 students (Lune & Berg, 2017). We informed the teachers we were researching the differences between small-scale and traditional laboratories, and thus they tailored their lessons to include two types of small-scale laboratories: small-scale and small-scale with glassware. The latter experiment, although not similar to the DCC kit, provided us with a secondary reference point to examine waste management procedures in a school and examine their usage of glassware.

We observed and noted the presence of designated waste disposals, storage of chemicals, and the teacher's lecturing content. We also paid close attention to how students performed the experiments, including any extra waste they used, what items from the kits they reused, and how they managed chemical and physical waste. We used phone cameras, paper, and pens to record all our observations as field notes. The camera captured the scene inside the classrooms. Before taking photos, we asked for consent to observe the teachers and students and consent to take photos. We used these photos as supplemental information to the notes we obtained. In addition, we recorded any keywords or phrases used, created sequential notes of events, and limited the time in which we were within the classroom (Lune & Berg, 2017, p. 120).

After our team conducted observations, we all interpreted our observations and utilized open coding to identify trends in classroom practices. Drawing from these trends, we can then compare them to similar procedures at the university level.

Participant observation provides us with first-hand experience into how both teachers and students learn and integrate green chemistry and waste management principles in the classroom. Manual instructions for the Dow Chemistry Classroom usually lack waste management instructions, and as such, physically observing the classroom practices is one method to fill the information gap and account for any deviations from official instructions (i.e., a student unsafely handling chemicals despite instructor's directions). Because we informed the teachers ahead of time, they may have demonstrated higher standards while we were observing; although we tried to observe as unobtrusively as possible, we had to engage with students to understand certain parts of the experiments. Additionally, the teachers informed the students of our presence before conducting observation as well, which could have distracted them from their procedure at hand.

3.3.2 Interviewed Educators about Waste Management and Integration of Green Chemistry Principles at their Schools

To understand how educators who actively teach green practices can enhance the students' understanding, fostering future sustainable development. As such, we asked the following questions:

1. “How have chemistry educators integrated Green Chemistry & Waste Management Principles into their teachings while using the Dow Chemistry Classroom kits?”
2. “What do chemistry educators think about current waste practices at their schools?”

To answer these questions for the small-scale DCC kits, we conducted semi-structured interviews during school hours at Prachinratsadorn-Amroong School, located in the Prachin Buri province. We conducted interviews with three groups from various grade levels to minimize selection bias. Our rationale for each group is illustrated in the table below:

Group	Rationale
Heads of Departments	Has the most influence over integrating waste management practices at the school Has an understanding of resources required to adopt the DCC into the school
Certified Dow Chemistry Classroom Teachers	Created own DCC kit and thus knows the green practices and waste management that may go into it Has experience teaching learning outcomes of DCC kit in the classroom
Non-certified teachers (potentially from other departments)	Has an outsider perspective on the impact of the DCC kit in schools Has experience with logistics around teaching in schools

Table 2: Rationale for interviewing with teacher groups at Prachinratsadorn-Amroong school

To conduct interviews, we took the following steps:

1. Wrote a set of questions regarding waste management and green chemical principles while using the DCC kits
2. Split our team into pairs with one Thai-speaking researcher and one English-speaking.
3. Conducted a semi-structured interview and obtained verbal consent with a teacher in a target group
4. Recorded conversations with teachers and took field notes
5. Leave the teachers with a gift for their time and efforts
6. Transcribed interviews and analyzed via coding

To answer our research questions for traditional laboratories, we interviewed laboratory technicians from the chemistry department who focus on maintaining the laboratory, managing the chemical waste, and preparing the equipment for the experiment for Chulalongkorn University's laboratories in the Mahamakut building. We employed similar steps as above to conduct the interviews.

To gain further insights than just adhering to the questions we pre-wrote, we chose semi-structured interviews to allow flexibility to jump off an in-conversation topic to reveal more information that our questions may otherwise not have captured. For example, jumping off a conversation point relating the specific equipment of each kit to its waste management procedure (where our questions only covered the procedure itself and not the equipment).

3.3 Ethical Considerations

All consent was obtained through verbal confirmation for the methods listed above. The permission was obtained after clearly explaining the purpose of the project. The participants' consent was a clear **yes** or **no** answer. This is informed verbal consent, in which the party was informed of all activities that are being requested of them. We retracted all names unless the participants gave direct permission to us as Thailand is under an authoritarian government, and the team wishes not to jeopardize any of the participants. To minimize potential harm, we did not ask controversial questions regarding Thailand's political system or the government. This includes asking about one's political affiliation or their opinions on the current government in place. Pseudonyms were used to ensure the security and protection of the participants if it made them more comfortable. All information collected was kept confidential, and the participants' privacy was respected unless express permission was given by all parties involved in the research methods, such as interviews, to use the information they provided.

3.4 Limitations

Each method has limitations, including temporal, logistical, expertise, and cultural blinders. We understand and acknowledge these limitations. Temporal limitations include the strict timeline of seven weeks for this research, and thus, we were constrained by the more time-intensive methods, such as performing a Life Cycle Assessment (LCA). Logistical limitations include funding and the resources to travel to areas most impacted. As such, we were limited in the group's exposure and the scope of the project.

Additionally, our limited knowledge of LCA hindered the accuracy of our data as we had to make a multitude of assumptions to account for the lack of time and data. We also lacked expertise in methods and real-world experience conducting interviews, observing the scenarios, etc. We observed and took notes to find any triangle of error and selection bias that needed to be minimized. To minimize the gap, we had our Thai team members translate and observe conversations and interactions since they have a deeper understanding of the culture and the parties' tones.

Another limitation we found was that Prachinratsadhorn-Amroong School provides different chemical experiment curricula in each department. Therefore, observing students from other programs will not give a consistent basis for comparison. Differences in curriculum design, experiment complexity, and teaching methods across departments may lead to variations in student engagement and learning outcomes. As a result, comparing students from different programs may not accurately reflect the impact of the curriculum on their performance or interest in chemistry. With all these limitations in mind, we can best navigate our research to provide the most accurate results.

4. Findings

This chapter presents the results obtained from conducting laboratory experiments, interviews with various stakeholders, research on previous case studies, and classroom observations at Prachinratsadorn-Amroong School.

The chapter begins with a discussion of our findings based on our analysis of the data collected to meet our first project objective: quantifying the environmental impact of DCC kits and traditional chemistry experiments. Next, we discuss our comparison of the two methods for the second objective with the data obtained from the first objective.

4.1 Calculating the Environmental Impact of Traditional Laboratories and Small-Scale Kits with a Carbon Footprint Analysis

Our team had limited knowledge of how to conduct an LCA, and thus, we consulted with two LCA experts, Varoon Varanyanond and Techin Charoenchitrwattana, who gave us guidance on the assumptions we should define, provided us with carbon emission sources, and validated our methodology for collecting data. We broke down the chemistry experiment into the following stages:

1. Production: Considering the materials required for the experiment that are used to produce the solutions, equipment, manuals, containers, and more
2. Preparation: Any resources required to prepare the experiment for student consumption (cleaning, pre-mixing solutions, etc.)
3. Use: Chemicals and materials used in the experiment itself, including how these resources are disposed of

4. End of Life: When the experiment equipment reaches the end of its use and needs to be replaced

Our analysis focused on the production, preparation, and end-of-life phases of the experiment. We met with the production engineer from Doing Sciences Co. Ltd, who helped us identify the source of materials and estimate the lifespan of the kits. From her information and the LCA experts we consulted, we generated the following assumptions to provide a realistic estimate of the case and eventually conducted a fair comparison between the traditional and DCC experiments. Additionally, we assumed:

1. Most materials are sourced from Thailand, and its carbon emissions can be found from reliable secondary sources (Thai National LCI Database)
2. All equipment are common items that can be found in any general chemistry suppliers.
3. Equipment does not need to be replaced before End-of-Life
    a. DCC kits have a lifespan of 20 uses
    b. Traditional experiments have a lifespan of 100 uses
4. Equipment can be simplified to a raw material composition (i.e., 100% PET plastic, 20% Glass, 10% ABS plastic, etc.)
5. Energy usage and transportation are not considered
6. All liquids/substances are assumed to be disposed of down the drain as wastewater
7. For each product's end of life, we assume glass is incinerated while plastics and other materials are landfilled
8. The indicator used (Phenolphthalein) is unaccounted for due to a lack of data
9. All equipment cleansing was done using tap water

To account for variations in the amount of waste generated and chemicals used between students, we also considered two cases:

1. Minimum Water
2. Without Water

In the traditional acid-base titration experiment, we observed that students used water to clean the equipment before and after the experiment. However, this varies greatly from person to person. To address this issue, we considered two cases: gather a “minimum” average of water used to thoroughly clean the apparatuses and exclude water from the analysis entirely. Additionally, titration requires solving for an unknown concentration, which can vary in chemical usage; thus, we considered an “ideal case” where students used the “minimum” amount of chemicals to complete the experiment without any excess chemical waste left over. Although we safely disposed of the chemicals in the traditional laboratory, for our analysis, we will assume they will be washed down the drain to provide a fair comparison to the DCC kit.

To create a baseline and also consider real-world usage, we considered the following cases after the DCC kit reaches its lifespan of 20 uses based on student observation and teacher interviews:

1. Replace the whole DCC kit (based on production engineer indicating 20 use lifespan)
2. Refill chemicals only (based on teachers indicating they reuse kits for several years)
3. Replace plastic equipment and refill chemicals (simulating plastic degradation)

To perform the necessary LCA calculations, we must know the emission factors for each type of material. These factors provide standardized and simplified values that estimate the amount of CO_2 emissions involved in the making of that specific type of material. The emissions from the Thai National LCI Database cover the raw material extraction and production of each material.

Thus, we created a rough estimate of the carbon emissions emitted during the production of DCC kits and traditional chemistry experiments, compared the differences between the two, and recommended ways to optimize the materials used to produce fewer emissions.

To quantify the environmental impact of the DCC kits and traditional experiments, we collected the quantity, mass, and type of each item in the experiments. Then, using the Thai National LCI Database (and other sources where needed), we gathered carbon emission data for each material and subsequently calculated the carbon emitted with Equation. 1 below.

$$E(k)_{I,M} = \sum_{i=1}^{|I|} \sum_{n=1}^{|M_i|} mass\ (kg)_{{M_i}^n} \times quantity_i \times uses_i \times E({M_i}^n)$$

Equation. 1: Calculating carbon emissions for a specific item, where k is the experiment type (traditional or DCC), I are the items in the experiment, M is a matrix of all the materials for a given item i, uses are the amount of times a quantity of chemicals are used or material is produced over the whole product's lifecycle, and $E(m)$ is from a database of emission materials for material m.

To best compare the DCC kit and the traditional case, we chose to compare just one use of each experiment to each other. We used Equation 2 to scale the emissions to one usage for both types of experiments. Scaling the carbon emissions in this way assumes that each use is simply a fraction of the emissions during the whole lifecycle; for example, one use of the DCC kit would contain 1/100th of the production carbon emissions for 5 kits produced in its lifespan (to accurately compare with 100 uses of a traditional chemistry experiment).

$$E(k)_{scaled} = \frac{E(k)_{I,M}}{100}$$

Equation. 2: Scaling the carbon emissions to 1 use by dividing by 100 uses.

The carbon emissions for each material, chemical, or disposal methods can be seen in the pie charts below (Figure 5 and 6).

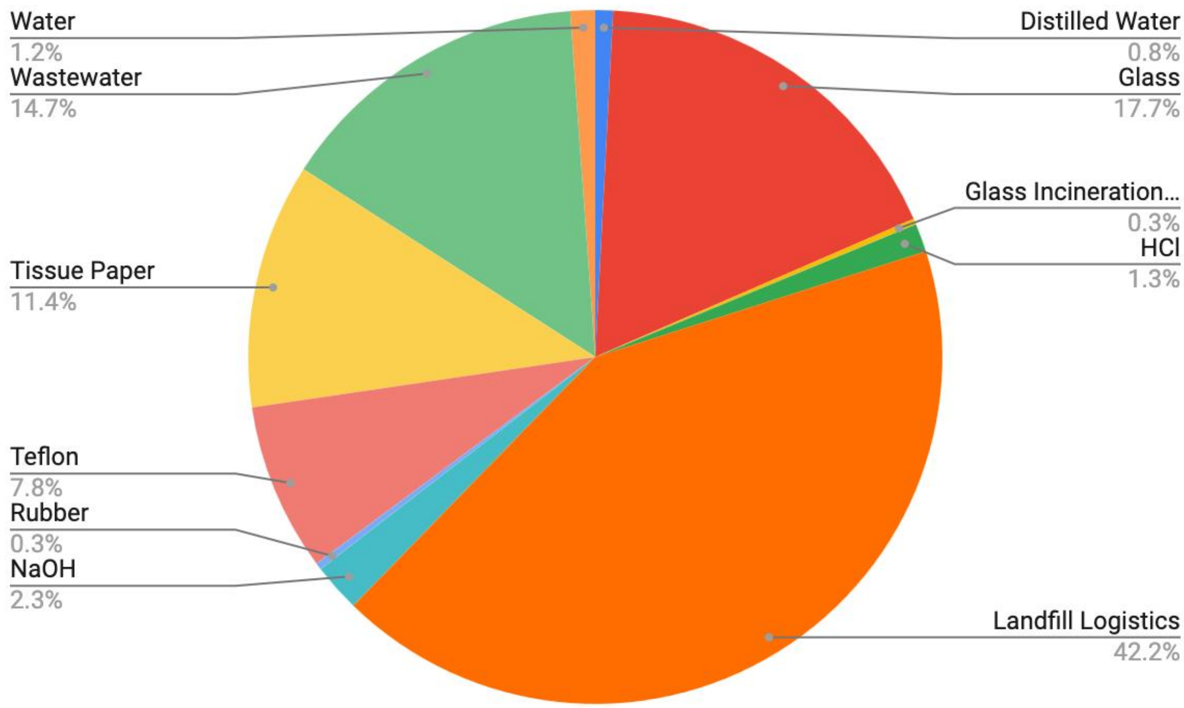

Figure 5: Carbon emissions of materials, chemicals, and disposal methods by percentage for the traditional chemistry laboratory (including water) case.

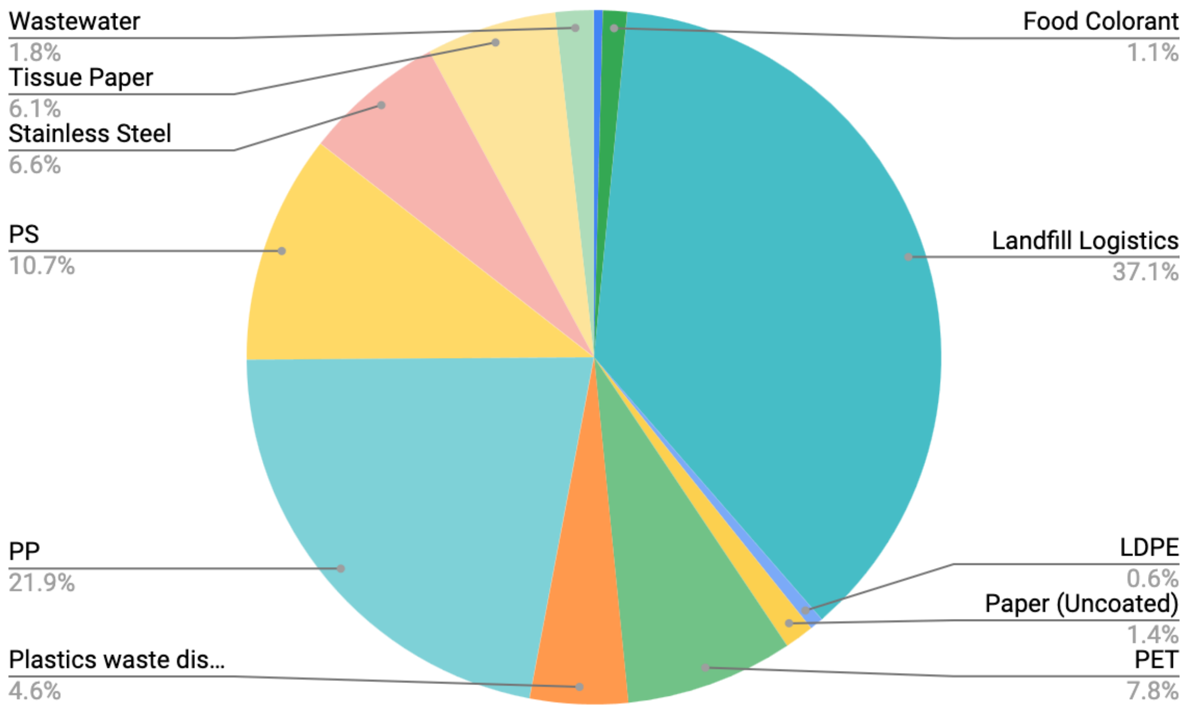

Figure 6: Carbon emissions of materials, chemicals, and disposal methods by percentage for the DCC kit (replacing the whole kit after 20 uses) case.

By quantifying the carbon emissions for both experiments, we discovered the relationship between each material, each other, and each phase, allowing us to conclude the experiment as a whole.

4.2 Dow Chemistry Classroom and Chulalongkorn Laboratories Have Various Advantages Over the Other in Terms of Carbon Emissions

Conducting a comparative analysis of our quantitative data above, we found that both types of experiments have advantages over each other in some areas in terms of their carbon emissions. For all our following analyses, we compared one use of each experiment to each other according to the cases we discussed earlier.

Assuming the whole Dow Chemistry Kit is replaced, traditional emits less emissions.

According to our calculations, traditional laboratories emit 82% less carbon than DCC if each kit were to be completely replaced (Figure 7).

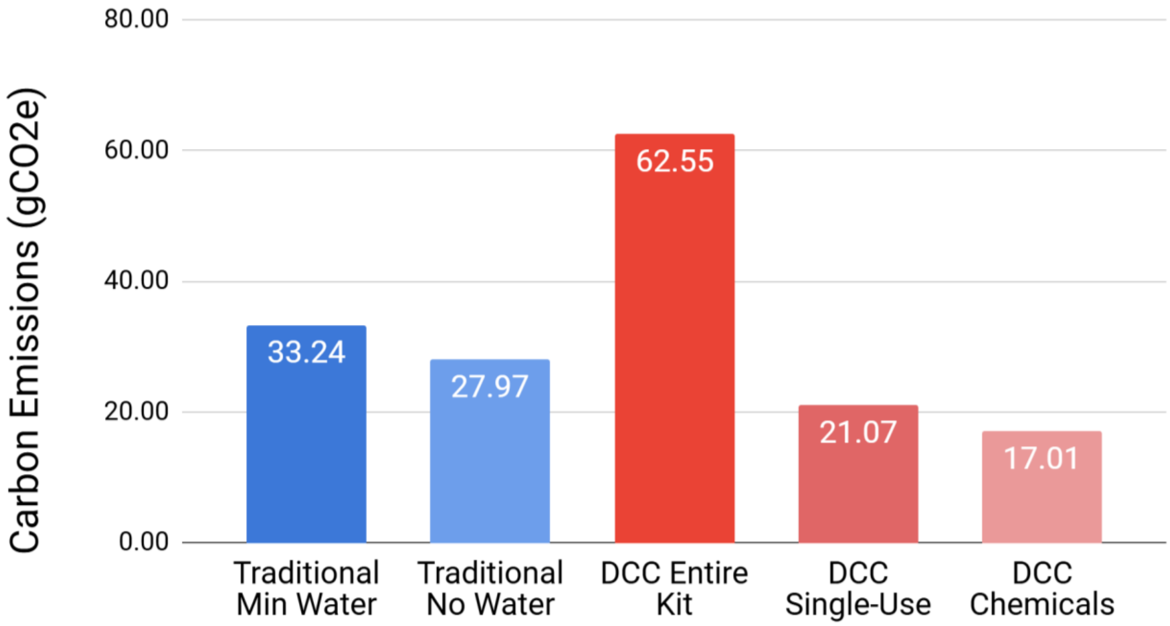

Figure 7: Carbon Footprint Comparison between Traditional and Small-Scale Experiments

We assume a lifespan of 20 uses per kit as per a production engineer from Doing Sciences Co Ltd, thus the DCC kits would have to be replaced 5 times to match the traditional laboratories' 100-use lifespan. With plastic production contributing to nearly 41.4% of the carbon emissions for the DCC kit, it seems to contribute the most carbon each time it is replaced.

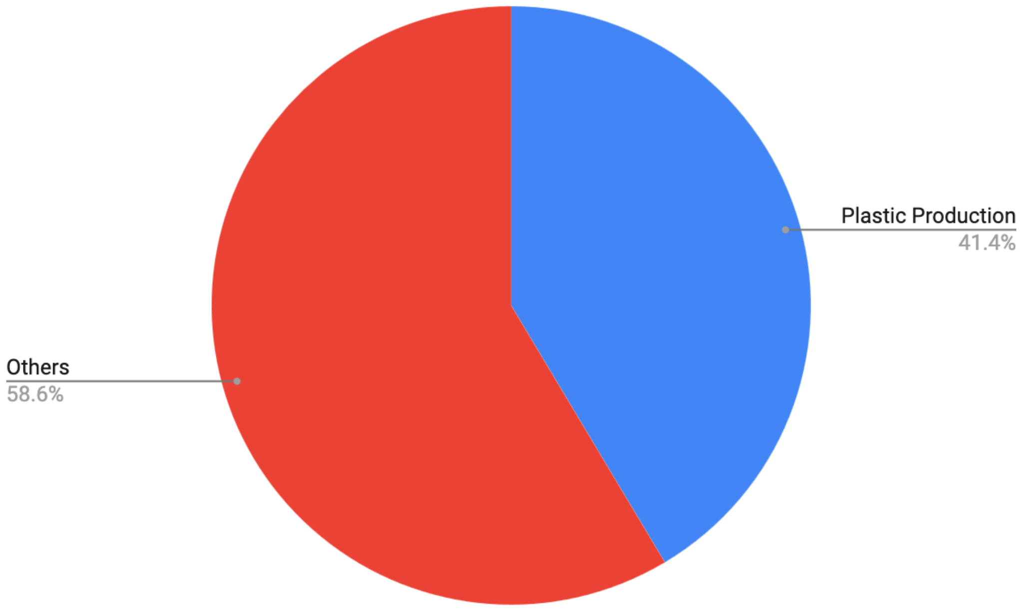

Figure 8: Plastic Production of the DCC kits Versus Other Emissions.

Note: "Others" contains transportation to landfill and plastic incineration, which could contribute more to the impact of the plastic.

Assuming the chemicals and some materials can be reused, the DCC kit emits less than traditional.

For traditional laboratories, we examined two cases: considering water and excluding water. For the DCC kit, we considered two additional cases: replacing chemicals for every 20 uses and replacing single-use items for every 20 uses. Laying and analyzing these cases in a comparison matrix, we found that in all these cases, small-scale emits slightly to moderately less carbon.

Based on interviews with educators at the Prachinratsadorn-Amroong school, we can reasonably assume they replace chemicals and the plastics in the kit as some of the educators state that they have been reusing the same kit box for several years. Excluding water, we find that the traditional experiment's carbon emissions are 158%-195% higher than the DCC kit (Table 3), depending on whether the teachers choose to replace the plastics in the kit as well.

Comparison Matrix	**Traditional Experiment**		
Small-Scale Experiment	Normal	No Water	Ideal
Replace Whole Kit	0.53	0.45	0.53
Replace Chemicals & Plastics	1.58	1.33	1.56
Replace Chemicals	1.95	1.64	1.94
Ideal	0.53	0.45	0.53

Table 3: Comparison matrix considering all cases for the traditional and small-scale laboratory experiments

Note: The numbers are represented by dividing the emissions of the traditional experiment by the small-scale experiment. Thus, a number >1 indicates that traditional emits more than small-scale and vice versa.

However, in the real world, chemistry laboratories require students to rinse equipment before and after with water. We find that replacing only single-use items (consumables, container bottles, and chemicals), as opposed to the whole kit, made the carbon emissions of DCC 63% of the traditional laboratory. Under the assumption of replacing the chemical solutions only after they are used up, the DCC's emissions were about half (51%) of the traditional (Table 3). Taking into consideration that we measured the water usage based on a *minimal* amount of water used to thoroughly clean the equipment, in actuality, the difference in carbon emissions based on how students use water can be much higher.

The use of tissues is more environmentally impactful than chemical usage in both types of experiments.

In the use phase of traditional and small-scale chemistry experiments, we considered the use of two tissue papers in both experiments. We found that the tissues contribute to around 72% and 84% of the total emissions.

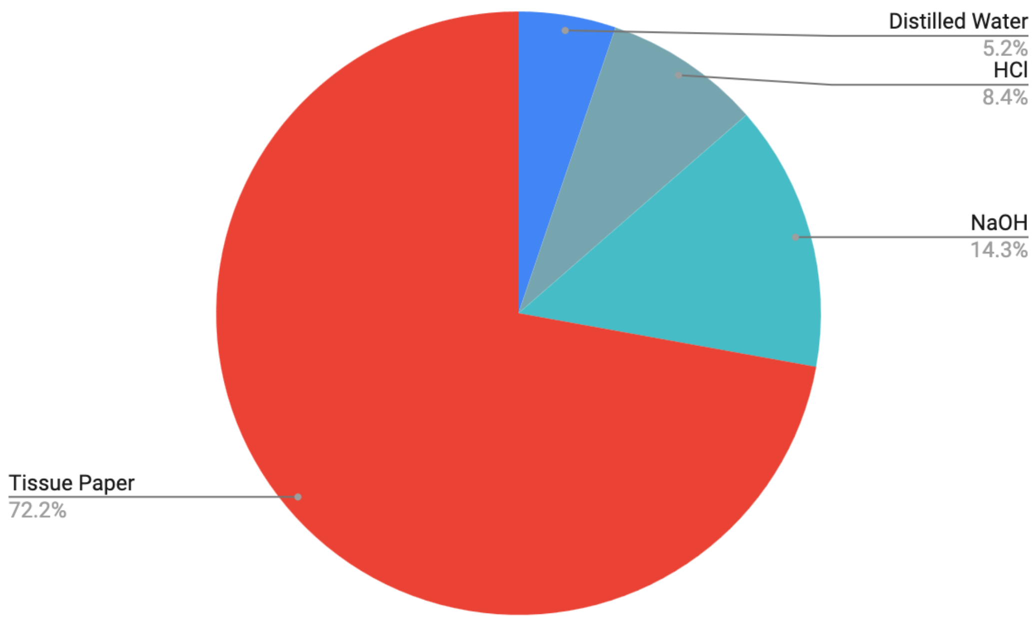

Figure 9: Use Phase Distribution of Traditional Laboratory (Minimum Water) Case

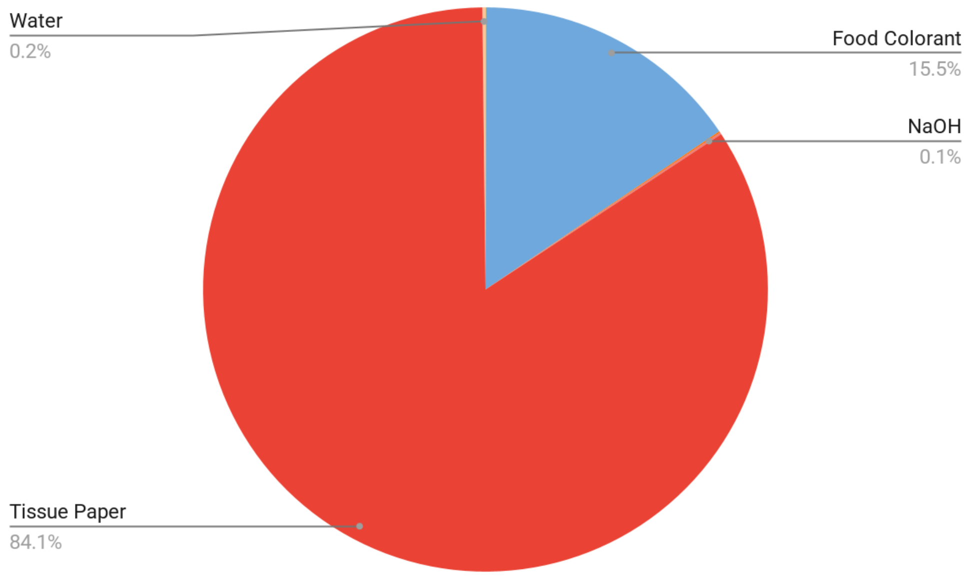

Figure 10: Use Phase Distribution of Dow Chemistry Classroom Kit (Replace Whole Kit) Case

This is consistent with prior research investigating the carbon emissions of tissues; high energy-intensive procedures such as debarking, chip refining, cooking, bleaching, washing, and drying are used to make tissue paper (Gemechu et al., 2013). Thus, using these single-use highly carbon-intensive products to clean up spillages or conduct experiments contributes to a far bigger impact than using the chemicals themselves.

The mass of equipment contributes greatly to carbon emissions.

Landfill collection emits a high amount of carbon as waste has to be collected, transported, sorted, and disposed of by pile, with transportation being a major contributor. In both the traditional laboratory experiment and the DCC kit, end-of-life landfilling is one of the top 3 areas that contribute the most emissions (Table 4). Landfill emissions and mass are directly correlated: since glass equipment is significantly heavier and at a larger scale, disposing of it has a larger impact than the DCC kit. Since landfilling makes up 42% of the total carbon emissions for one traditional titration experiment, any added mass can cause a sharp increase in emissions.

Experiment Type	**Material**	**Carbon Emissions (gCO2)**
Traditional	Landfill Logistics	14.03
	Glass	5.87
	Tissue Paper	3.80
Small Scale (Replace Kits)	Landfill Logistics	23.19
	PP	13.71
	PS	6.67

Table 4: Top three most impactful materials in the traditional and small-scale laboratories.

Note: “Landfill Logistics” refers to the carbon emitted during collection, sorting, and landfilling of waste.

Assuming chemicals and plastics are replaced, the DCC emits more carbon during production and less during end-of-life.

Analyzing two cases of the DCC kit and the case including water for the traditional experiment, we find that in the former case, the DCC kit emits far more emissions than the traditional laboratory (Figure 11). In the latter case, and because of the more carbon-intensive nature of producing plastics for the Dow Chemistry Classroom, its production phase is moderately higher than producing the traditional experiment. However–and in line with our previous finding above–the transportation of heavier materials for the traditional experiment is significantly higher (Table 4).

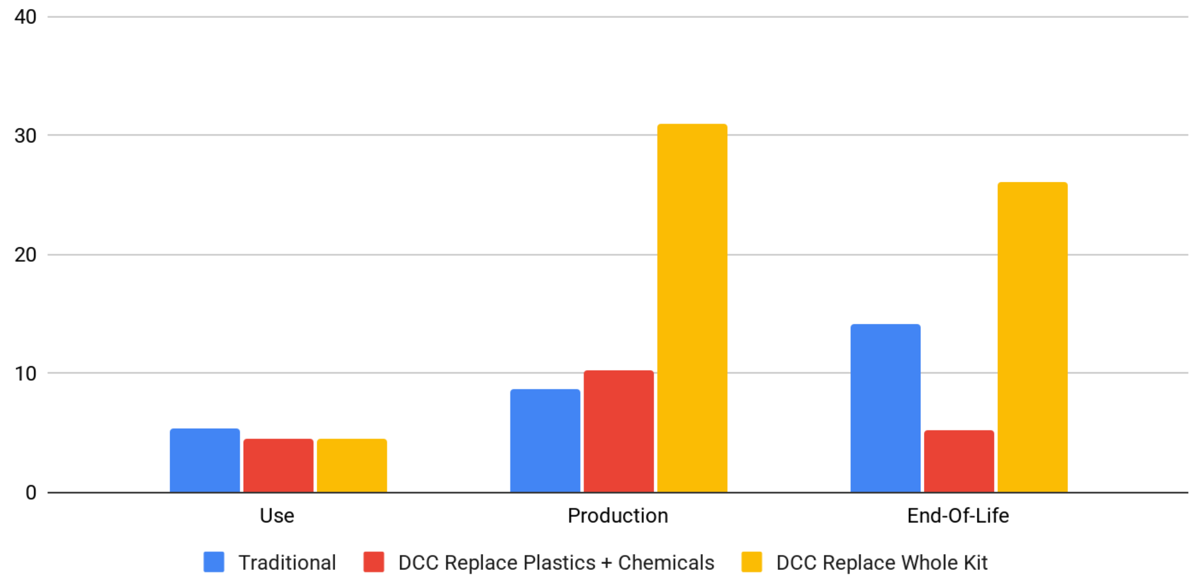

Figure 11: Phase comparisons between Chulalongkorn Traditional Experiment (including water) and Dow Chemistry Classroom cases.

Limitations

These findings are limited by our assumptions, and the majority of the calculations were done based on secondary data. In addition, production emissions may be inaccurate for the specific materials listed in each of the chemistry kits. Nevertheless, by conducting the same methodology for both the DCC kits and traditional chemistry experiments, we drew relative comparisons that speak to the effective measures of both kits.

4.3 Waste Management in Traditional and Small-Scale Laboratories

Waste management in the laboratory is an important issue that directly impacts environmental sustainability. Laboratories generate many types of waste, such as chemical and plastic waste, which, if not handled correctly, can cause a significant environmental impact. The approach to managing this waste differs depending on each laboratory's scale and resources.

Laboratories in universities are commonly used for high-level experiments on a traditional scale. This method produces large amounts of hazardous waste, and the disposal has to follow regulatory guidelines. Laboratories present in secondary schools typically generate less chemical waste and are less intense with the disposal of chemicals due to the smaller scale. Hence, the DCC kits are designed with sustainability in mind, prioritizing the reduction of chemical waste produced.

We compared the environmental impact of waste management with traditional chemistry experiments, such as those in universities with DCC kits. University-level chemistry waste management procedures serve as a benchmark for comparison with DCC kits, keeping in mind that university standards are not the norm. Interviewing with teachers and laboratory technicians and conducting classroom observations, we found that traditional chemistry experiments require more intensive waste management due to their more extensive chemical usage and stricter disposal regulations. Small-scale chemistry kits are designed to minimize chemical waste production. This comparison highlighted the key differences in waste generation, disposal methods, and sustainability practices across these laboratories.

4.3.1 Traditional Laboratories Require More Intensive Waste Management

The interviews with Chulalongkorn's laboratory technicians provided valuable insights into how large universities handle and manage chemical waste. We used Chulalongkorn University as a case study as it is one of the largest universities in Thailand that uses traditional chemistry experiments. The Center for Safety, Health, and Environment of Chulalongkorn University (SHECU) is an initiative at Chulalongkorn University that promotes a safe and healthy environment for both students and staff. It focuses on safety management, training programs, and ensuring compliance with relevant regulations (Center for Safety, Health and Environment of Chulalongkorn University, 2018). At Chulalongkorn University, laboratory rooms have designated

SHECU tables that guide students on the categorization and disposal of the waste generated in the laboratory (Figure 12).

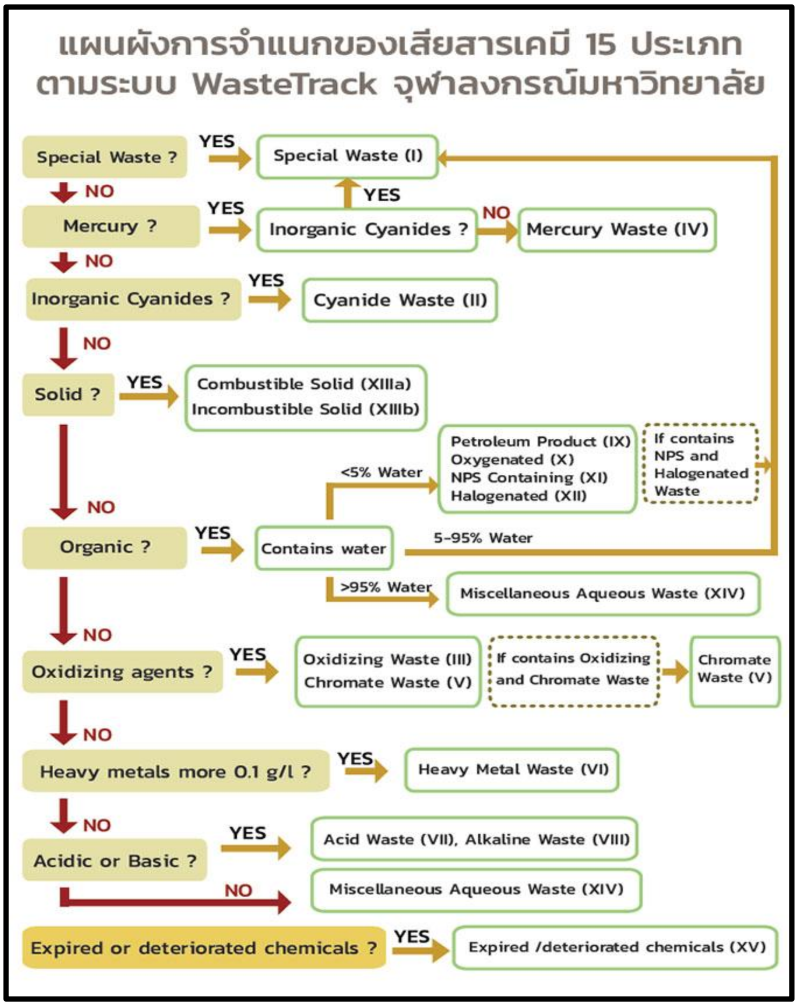

Figure 12: SHECU table

Note: The procedure for the classification of chemical wastes at Chulalongkorn University (Chulalongkorn University, 2020).

This method ensures that the students can correctly dispose of the chemical waste in the appropriate container. To ensure all the students follow the same waste management procedures, professors begin each class with a briefing on how to clean up and manage waste from experiments. For example, after an acid-base titration experiment, laboratory technicians neutralize the waste to a neutral pH before safely draining it down the sink. For other types of chemical experiments, hazardous waste such as heavy metal waste and its precipitates must undergo proper treatment before being sent to the waste disposal company.

Moreover, at the university level, students are tasked with recording their chemical usage, including the volume of chemicals before and after the experiment. The laboratory manual also specifies the types of glassware required for each experiment. The waste management procedures at the university level can be considered a reference in comparison to those at the secondary school level. On the other hand, universities must carefully manage chemicals before and after use, they face significant costs in purchasing chemicals and ensuring proper disposal. Moreover, universities have to work with reputable suppliers and waste disposal companies to handle hazardous waste safely and responsibly.

4.3.2 Waste Management for Large-Scale Chemistry Kits Remains a Major Challenge

We used Prachinratsadorn-Amroong School as a case study to examine waste management practices in schools using small-scale and large-scale chemistry kits. It is important to note that large-scale experiments at the school imitated traditional laboratories but were not standard traditional laboratories hence our use of the term "large-scale." Through interviews with secondary school teachers and classroom observations, we found that waste management for large-scale chemistry kits remains a significant challenge. On the other hand, the handling of waste in small-scale laboratory kits is easier to follow and maintain.

Since laboratory management at the school is less intense than at the university level, proper waste disposal methods are often lacking and inconsistent. Chemical wastes such as solutions are disposed of by draining them in the sink, while other wastes are stored in the laboratory rooms until a disposal company or charity collects them. For example, in electrochemistry experiments, students who performed large-scale chemistry experiments poured their solutions of copper sulfate and zinc sulfate chemicals down the sink and rinsed the beakers with water. This practice is unsustainable and contradicts SDG 12, which encourages the proper management of chemical waste. Rigorous management of waste reduces waste generation and is more environmentally friendly. Through proper management of waste, classrooms can reduce waste generation and improve environmental sustainability.

Despite the poor waste disposal methods, the school has attempted to align with proper waste management procedures. One example is in the metal-metal ions experiment, where chemical solutions that reacted with metal strips and those that did not were separated into different containers. The chemical solutions reacted in this experiment contain heavy metal precipitation that cannot be directly poured down the drainage system due to their high environmental toxicity. Hence, they are kept in containers and stored in the school's storage room, waiting to be sent out to be properly disposed of. The school is actively searching for the best waste disposal solution, such as partnerships with disposal companies, charities, universities, and online networks to manage chemical waste.

4.3.3 Small-scale Chemistry Kits are Easier to Maintain

From our previous case study at Prachinratsadorn-Amroong School, most small-scale chemistry kits are reusable, which benefits waste reduction and sustainability. The chemicals in small-scale chemistry kits are diluted with water to very low concentrations, making them relatively harmless for students and the environment when disposing of chemical waste. The clean-up procedure consists of using a small volume of water to rinse the plastic apparatus and wash the chemicals in containers such as plastic droppers and 96-well plates. Tissues are then used to wipe off leftover water to dry the equipment inside the kits. Used tissues were later disposed of in the trash as the only physical waste present during the experiment. In experiments involving the use of chemicals such as heavy metal solutions, small droplets of these solutions are pipetted onto metal strips. After the experiment has finished, the chemicals on the metal strips are absorbed into tissues and trashed in rubbish bins. Overall, small-scale chemistry kits are easier to maintain as they require fewer chemicals in lower quantities and concentrations compared to larger, traditional laboratory setups.

4.4 Evaluating the Impact of Large-Scale and Small-Scale Chemistry Laboratories

Our gathered data suggested that there are sustainability practices in small-scale chemistry laboratories. We found that:

1. Green chemistry principles are implemented in chemistry classrooms.
2. Small-scale laboratories incorporate sustainable practices.

4.4.1 Sustainable Practices in Small-Scale Chemistry Kits

While interpreting our data, we observed that sustainability practices are likely incorporated in small-scale chemistry kits. We developed this finding based on our observations of waste management and green chemistry principles. Small-scale laboratories use relatively fewer chemicals that can be disposed of with a couple of pipetted drops of water and a tissue to dry the material used. This is a simpler approach for students to use compared to the larger-scale version of their experiments.

Small-scale chemistry kits are safer alternatives to traditional laboratories.

By analyzing the equipment used, we found that small-scale materials reduce the risk of harm caused by glassware breakage. Since the materials are made of plastic, they are less prone to breakage than traditional laboratories that use glassware as their primary material. The change in material type from glass to plastic provides a safer environment for middle and high school students to conduct chemistry experiments. However, it is important to note that the use of plastic also has its limitations, such as limited usage before it needs to be disposed of.

Some materials are recycled and reused for future experiments.

We observed that in an electrolytic cell experiment, teachers reuse the small-scale chemistry kit box and replace the materials within the box to prepare for a subsequent experiment. Rather than being disposed of, students leave water on tables and reuse it for future experiments until it is depleted. In another experiment, metal-metal ions displacement reaction, the metal strips used in the displacement reaction can be reused for the next class. To reuse the reacted metal strips, students from the previous class dry the metal strips using tissues. Students from the next class are then tasked with grinding the metal strips using sandpaper to remove the foreign metal on the surface. These examples align with the 1st green chemistry principle, waste prevention, and SDG target 12.5 by reducing waste generation through prevention and the 3Rs. Recycling materials reduces the need to replace the materials used in experiments.

DCC Kit training incorporates waste management and green chemistry principles.

We found that teachers are trained to utilize DCC kits. The teachers we interviewed explained that they undergo lectures during their training on waste management and green chemistry, emphasizing sustainability by reducing waste and utilizing locally available materials. This engaged teachers in using more natural and renewable resources such as butterfly peas, a flower that is commonly found in Thailand. The flower can also be used as a natural indicator in titration experiments, providing an eco-friendlier alternative to chemical pH indicators used in the DCC kits. Another example is the use of eggshells; calcium carbonate ($CaCO_3$) contained within the shells can react with acids such as hydrochloric acid to produce CO_2. Moreover, since $CaCO_3$ is not directly soluble in water, students can apply a back titration method to determine the amount of acid that has reacted with the compound. Our interviews with teachers suggest that classrooms use green chemistry principles. Teachers can continue to raise awareness of green chemistry principles and integrate them into classrooms by using locally, naturally sourced materials and enhancing waste management and chemical safety practices.

Areas for improvement within the small-scale chemistry experiments

While green chemistry is incorporated in classrooms, there are areas where it is lacking, such as the use of plastic materials and the minimal use of reusable materials, such as cotton buds used in an experiment exploring the properties of oxygen. In addition, pouring untreated chemical waste down the sink does not support the green chemistry principle of waste prevention. The chemicals can contaminate sink drains, which further causes issues. The "Safer Chemistry for Accident Prevention" principle was also observed in some classrooms. Specifically, some teachers discuss safety procedures, however, many teachers do not. As a result, during the experiment of gas diffusion, students mixed droppers, causing contamination of chemicals. This shows that students need to learn chemical safety before experimenting.

4.4.2 Engagement of Students and Teachers in Chemistry Experiments

We identified a potential theme pertaining to students' and teachers' engagement of the large-scale and small-scale chemistry kits. Although these small-scale chemistry experiments performed at the school were not all DCC kits, the data collected provided a better understanding of students' and teachers' perspectives.

There is a similar level of student engagement between small-scale and large-scale chemistry experiments.

Student engagement was similar regardless of whether they used small-scale or large-scale chemistry experiments. We observed students recording and photographing their experimental progress. Generally, teachers were very engaged in the students’ progress during the experiment. They reassured students' understanding by asking questions about the concept before commencing the experiment. The teachers also used this opportunity to improve students’ scientific presentation and confidence skills by having them present their findings to the class. For example, in the electrolytic cell experiment, we observed a representative from each group present their experiment findings to the class. It can be concluded that regardless of whether students were conducting small-scale or large-scale experiments, they seemed engaged and excited about chemistry experiments. By learning and performing experiments through small-scale chemistry kits, sustainable practices such as using minimal chemicals are ingrained into the students.

5. Conclusion and Recommendations

This chapter suggests recommendations for future studies and improving the DCC kits, ensuring their long-term sustainability, environmental impact assessment, and credibility.

5.1 Recommendations for the Future Improvement of the DCC Kits

We recommend the following adjustments to be taken into consideration to further improve the sustainability and lower the environmental impact of the DCC kits.

5.1.1 Considering Alternative Materials for the Containers

To improve the environmental impact of the DCC kits, we recommend alternative materials for the containers to reduce their carbon footprint. According to our DCC kit's carbon footprint calculation, while using smaller amounts of chemicals can reduce carbon emissions, approximately 41% of carbon emissions are from plastic (PET, PP, PS, and LDPE) (Figure 8). Even though the DCC kits are lightweight and cost-effective, they have a high carbon emission factor due to their production and disposal processes. Plastic manufacturing through the extraction and refining of fossil fuels contributes significantly to GHG emissions and is a main factor in increasing carbon footprint and impacting climate change globally (Zheng & Suh, 2019). While plastic components make the kits accessible and durable, their sustainability can be improved by exploring alternative materials, increasing the use of recycled plastics, or optimizing the design to reduce material usage while maintaining functionality. One viable option is the use of bioplastics, which are derived from renewable sources such as corn starch, sugarcane, or algae. Unlike conventional petroleum-based plastics, bioplastics can have a lower carbon footprint and, in some cases, are biodegradable or compostable, reducing long-term waste (European Bioplastics, 2021).

5.1.2 Considering the Use of Natural Indicators and More Implementation of Green Chemistry in Experiments

We found that the DCC kits align with the green chemistry practices, however, we suggest stakeholders focus more on the Safer Solvents and Auxiliaries principle, which can be done with the implementation of natural indicators in experiments, such as titrations. The traditional chemistry experiments indicator in the DCC kits is phenolphthalein (PP), a synthetic chemical that may cause cancer in humans (Chemos GmbH Co.KG, 2020). Red cabbage juice, which is a known natural indicator choice for phenolphthalein in the chemistry industry, contains anthocyanin pigments that change color depending on the pH of the solution, mimicking the behavior of phenolphthalein (Anne Marie Helmenstine, 2024). We recommend this indicator as a highly effective and eco-friendly indicator for acid-base titrations.

5.1.3 Reducing the Use of Tissues

After interviewing Ms. Jiraphan Charoensinvorakul, the production engineer from Doing Science Co., Ltd., we learned that there are no waste disposal procedures in any DCC Kits due to the small amounts of chemicals required in each experiment. Thus, students will use external materials unregulated to experiment. During the classroom observation, we saw that too many tissues were used for cleaning and drying the equipment. The tissues are dumped through landfills and incinerators, creating carbon emissions that cause a carbon footprint. Similar to the documented waste procedure of Chulalongkorn, the use of tissues should be imposed in manuals to one paper or none if possible per one-time use of the DCC kits to minimize the carbon emissions and their impact on the environment.

5.1.4 Reaching Out to Universities to Promote the Use in Schools

By obtaining academic adoption proposals and reaching out to universities for endorsement and approval, the DCC kits' cost-effectiveness, efficiency, and sustainability. Justifying how the DCC kits should be adopted into the school curriculum as an alternative to traditional chemistry experiments.

5.1.5 Enhance the Chemistry Kits in Curriculum and Carbon Footprint Certification by TGO

To enhance the use of the DCC kits in the chemistry curriculum, we recommend Dow Chemistry Classroom reach out to Thailand Greenhouse Gas Management Organization (TGO) to obtain certification. TGO certification will provide an independent, transparent assessment of the kits' environmental impact, focusing on the greenhouse gas emissions associated with their production, transportation, and disposal. The certification will not only validate the DCC kit's commitment to sustainability but also improve its credibility, fostering greater trust among educational institutions and supporting the adoption of environmentally responsible practices (*Carbon Footprint for Organizations Certification, A Step Toward a Sustainable Future - Banpu NEXT*, 2024). We have conducted a preliminary carbon footprint analysis of a kit (acid-base titration) and stated what key areas could be improved, such as reducing the carbon emission of manufacturing processes or considering alternative materials with lower environmental impacts. This should be used as a model for the next steps to earn TGO certification.

Figure 13: TGO's Roadmap to Obtain Carbon Certification (Theerakul, 2023)

Figure 13 shows the certification procedures. By obtaining certification from TGO, the kits will gain official recognition for their environmental responsibility, which can encourage greater adoption by educational institutions seeking to align with sustainable practices. In addition to environmental improvements, promoting the DCC kits in the curriculum to enhance their educational value is important. Incorporating the DCC kits into science curricula will allow teachers and students to use them as practical tools for demonstrating key concepts and encouraging hands-on learning and critical thinking with limited time and resources. We recommend collaborating with educational experts to develop lesson plans and teaching resources that align with national and international science education standards. By fostering a curriculum that integrates these kits and green chemistry practices, along with waste management procedures, into regular classroom activities, Dow can help make sustainable chemistry education more accessible and engaging for students while reinforcing the importance of responsible consumption and production in scientific practice.

5.2 Recommendations for Future Study

We recommend that future researchers on a similar study focus on evaluating the environmental impact by conducting LCA and interviewing stakeholders.

5.2.1 Recommendations for LCA Calculations

We conducted a life cycle assessment to quantify and compare the carbon emission between traditional acid-base titration and small-scale kit titration. We made many assumptions in our calculations due to our limited time for this research. We recommended that to cradle-to-grave the LCA and ensure the accuracy of the results, future researchers should obtain primary data at each stage in the life cycle. The source of raw materials plays a crucial role in determining carbon emissions, as factors such as environmental impacts from extraction, mining, or processing, along with the renewability of these resources, influence overall emissions. The production phase, including energy consumption, emissions, and waste generation from manufacturing, should be focused on the most due to the release of energy from each piece of equipment that will show the most impactful materials. The transportation phase should assess the carbon footprint associated with the movement of raw materials, parts, and final products, distances and fuel efficiency. This stage should take time to track every factor in the movement because different types of cars and fuel have different impacts on the environment. For the use phase, evaluate the product’s durability, maintenance needs, energy consumption, and longevity, as these factors will significantly influence the overall environmental impact. Lastly, the end-of-life phase, consideration of how the waste is disposed of or recycled, evaluates landfill, incineration, and transportation of waste to the disposal company. Each waste produced from the experiment has to be considered carefully as they have different ways of dealing with it, which will significantly affect the outcome of LCA calculations.

5.2.2 Performing LCAs for Other Traditional/Small-Scale Chemistry Experiments

We recommend performing other comparisons of the DCC Kits and traditional chemistry experiments to provide a broader understanding of the environmental impact of both methods. By examining a wider range of experiments and identifying additional advantages and disadvantages, such as differences in chemical usage, waste production, and energy consumption, future researchers can help further refine the overall environmental footprint of both traditional and small-scale laboratory methods. Some experiments may produce more hazardous waste or require more intensive disposal procedures, which could point out the sustainability between the two methods. Extending the range would show a clearer picture of how specific green chemistry practices could be integrated into both methods. For example, traditional chemistry experiments may have opportunities to reduce their carbon footprint by evaluating the most environmental impact factors to be more sustainable. The DCC Kits could be redesigned to minimize carbon emissions that rely on non-renewable materials.

5.2.3 Recommendations for Participant Interviews

We recommend interviewing experts who specialize in chemical waste management, as they can provide valuable insights into accurately and reliably calculating the amount of gaseous waste or solid waste (filter papers, foams, and plastics) released from DCC kits and traditional chemistry experiments. We also suggest reaching out to researchers who design the DCC kits as opposed to the ones who produce the kits because we lacked the reason the designers chose to use plastic for the small-scale kits. Furthermore, we recommend interviewing people who work in the waste disposal company. This is because they could be able to give information about the amount of waste from the leftover chemicals in high school large-scale experiments. Last but not least, we recommend interviewing sustainable materials experts. They could offer alternative ideas for plastics in small-scale chemistry kits to make small-scale kits more sustainable.

5.2.4 Recommendations for Visiting Various Schools with DCC

We recommend visiting schools with various distinguished chemistry teachers. Visitations to schools will ensure that future researchers can gather the most comprehensive information from these teachers who are truly experts in DCC kits and large-scale experiments. We believe that they can similarly provide the most valuable and in-depth insights as Prachinratsadhorn-Amroong school can.

Another important factor to consider is the school's location. To ensure efficiency and convenience, we recommend choosing a school that is easily accessible and does not require excessive travel time. Therefore, it is important to calculate the estimated transportation time to ensure minimal travel time and avoid unnecessary delays.

5.3 Conclusion

Carbon Emissions Calculated from Life Cycle Assessment

To provide a clear comparison between traditional laboratories and DCC kits, we quantified both of these experiments' carbon emissions. As we learned from Mr. Varoon Varanyanond and Mr. Techin Charoenchitrwattana, the experts in calculating LCA, setting assumptions and boundaries is necessary as a first step in the calculation process. Hence, we set several assumptions and boundaries for the LCA due to the time constraints of the project and the knowledge limitations of the team, such as the transportation of both methods, the lifespan of the equipment before disposal, and the source of the database for the calculation. Our data collected during the time of our project seems to suggest that traditional experiments produce less carbon emissions when small-scale kits are entirely replaced and more carbon if only essential plastics and chemicals are replaced. Combining these findings from interviews from teachers that indicate a lifespan of several years of the DCC kits, our findings may indicate that the DCC kit, despite being composed entirely of plastic, seems to be a more sustainable alternative than traditional experiments in the real world.

Waste Management Evaluation for Chemistry Laboratories

Incorporating green chemistry and defining well-maintained waste management procedures are essential to reducing the environmental impact of a product. As such, we wanted to better understand how educators were integrating these principles into the classroom as they used the DCC kits to teach their students. We found that at Prachinratsadorn-Amroong School, waste management procedures were lacking, and only some teachers incorporated safety training and green chemistry into the curriculum. In comparison, traditional laboratories at Chulalongkorn University have a well-written policy on waste management and hire organizations to safely dispose of chemicals. Dow Chemistry Classroom could develop similar practices to promote safe environmental practices from its teachers and kits, down to their students–an important part of a sustainable future.

Dow Chemistry Classroom Kits as an Alternative to Traditional Laboratories

To promote a more sustainable future for both Thailand and educators, Dow Chemical Thailand should continue to integrate green chemistry and waste management principles into its training for teachers while also iterating on the materials used in the production of the kits. Although we found that the DCC kits may lack green chemistry and waste management aspects, we believe the kits emit far fewer carbon emissions and save cost, time, and the infrastructure required to bring the kits to schools that lack the resources for traditional chemistry experiments. Further iteration and promotion of small-scale kits can both be environmentally friendly, provide a highly accessible solution to garner students' interest in science education, and help foster the next generation of scientists in the industry. The DCC kits serve as a case study in Thailand for small-scale laboratory kits as a whole; once the DCC kits iterate regarding green principles, they can serve as a comprehensive reference to be further promoted internationally.

References

Anastas, P. T., & Warner, J. C. (1998). *Green chemistry: Theory and practice* (1st ed.). Oxford University Press.

Anne Marie Helmenstine. (2024, July 18). *How to Make a Red Cabbage pH Indicator*. ThoughtCo. https://www.thoughtco.com/making-red-cabbage-ph-indicator-603650

Brunning, A. (2015, September 24). *Compound Interest: The Twelve Principles of Green Chemistry: What it is, & Why it Matters*. Compound Interest. https://www.compoundchem.com/2015/09/24/green-chemistry/

Carbon Footprint for Organizations Certification, A Step Toward a Sustainable Future—Banpu NEXT. (2024, December 6). https://www.banpunext.com/carbon-footprint-for-organizations-certification-a-step-toward-a-sustainable-future/

Center for Safety, Health and Environment of Chulalongkorn University. (2018, January 10). *Safety Management System*. https://www.shecu.chula.ac.th/home/content.asp?Cnt=28&Lang=1&utm_source=chatgpt.com

Chemos GmbH&Co.KG. (2020, March 2). *Safety Data Sheet: Phenolphthalein*. https://www.chemos.de/import/data/msds/GB_en/77-09-8-A0000882-GB-en.pdf

Chulalongkorn University. (2020). *Management of Chemical Waste at Chula – Chulalongkorn University For Sustainable Development*. http://www.sustainability.chula.ac.th/report/379/

Clarke, S. (2023, February 9). *Thailand’s sustainability policy: Getting its act together*. Economist Intelligence Unit. https://www.eiu.com/n/thailand-sustainability-policy-getting-its-act-together/

Day, E. L., Cooper, M. M., & Zhang, M. (2019). *Small-Scale Chemistry*. https://openbooks.lib.msu.edu/orgchemlabmanual/chapter/small-scale-chemistry14-2/ Book Title: Cooperative Organic Chemistry Student Laboratory Manual

Dow Thailand Group. (n.d.). *Dow Thailand*. Retrieved January 15, 2025, from https://th.dow.com/en-us.html

Dow Thailand Group, established in 1967, is a leading science and technology company in Thailand and serves as Dow's largest manufacturing base in the Asia-Pacific region. Operating 13 world-class manufacturing facilities, the company produces a diverse range of products, including polystyrene, polyethylene, and synthetic latex, catering to various industries such as agriculture, construction, electronics, and consumer goods. Dow Thailand emphasizes innovation, safety, and environmental responsibility, contributing significantly to the nation's industrial growth and sustainable development.

Dow Thailand Group. (2018, September 21). *Dow Thailand Celebrates 'Dow Chemistry Classroom 2018' Success*. https://th.dow.com/en-us/news/press-releases/dow-thailand-celebrates-dow-chemistry-classroom-2018-success.html

This article highlights the success of the Dow Chemistry Classroom 2018, an initiative by Dow Thailand to enhance science education. The program trained teachers and provided resources for hands-on chemistry experiments, focusing on safety, sustainability, and accessibility. It aimed to improve STEM education while fostering environmental awareness among students. The initiative reflects Dow Thailand's commitment to corporate social responsibility, emphasizing the role of education in addressing global challenges. This resource is valuable for understanding how private-sector efforts can contribute to sustainable development through education.

Dow Thailand Group. (2019, February 8). *Dow Launches Science Idea Sharing Scheme among Thai-ASEAN Teachers to Excite Young Scientists*. https://th.dow.com/en-us/news/press-releases/dow-launches-science-idea-sharing-scheme-among-thai-asean-teachers.html

Dow Thailand Group. (2020). *Global Citizenship*. https://th.dow.com/en-us/global-citizenship.html

Dow Thailand Group. (2021, July 7). *Dow joins forces with the Chemistry Society of Thailand and OBEC to develop Thai science teachers*. https://th.dow.com/en-us/news/press-releases/dow-joins-chemistry-society-thailand-obec-to-develop-thai-science-teachers.html

Dow Thailand Group. (2022, May 12). *Dow and the Chemical Society of Thailand join forces with the Office of the Basic Education Commission to support "small-scale laboratories" in schools nationwide*. https://th.dow.com/en-us/news/press-releases/dow-and-the-chemical-society-of-thailand-join-forces-with-the-office-of-the-basic-education-commission.html

This press release announces a collaboration between Dow Thailand, the Chemical Society of Thailand, and the Office of the Basic Education Commission to enhance science education in Thailand. The initiative focuses on improving the quality of teaching, providing better resources, and fostering innovation in science education across the country.

Dow Thailand Group. (2023, January). *2023 Dow Thailand ESG Report*.

https://corporate.dow.com/documents/science-sustainability/919-00037-01-2023-dow-thailand-esg-report.pdf

Dow Thailand's 2023 Environmental, Social, and Governance (ESG) Report details the company's initiatives in reducing carbon emissions, promoting a circular economy for plastics, and enhancing employee experiences. The report highlights Dow's commitment to sustainability through material science expertise and strategic partnerships, aiming to create a positive impact on Thailand's environmental and social landscape. Key projects include efforts in carbon reduction, circular plastics ecosystem development, STEM education promotion, and community engagement. The report is available for download on Dow Thailand's official website.

Du Toit, M. H., & Du Toit, J. I. (2024). Accessible chemistry: The success of small-scale laboratory kits in South Africa. *Chemistry Teacher International*. https://doi.org/10.1515/cti-2022-0042

École Polytechnique fédérale de Lausanne. (2022). *Environmental impact assessments of lab activities*. EPFL. https://www.epfl.ch/schools/sv/school-of-life-sciences/about-us/sv-sustainability-office/green-lab-project/

European Bioplastics. (2021). *Materials*. https://www.european-bioplastics.org/bioplastics/materials/

Farooq, F., Ahmed, W., Akbar, A., Aslam, F., & Alyousef, R. (2021). Predictive modeling for sustainable high-performance concrete from industrial wastes: A comparison and optimization of models using ensemble learners. *Journal of Cleaner Production*, *292*. https://doi.org/10.1016/j.jclepro.2021.126032

Fialli, A., Awada, R., Silvia, A., Phoomtrakul, B., Pattarawimon, P., Torprasertkul, W., & Watthanawareekun, P. (2020, March 7). *Promoting Science Education in Thailand with Small-scale Chemistry Experiments*.

The "Promoting Science Education in Thailand with Small-Scale Chemistry Experiments" initiative emphasizes the adoption of innovative, cost-effective, and eco-friendly methods for teaching chemistry in schools. Developed in collaboration with Dow Thailand, the Chemical Society of Thailand, and other partners, this program introduces small-scale chemistry experiments that require minimal resources, reduce chemical waste, and ensure safety for students and teachers. By providing training and resources, the initiative enhances the quality of science education, making it more accessible and sustainable.

Franchetti, M. J. (with Apul, D.). (2012). *Carbon footprint analysis: Concepts, methods, implementation, and case studies* (1st ed.). CRC Press/Taylor & Francis Group. https://books.google.com/books?hl=en&lr=&id=UIUmD75qyzUC&oi=fnd&pg=PP1&dq=10.1201/b12173&ots=vznDjJJLjK&sig=09m-I5xGoCOTEgoNty2VIMUVamw#v=onepage&q&f=false

This book provides a practical guide to measuring greenhouse gas emissions for any organization, from manufacturing to service facilities. It provides a detailed framework and outlines an assessment procedure. The book then goes into detail about different assessments done for different industries.

Freese, T., Elzinga, N., Heinemann, M., Lerch, M. M., & Feringa, B. L. (2024). The relevance of sustainable laboratory practices. *RSC Sustainability*, *2*(5), 1300–1336. https://doi.org/10.1039/D4SU00056K

Gemechu, E. D., Butnar, I., Gomà-Camps, J., Pons, A., & Castells, F. (2013). A comparison of the GHG emissions caused by manufacturing tissue paper from virgin pulp or recycled waste paper. *The International Journal of Life Cycle Assessment*, *18*(8), 1618–1628. https://doi.org/10.1007/s11367-013-0597-x

Goh, H. Y., Wong, W. W. C., & Ong, Y. Y. (2020). A Study To Reduce Chemical Waste Generated in Chemistry Teaching Laboratories. *Journal of Chemical Education*, *97*(1), 87–96. https://doi.org/10.1021/acs.jchemed.9b00632

Hopkinson, L., James, P., Lenegan, N., McGrath, T., & Tait, M. (2011). *Energy Consumption of University Laboratories: Detailed Results from S-Lab Audits*.

Khan, M. I. (1996). *A Study of the Impact of Microscale/Small Scale Chemistry Experiments on the Attitudes and Achievements of the First Year Students in Glasgow University* [M.Sc., University of Glasgow (United Kingdom)]. https://www.proquest.com/docview/2165320608/abstract/6E7B62F45B194436PQ/1

Kimel, H., Bradley, J. D., Durbach, S., Bell, B., & Mungarulire, J. (1998). Hands-On Practical Chemistry for All: Why and How? *Journal of Chemical Education*, *75*(11), 1406. https://doi.org/10.1021/ed075p1406

Lune, H., & Berg, B. L. (2017). *Qualitative research methods for the social sciences* (Ninth edition, global edition). Pearson.

Marks, D. (2011). Climate Change and Thailand: Impact and Response. *CONTEMPORARY SOUTHEAST ASIA*, *33*(2), 229. https://doi.org/10.1355/cs33-2d

Ministry of Natural Resources and Environment. (2022). Thailand Long-Term Low Greenhouse Gas Emission Development. *Office of Natural Resources and Environmental Policy and Planning*. https://unfccc.int/sites/default/files/resource/Thailand%20LT-

LEDS%20%28Revised%20Version%29_08Nov2022.pdf

R. V. Listyarini, F. D. N. Pamenang, J. Harta, L. W. Wijayanti, M. Asy'ari, & W. Lee. (2019). The Integration of Green Chemistry Principles into Small Scale Chemistry Practicum for Senior High School Students. *Jurnal Pendidikan IPA Indonesia*, *8*(3), 371–378. https://doi.org/10.15294/jpii.v8i3.19250

Schwarcz, J. (2017, March 20). *Pollution from Incinerators | Office for Science and Society—McGill University*. https://www.mcgill.ca/oss/article/science-science-everywhere/pollution-incinerators

Sevian, H., & Talanquer, V. (2014). Rethinking chemistry: A learning progression on chemical thinking. *Chem. Educ. Res. Pract.*, *15*(1), 10–23. https://doi.org/10.1039/C3RP00111C

Steely, S. (2012). Traditional and alternative delivery methods of general chemistry labs: Environmental, monetary, and pedagogical comparisons. *Western Washington University*, 135.

Tangkitvanich, S. (2023, November 8). Heat's rising for Thailand to go green. *Bangkok Post*. https://www.bangkokpost.com/opinion/opinion/2680559/heats-rising-for-thailand-to-go-green

Thailand. (2022, December 13). Climate Action Tracker. https://climateactiontracker.org/countries/thailand/

This webpage provides an analysis of Thailand's climate policies and actions in relation to the Paris Agreement goals. It evaluates the country's progress toward reducing greenhouse gas emissions, implementing renewable energy strategies, and achieving net-zero targets. The information is regularly updated to reflect the latest developments in Thailand's climate action framework.

Theerakul, T. (2023). *ขั้นตอนการยื่นขออนุญาตใช้เครื่องหมายรับรอง*. https://thaicarbonlabel.tgo.or.th/index.php?lang=TH&mod=Y0hKdlpIVmpkSE5mY0hKdlkyVnpjdz09

United Nations. (2023). Goal 12: Ensure sustainable consumption and production patterns. *Sustainable Development Goals*. https://www.un.org/sustainabledevelopment/sustainable-consumption-production/

United Nations Framework Convention on Climate Change. (2022, November 2). *Thailand's Updated NDC*. https://unfccc.int/sites/default/files/NDC/2022-11/Thailand%202nd%20Updated%20NDC.pdf

This document outlines Thailand's second updated Nationally Determined Contribution (NDC) under the Paris Agreement. It details the country's commitments to reducing greenhouse gas emissions, transitioning to renewable energy, and implementing adaptation strategies to address climate change. The updated NDC emphasizes Thailand's increased ambition in aligning with global climate targets.

United Nations Thailand. (2023, February 8). *2022 UN Thailand Results Report | United Nations in Thailand*. https://thailand.un.org/en/218314-2022-un-thailand-results-report

The 2022 Annual Results Report by the UN Country Team in Thailand outlines key initiatives, achievements, and strategies that align with the UN Sustainable Development Cooperation Framework (2022-2026). The report highlights the UN's efforts to promote a green economy, digital transformation, and social inclusion, targeting Thailand's transition to a low-carbon, resilient, and inclusive society. Significant achievements include partnerships with government and private sectors to advance carbon neutrality, expand renewable energy adoption, and implement waste management programs. Initiatives also addressed social protection, health, and education, such as expanding maternal health services, enhancing digital literacy, and empowering marginalized communities. The report emphasizes SDG localization, with provincial-level engagement and data-driven policymaking as central elements. These efforts illustrate a commitment to fostering sustainable, inclusive development in Thailand.

United States Environmental Protection Agency. (2024, May 2). *Basics of Green Chemistry* [Overviews and Factsheets]. https://www.epa.gov/greenchemistry/basics-green-chemistry

The U.S. Environmental Protection Agency (EPA) provides an overview of green chemistry, which focuses on designing products and processes that minimize hazardous substance use and generation. This approach aims to reduce environmental and health risks while promoting efficiency and sustainability in chemical production. The article highlights the 12 principles of green chemistry, including waste prevention, energy efficiency, and the use of renewable feedstocks, which guide the development of eco-friendly technologies and practices.

Vailikhit, V., Changto, W., & Janthondee, S. (2013). *Bringing Affordable Experimental Chemistry to Rural Thai Government High Schools.*

Zakaria, Z., Latip, J., & Tantayanon, S. (2012). Organic Chemistry Practices for Undergraduates using a Small Lab Kit. *Procedia - Social and Behavioral Sciences*, *59*, 508–514. https://doi.org/10.1016/j.sbspro.2012.09.307

Zheng, J., & Suh, S. (2019). Strategies to reduce the global carbon footprint of plastics. *Nature Climate Change*, *9*(5), 374–378. https://doi.org/10.1038/s41558-019-0459-z

The World Bank Group. (2021). *Thailand*.
https://climateknowledgeportal.worldbank.org/country/thailand/climate-data-historical

Appendices

Appendix A

Institutional Review Board Approval Letters

WORCESTER POLYTECHNIC INSTITUTE

100 INSTITUTE ROAD, WORCESTER MA 01609 USA

Institutional Review Board

FWA #00030698 - HHS #00007374

Notification of IRB Approval

Date:	16-Jan-2025
PI:	Esther F Boucher-Yip
Protocol Number:	IRB-25-0405
Protocol Title:	Evaluating the Environmental Impact of the Dow Chemistry Classroom

Approved Study Personnel: Tam, Connor M~Guerrier, Samyra~Reilly, Declan D~Boonratanakornkit, Tanat~Neer, Caitlin A~Boucher-Yip, Esther F~

Effective Date:	16-Jan-2025
Exemption Category:	2
Sponsor*:	

The WPI Institutional Review Board (IRB) has reviewed the materials submitted with regard to the above-mentioned protocol. We have determined that this research is exempt from further IRB review under 45 CFR § 46.104 (d). For a detailed description of the categories of exempt research, please refer to the IRB website.

The study is approved indefinitely unless terminated sooner (in writing) by yourself or the WPI IRB. Amendments or changes to the research that might alter this specific approval must be submitted to the WPI IRB for review and may require a full IRB application in order for the research to continue. You are also required to report any adverse events with regard to your study subjects or their data.

Changes to the research which might affect its exempt status must be submitted to the WPI IRB for review and approval before such changes are put into practice. A full IRB application may be required in order for the research to continue.

No minors involved in study

Please contact the IRB at irb@wpi.edu if you have any questions.
*if blank, the IRB has not reviewed any funding proposal for this protocol

Appendix B
Life Cycle Assessment (LCA) Calculation Spreadsheets

Phase	Item	Material	Act. Mass	Act. Units	Quantity	Uses	Mass (kg)	Total Mass (kg)	Carbon Emissions (gCO2)	Carbon Emissions (1 use)
Production	Burette (Glass)	Glass	103.571	g	1	1	0.103571	0.103571	86.0157155	0.860157155
Production	Burette (Plastic)	Teflon	18.02	g	1	1	0.01802	0.01802	260.2088	2.602088
Production	Burette (Rubber)	Rubber	0.331	g	1	1	0.000331	0.000331	0.1291893	0.001291893
Production	Flask (125mL)	Glass	80.81516667	g	3	1	0.08081516667	0.2424455	201.3509878	2.013509878
Production	Beaker (250mL)	Glass	100.894	g	3	1	0.100894	0.302682	251.377401	2.51377401
Production	Pipette (10mL)	Glass	28.919	g	1	1	0.028919	0.028919	24.0172295	0.240172295
Production	Pipette Rubber	Rubber	26.107	g	1	1	0.026107	0.026107	10.1895621	0.101895621
Production	Funnel	Glass	29.24666667	g	1	1	0.02924666667	0.02924666667	24.28935667	0.2428935667
Use	Tissue	Tissue Paper	1	g	2	100	0.001	0.002	380	3.8
Use	0.1M NaOH	NaOH	84.25	ml	1	100	0.000339022	0.000339022	37.79417256	0.3779417256
Use	0.1M HCl	HCl	43.75	ml	1	100	0.0001595125	0.0001595125	13.2395375	0.132395375
Clean Up	Water (Tap)	Water	483.806	g	1	100	0.483806	0.483806	38.45290088	0.3845290088
Clean Up	Water (Tap)	Wastewater	483.806	g	1	100	0.483806	0.483806	488.64406	4.8864406
Clean Up	Tissue	Landfill Logistics	1	g	0	100	0.001	0	0	0

Clean Up	0.1M NaOH	Wastewater	84.25	ml	1	100	0.000339022	0.000339022	0.34241222	0.0034241222
Clean Up	0.1M HCl	Wastewater	43.75	ml	1	100	0.0001595125	0.0001595125	0.161107625	0.00161107625
EOL		Glass Incineration (SG)	0.7068641667	kg	1	1	0.7068641667	0.7068641667	8.835802084	0.08835802084
EOL		Landfill Logistics	0.7533221667	kg	1	1	0.7533221667	0.7533221667	1402.911871	14.02911871

Table B1: CFA for Traditional Laboratory (including water)

Phase	Item	Material	Act. Mass	Act. Units	Quantity	Uses	Mass (kg)	Total Mass (kg)	Carbon Emissions (kgCO2)	Carbon Emissions (1 use)
Production	Burette (Glass)	Glass	103.571	g	1	1	0.103571	0.103571	86.0157155	0.860157155
Production	Burette (Plastic)	Teflon	18.02	g	1	1	0.01802	0.01802	260.2088	2.602088
Production	Burette (Rubber)	Rubber	0.331	g	1	1	0.000331	0.000331	0.1291893	0.001291893
Production	Flask (125mL)	Glass	80.81516667	g	3	1	0.08081516667	0.2424455	201.3509878	2.013509878
Production	Beaker (250mL)	Glass	100.894	g	3	1	0.100894	0.302682	251.377401	2.51377401
Production	Pipette (10mL)	Glass	28.919	g	1	1	0.028919	0.028919	24.0172295	0.240172295
Production	Pipette Rubber	Rubber	26.107	g	1	1	0.026107	0.026107	10.1895621	0.101895621
Production	Funnel	Glass	29.24666667	g	1	1	0.02924666667	0.02924666667	24.28935667	0.2428935667
Use	Tissue	Tissue Paper	1	g	2	100	0.001	0.002	0.038	0.00038
Use	0.1M NaOH	NaOH	84.25	ml	1	100	0.000339	0.000339	0.003779417256	0.00003779417256

							022	022		
Use	0.1M HCl	HCl	43.75	ml	1	100	0.0001595125	0.0001595125	0.00132395375	0.0000132395375
Clean Up	Tissue	Landfill Logistics	1	g	0	100	0.001	0	0	0
Clean Up	0.1M NaOH	Wastewater	84.25	ml	1	100	0.000339022	0.000339022	0.000034241222	0.00000034241222
Clean Up	0.1M HCl	Wastewater	43.75	ml	1	100	0.0001595125	0.0001595125	0.0000161107625	0.000000161107625
EOL		Glass Incineration (SG)	0.343445833	kg	1	1	0.343445833	0.343445833	4.293072917	0.04293072917
EOL		Landfill Logistics	0.7533221667	kg	1	1	0.7533221667	0.7533221667	1402.911871	14.02911871

Table B2: CFA for Traditional Laboratory (excluding water)

Phase	Item	Material	Act. Mass	Act. Units	Quantity	Uses	Mass (kg)	Total Mass (kg)	Carbon Emissions (kgCO2)	Carbon Emissions (1 use)
Production	Box	PP	142.28	g	1	5	0.14228	0.14228	1338.42796	13.3842796
Production	96-well Microplate	PS	41.335	g	1	5	0.041335	0.041335	667.1675675	6.671675675
Production	30 ml Container	PET	9.858	g	2	5	0.009858	0.019716	284.442732	2.84442732
Production	10 ml Container	PET	5.927	g	2	5	0.005927	0.011854	171.017658	1.71017658
Production	Cotton Swabs	Cotton Swab	0.179	g	10	5	0.000179	0.00179	0.1737791667	0.001737791667
Production	Plastic Bag	LDPE	1.21	g	1	5	0.00121	0.00121	15.88609	0.1588609
Production	Scissors	LDPE	1.797	g	1	5	0.001	0.001	23.59	0.235

	Bag						797	797	2813	92813
Production	Plastic Straw	PP	0.309	g	3	5	0.000 309	0.000 927	8.720 289	0.087 20289
Production	DSC Dropper	PET	0.768	g	3	5	0.000 768	0.002 304	33.23 9808	0.332 39808
Production	Plastic 30 ml cup	PP	1.015	g	1	5	0.001 015	0.001 015	9.548 105	0.095 48105
Production	Manual	Paper (Uncoated)	5.32	g	1	5	0.005 32	0.005 32	55.91 32	0.559 132
Production	Plastic holder for paper	PP	1.476	g	1	5	0.001 476	0.001 476	13.88 4732	0.138 84732
Production	Paper warnings	Paper (Uncoated)	1.379	g	2	5	0.001 379	0.002 758	28.98 658	0.289 8658
Production	Scissors	Stainless Steel	10.89 63	g	1	5	0.012 107	0.012 107	411.6 38	4.116 38
Production	Scissors	ABS	1.210 7	g	1	5	0.001 2107	0.001 2107	25.18 07439 5	0.251 80743 95
Use	Water	Water	10	ml	1	100	0.01	0.01	0.794 8	0.007 948
Use	Food Coloring	Food Colorant	0.1	ml	1	100	0.000 1	0.000 1	70	0.7
Use	Tissue	Tissue Paper	1	g	2	100	0.001	0.002	380	3.8
Use	0.1M NaOH	NaOH	0.56	ml	1	100	0.000 00226 016	0.000 00226 016	0.251 96263 68	0.002 51962 6368
Use	0.2M HCl	HCl	0.18	ml	1	100	0.000 00131 256	0.000 00131 256	0.108 94248	0.001 08942 48
Clean Up	Water	Wastewater	10	ml	1	100	0.01	0.01	10.1	0.101
Clean Up	Food Coloring	Wastewater	0.1	ml	1	100	0.1	0.1	101	1.01
Clean Up	Tissue	Tissue Paper	1	g	0	100	0.001	0	0	0
Clean Up	0.1M NaOH	Wastewater	0.56	ml	1	100	0.000 00226 016	0.000 00226 016	0.002 28276 16	0.000 02282 7616
Clean Up	0.2M HCl	Wastewater	0.18	ml	1	100	0.000 00131 256	0.000 00131 256	0.001 32568 56	0.000 01325 6856

EOL		Plastics waste disposal (landfill) (UK)	0.2251247	kg	1	1	0.2251247	0.2251247	56.9565491	0.5695654911
EOL		Landfill Logistics	0.2281707	kg	1	1	0.2281707	0.2281707	424.9222946	4.249222946

Table B3: CFA for Small-Scale DCC Kit (replacing kit)

Phase	Item	Material	Act. Mass	Act. Units	Quantity	Uses	Mass (kg)	Total Mass (kg)	Carbon Emissions ($kgCO_2$)	Carbon Emissions (1 use)
Production	Box	PP	142.28	g	1	1	0.14228	0.14228	267.685592	2.67685592
Production	96-well Microplate	PS	41.335	g	1	1	0.041335	0.041335	133.4335135	1.334335135
Production	30 ml Container	PET	9.858	g	2	1	0.009858	0.019716	56.8885464	0.568885464
Production	10 ml Container	PET	5.927	g	2	1	0.005927	0.011854	34.2035316	0.342035316
Production	Cotton Swabs	Cotton Swab	0.179	g	10	1	0.000179	0.00179	0.03475583333	0.0003475583333
Production	Plastic Bag	LDPE	1.21	g	1	1	0.00121	0.00121	3.177218	0.03177218
Production	Scissors Bag	LDPE	1.797	g	1	1	0.001797	0.001797	4.7185626	0.047185626
Production	Plastic Straw	PP	0.309	g	3	1	0.000309	0.000927	1.7440578	0.017440578
Production	DSC Dropper	PET	0.768	g	3	1	0.000768	0.002304	6.6479616	0.066479616
Production	Plastic 30 ml cup	PP	1.015	g	1	1	0.001015	0.001015	1.909621	0.01909621

Production	Manual	Paper (Uncoated)	5.32	g	1	1	0.00532	0.00532	11.18264	0.1118264
Production	Plastic holder for paper	PP	1.476	g	1	1	0.001476	0.001476	2.7769464	0.027769464
Production	Paper warnings	Paper (Uncoated)	1.379	g	2	1	0.001379	0.002758	5.797316	0.05797316
Production	Scissors	Stainless Steel	10.8963	g	1	1	0.012107	0.012107	82.3276	0.823276
Production	Scissors	ABS	1.2107	g	1	1	0.0012107	0.0012107	5.03614879	0.0503614879
Use	Water	Water	10	ml	1	100	0.01	0.01	0.7948	0.007948
Use	Food Coloring	Food Colorant	0.1	ml	1	100	0.0001	0.0001	70	0.7
Use	Tissue	Tissue Paper	1	g	2	100	0.001	0.002	380	3.8
Use	0.1M NaOH	NaOH	0.56	ml	1	100	0.00000226016	0.00000226016	0.25196263 68	0.0025196263 68
Use	0.2M HCl	HCl	0.18	ml	1	100	0.00000131256	0.00000131256	0.10894248	0.0010894248
Clean Up	Water	Wastewater	10	ml	1	100	0.01	0.01	10.1	0.101
Clean Up	Food Coloring	Wastewater	0.1	ml	1	100	0.1	0.1	101	1.01
Clean Up	Tissue	Tissue Paper	0	g	2	100	0	0	0	0
Clean Up	0.1M NaOH	Wastewater	0.56	ml	1	100	0.00000226016	0.00000226016	0.0022827616	0.0000228276 16
Clean Up	0.2M HCl	Wastewater	0.18	ml	1	100	0.00000131256	0.00000131256	0.0013256856	0.0000132568 56
EOL		Plastics waste disposal (landfill) (UK)	0.2251247	kg	1	1	0.2251247	0.2251247	56.9565491	0.5695654 91
EOL		Landfill Logistics	0.2271707	kg	1	1	0.2271707	0.2271707	423.0599946	4.2305999 46

Table B4: CFA for Small-Scale DCC Kit (replacing chemicals)

Phase	Item	Material	Act. Mass	Act. Units	Quantity	Uses	Mass (kg)	Total Mass (kg)	Carbon Emissions (kgCO2)	Carbon Emissions (1 use)
Production	Box	PP	142.28	g	1	1	0.14228	0.14228	267.685592	2.67685592
Production	96-well Microplate	PS	41.335	g	1	1	0.041335	0.041335	133.4335135	1.334335135
Production	30 ml Container	PET	9.858	g	2	5	0.009858	0.019716	284.442732	2.84442732
Production	10 ml Container	PET	5.927	g	2	5	0.005927	0.011854	171.017658	1.71017658
Production	Cotton Swabs	Cotton Swab	0.179	g	10	5	0.000179	0.00179	0.1737791667	0.001737791667
Production	Plastic Bag	LDPE	1.21	g	1	1	0.00121	0.00121	3.177218	0.03177218
Production	Scissors Bag	LDPE	1.797	g	1	1	0.001797	0.001797	4.7185626	0.047185626
Production	Plastic Straw	PP	0.309	g	3	5	0.000309	0.000927	8.720289	0.08720289
Production	DSC Dropper	PET	0.768	g	3	5	0.000768	0.002304	33.239808	0.33239808
Production	Plastic 30 ml cup	PP	1.015	g	1	5	0.001015	0.001015	9.548105	0.09548105
Production	Manual	Paper (Uncoated)	5.32	g	1	1	0.00532	0.00532	11.18264	0.1118264
Production	Plastic holder for paper	PP	1.476	g	1	1	0.001476	0.001476	2.7769464	0.027769464
Production	Paper warnings	Paper (Uncoated)	1.379	g	2	1	0.001379	0.002758	5.797316	0.05797316
Production	Scissors	Stainless Steel	10.8963	g	1	1	0.012107	0.012107	82.3276	0.823276
Production	Scissors	ABS	1.2107	g	1	1	0.0012107	0.0012107	5.03614879	0.0503614879

Use	Water	Water	10	ml	1	100	0.01	0.01	0.7948	0.007948
Use	Food Coloring	Food Colorant	0.1	ml	1	100	0.0001	0.0001	70	0.7
Use	Tissue	Tissue Paper	1	g	2	100	0.001	0.002	380	3.8
Use	0.1M NaOH	NaOH	0.56	ml	1	100	0.00000226016	0.00000226016	0.25196263 68	0.00251962 6368
Use	0.2M HCl	HCl	0.18	ml	1	100	0.00000131256	0.00000131256	0.10894248	0.00108942 48
Clean Up	Water	Wastewater	10	ml	1	100	0.01	0.01	10.1	0.101
Clean Up	Food Coloring	Wastewater	0.1	ml	1	100	0.1	0.1	101	1.01
Clean Up	Tissue	Landfill Logistics	0	g	2	100	0	0	0	0
Clean Up	0.1M NaOH	Wastewater	0.56	ml	1	100	0.00000226016	0.00000226016	0.00228276 16	0.00002282 7616
Clean Up	0.2M HCl	Wastewater	0.18	ml	1	100	0.00000131256	0.00000131256	0.00132568 56	0.00001325 6856
EOL		Plastics waste disposal (landfill) (UK)	0.2251247	kg	1	1	0.2251247	0.2251247	56.9565491	0.56956549 1
EOL		Landfill Logistics	0.2271707	kg	1	1	0.2271707	0.2271707	423.059994 6	4.23059994 6

Table B5: CFA for Small-Scale DCC Kit (replacing chemicals and plastics)

Item	kgCO2E	Description	Source
PET	2.8854	Polyethylene terephthalate, granulate, bottle grade, at plant	Ecoinvent 2.2, IPCC 2007 GWP 100a
PS	3.2281	Made from Styrene and Ethylbenzene; LCIA method IPCC 2013 GWP 100a V1.0	Thai National LCI Database,
PP	1.8814	Produced by Liquid phase and Gas phase processes; LCIA method IPCC 2013 GWP 100a V1.03	Thai National LCI Database

Cotton Swab	0.0194166 6667	FOAM SWABS, 3",100PPi w/COTTON,ROUND TIP HT1318, Foam Tech International Company Limited	Thai Carbon Label
LDPE	2.6258	Produced from Solution phase and Gas phase processes; LCIA method IPCC 2013 GWP 100a V1.03	Thai National LCI Database
Paper (Uncoated)	2.102	Covers from pulp preparation, papermaking, processing and packaging; LCIA method IPCC 2013 GWP 100a V1.03	Thai National LCI Database, TIIS-MTEC-NSTDA
Water	0.0007948	Tap water - Metropolitan Waterworks Authority, Produced using ethanol; LCIA method IPCC 2013 GWP 100a V1.03,	Thai National LCI Database
NaOH	1.1148	Sodium hydroxide, 50% in H2O, membrane cell, at plant	Ecoinvent 2.2, IPCC 2007 GWP 100a
HCl	0.83	Hydrochloric acid, 30% in H2O, at plant	Ecoinvent 2.2, IPCC 2007 GWP 100a
Distilled Water	2.155	Deionized water produced by reverse osmosis technology, Produced using soft water; LCIA method IPCC 2013, GWP 100a V1.03	Thai National LCI Database
Landfill Logistics	1.8623	Waste collection and transportation + Disposal by pile + Sorting of community waste + Proper landfilling	Thai National LCI Database
Glass	0.8305	Made from glass sand and glass scraps melted in a furnace. Melt glass (add ingredients that give color) and Take it through a molding process to get a glass bottle shape. Various as required; LCIA method IPCC 2013 GWP 100a V1.03	Thai National LCI Database
Rubber	0.3903	Skim rubber, DRC 90%; mixed types of skim rubber products and Quality; LCIA method IPCC 2013 GWP 100a V1.03	Thai National LCI Database
Teflon	14.44	Emission intensity of polytetrafluoroethylene foil (ptfe). The lifecycle assessment for modules A1-A3 includes: the extraction and processing of raw materials (A1) their transportation to the manufacturer (A2) and the actual manufacturing of the product (A3). Retrieved from the Oekobaudat database v20.19.120.	Oekobaudat database v20.19.120
Tissue Paper	1.9	Made from virgin pulp	Gemechu, E.D., Butnar, I., Gomà-Camps, J. et al. A comparison of the GHG emissions caused by manufacturing tissue paper from virgin pulp or recycled wastepaper. Int J Life Cycle

			Assess 18, 1618–1628 (2013). https://doi.org/10.1007/s11367-013-0597-x
Wastewater	0.0101	Community wastewater collection in the country, Thailand average	Thai National LCI Database
Stainless Steel	6.8	Electric furnace and Argon – Oxygen Decarburization	World Stainless steel
ABS	4.1597	Product from the alkylation process of benzene and Tetrachloride; LICA method IPCC 2013 GWP 100a V1.03	Thai National LCI Database
Food Colorant	7	Food colorant data	Science direct
Glass (UK)	0.8232	Emission intensity of glass (closed-loop recycled source). The emission factor should be used to report on consumption of procured recycled materials. The emission factor covers sorting/processing/manufacturing and transportation to the point of sale. Retrieved from the Conversion Factors 2024: flat file published by the UK BEIS/Defra at the source URL.	https://www.climatiq.io/data/explorer?search=recycled+glass&data_version=%5E20
Glass (Recycled) (UK)	0.02476	Emission intensity of glass (open-loop recycled source). The emission factor should be used to report on consumption of procured recycled materials. The emission factor covers sorting/processing/manufacturing and transportation to the point of sale. Retrieved from the Conversion Factors 2021: flat file published by the UK BEIS/Defra at the source URL.	https://www.climatiq.io/data/explorer?search=recycled+glass&data_version=%5E20
Plastics waste disposal (landfill) (UK)	0.253	For landfill disposal of plastic the emissions of CO2 amounts to 253 g kg−1 plastic.	https://pubs.rsc.org/en/content/articlelanding/2009/ee/b908135f
Glass Incineration (SG)	0.0125	Emission intensity of incineration of glass waste. The GHG emissions standard applied is the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Boundaries: Only consider emissions released from waste incineration. Excludes use stage / transport of waste and ash to landfill. Retrieved from Singapore Emission Factors Registry (SEFR) database. The primary data source is National Environment Agency (NEA)	https://www.climatiq.io/data/emission-factor/0f1384f5-e78b-48b4-a02c-6bdd576644fb

		Singapore. According to the source: Calculated based on 2006 IPCC Guidelines for National Greenhouse Gas Inv.	

Table B6: Numerical carbon emissions and their sources

1 Use of Chulalongkorn Titration Experiment (gCO2/kg)	*Phase*				
Material	Use	Production	End-Of-Life	Clean Up	Grand Total
Distilled Water	0.27				0.27
Glass		5.87			5.87
Glass Incineration (SG)			0.09		0.09
HCl	0.44				0.44
Landfill Logistics			14.03		14.03
NaOH	0.75				0.75
Rubber		0.10			0.10
Teflon		2.60			2.60
Tissue Paper	3.80				3.80
Wastewater				4.90	4.90
Water				0.38	0.38
Grand Total	**5.27**	**8.58**	**14.12**	**5.28**	**33.24**

Table B7: Carbon emissions for the Dow Chemistry Classroom's acid-base titration experiment by phase and material.

1 Use of Chulalongkorn Titration Expeirment (excluding water) (gCO2/kg)	*Phase*				
Material	Use	Production	End-Of-Life	Clean Up	Grand Total
Distilled Water	0.27				0.27
Glass		5.87			5.87
Glass Incineration (SG)			0.09		0.09
HCl	0.44				0.44
Landfill Logistics			14.03		14.03
NaOH	0.75				0.75
Rubber		0.10			0.10
Teflon		2.60			2.60
Tissue Paper	3.80				3.80
Wastewater				0.01	0.01
Grand Total	**5.27**	**8.58**	**14.12**	**0.01**	**27.97**

Table B8: Carbon emissions for the Dow Chemistry Classroom's acid-base titration experiment by phase and material (excluding water).

1 Use of DCC Carbon Emissions (gCO2/kg)	*Phase*				
Material	Use	Production	End-Of-Life	Clean Up	Grand Total
ABS		0.25			0.25
Cotton Swab		0.00			0.00
Distilled Water	0.00				0.00
Food Colorant	0.70				0.70
HCl	0.00				0.00
Landfill Logistics			23.19		23.19
LDPE		0.39			0.39
NaOH	0.00				0.00
Paper (Uncoated)		0.85			0.85
PET		4.89			4.89

Plastics waste disposal (landfill) (UK)			2.85		2.85
PP		13.71			13.71
PS		6.67			6.67
Stainless Steel		4.12			4.12
Tissue Paper	3.80				3.80
Wastewater				1.11	1.11
Water	0.01				0.01
Grand Total	**4.52**	**30.88**	**26.04**	**1.11**	**62.55**

Table B8: Carbon emissions for the Dow Chemistry Classroom's acid-base titration experiment by phase and material (replacing kit). 1 use of this experiment is based on a lifespan of 100 uses with the chemicals and plastics replaced every 20 uses.

1 Use of DCC Carbon Emissions (Replacing Chemicals) (gCO2/kg)	*Phase*				
Material	Use	Production	End-Of-Life	Clean Up	Grand Total
ABS		0.05			0.05
Cotton Swab		0.00			0.00
Distilled Water	0.00				0.00
Food Colorant	0.70				0.70
HCl	0.00				0.00
Landfill Logistics			4.64		4.64
LDPE		0.08			0.08
NaOH	0.00				0.00
Paper (Uncoated)		0.17			0.17
PET		0.98			0.98
Plastics waste disposal (landfill) (UK)			0.57		0.57
PP		2.74			2.74
PS		1.33			1.33
Stainless Steel		0.82			0.82
Tissue Paper	3.80				3.80
Wastewater				1.11	1.11

Water	0.01				0.01
Grand Total	**4.52**	**6.18**	**5.21**	**1.11**	**17.01**

Table B9: Carbon emissions for the Dow Chemistry Classroom's acid-base titration experiment by phase and material (replacing chemicals).1 use of this experiment is based on a lifespan of 100 uses with the chemicals replaced every 20 uses.

1 Use of DCC Carbon Emissions (gCO2/kg)	*Phase*				
Material	Use	Production	End-Of-Life	Clean Up	Grand Total
ABS		0.25			0.25
Cotton Swab		0.00			0.00
Distilled Water	0.00				0.00
Food Colorant	0.70				0.70
HCl	0.00				0.00
Landfill Logistics			23.19		23.19
LDPE		0.39			0.39
NaOH	0.00				0.00
Paper (Uncoated)		0.85			0.85
PET		4.89			4.89
Plastics waste disposal (landfill) (UK)			2.85		2.85
PP		13.71			13.71
PS		6.67			6.67
Stainless Steel		4.12			4.12
Tissue Paper	3.80				3.80
Wastewater				1.11	1.11
Water	0.01				0.01
Grand Total	**4.52**	**30.88**	**26.04**	**1.11**	**62.55**

Table B10: Carbon emissions for the Dow Chemistry Classroom's acid-base titration experiment by phase and material (replacing chemicals and plastics). 1 use of this experiment is based on a lifespan of 100 uses with the chemicals and plastics replaced every 20 uses.

1 Use of Chulalongkorn Titration Experiment (gCO2e)	*Phase*				
Material	Use	Production	End-Of-Life	Clean Up	Grand Total
Distilled Water	2.74E-01				2.74E-01
Glass		5.87E+00			5.87E+00
Glass Incineration (SG)			8.84E-02		8.84E-02
HCl	4.41E-01				4.41E-01
Landfill Logistics			1.40E+01		1.40E+01
NaOH	7.51E-01				7.51E-01
Rubber		1.03E-01			1.03E-01
Teflon		2.60E+00			2.60E+00
Tissue Paper	3.80E+00				3.80E+00
Wastewater				4.90E+00	4.90E+00
Water				3.85E-01	3.85E-01
Grand Total	**5.27**	**8.5818**	**14.123**	**5.28**	**33.24**

Table B10: Carbon emissions for Chulalongkorn's GEN CHEM acid-base titration experiment by phase and material. 1 use of this experiment is based on a lifespan of 100 uses.

Items In Dow Chemistry Classroom Kit	Items in Chulalongkorn Traditional Lab
96-well microplate	Burette (Glass)
30 ml Container	Burette (Plastic)
0.1M NaOH	Flask (125mL)
Water	Beaker (250mL)
0.2M HCl	Pipette (10mL)
Phenolphthalein	Pipette Rubber
Cotton Swabs	Funnel
Plastic Stirrer	Water (Tap)
Plastic Bag	Phenolphthalein
Plastic Straw	0.1M NaOH
Food Coloring	0.1M HCl

Scissors	Burette (Rubber)
Scissors Bag	Tissue
DSC Dropper	
Plastic 30 ml cup	
Paper warnings	
Plastic holder for paper	
Box	
Manual	
Tissue	
10 ml Container	

Table B11: Equipment considered in both DCC kit and Chulalongkorn traditional experiment

Appendix C
Interview Consent Forms

Consent Script (Teachers from Prachinratsadorn-Amroong school)

You are being asked to participate in a research study concerning the use of the Dow Chemistry Classroom kits and their use in the classroom. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks, or discomfort that you may experience as a result of your participation. We will present this information to you so that you may make a fully informed decision regarding your participation.

We are students from Worcester Polytechnic Institute (WPI) and Chulalongkorn University (CU) who will be conducting this study. You will be asked a series of questions based on your experience using the chemistry kits. These questions concern the kit's products, chemicals, and waste disposal. The purpose of the study is to explore the procedures of these kits in relation to sustainability and carbon footprint and to determine if it is a viable alternative to traditional chemistry classrooms.

The interview will be recorded for further review by our team and the report will be published with our findings and your responses online. We will delete all traces of the recording after completing our research and any individually identifying information such as names, dates, and locations will not be reported.

It is crucial to know that your participation is voluntary, and you are not required to share any information or answer any questions that you prefer to keep private. If, at any time, you decide not to continue, you may simply say so and we will promptly stop the interview and destroy any information you've provided.

Do you consent to continue with the interview?

- I consent to give the interview
- I do not consent to give the interview

สคริปต์แสดงความยินยอม

เรียนถึง ผู้บริหาร หัวหน้ากลุ่มสาระ และคุณครูท่านอื่นๆจากโรงเรียนปราจิณราษฎรอำรุง

ท่านได้ถูกเชิญชวนให้เข้าร่วมในการศึกษาวิจัยของทางมหาวิทยาลัย Worcester Polytechnic Institute (WPI) และจุฬาลงกรณ์วิทยาลัย (CU)

เกี่ยวกับการใช้ชุดอุปกรณ์การทดลองเคมีแบบย่อส่วนของห้องเรียนเคมีดาวและการใช้งานของชุดอุปกรณ์พวกนี้ในห้องเรียน

ก่อนที่ท่านจะตอบตกลง ท่านต้องทราบวัตถุประสงค์ของการศึกษา ขั้นตอนการปฏิบัติ

ประโยชน์และความเสี่ยงหรือความไม่สบายใจต่างๆที่ท่านอาจประสบ

ทางพวกเรามีหน้าที่ในการนำเสนอข้อมูลเหล่านี้เพื่อให้ท่านสามารถตัดสินใจในการมีส่วนร่วมในการสัมภาษณ์อย่างถี่ถ้วน

ในการสัมภาษณ์ครั้งนี้

พวกเราจะถามคำถามเกี่ยวกับประสบการณ์ของเหล่าคุณครูในการใช้ชุดอุปกรณ์การทดลองเคมีแบบย่อส่วน

โดยที่คำถามเหล่านี้จะเกี่ยวข้องกับผลิตภัณฑ์ สารเคมีที่ใช้ และวิธีการกำจัดของเสียของชุดเคมีดาว

วัตถุประสงค์ของการศึกษานี้คือการสำรวจขั้นตอนของชุดอุปกรณ์เหล่านี้โดยการเอามาเชื่อมโยงกับคอนเซ็ปต์ เช่น

การพัฒนาสิ่งแวดล้อมอย่างยั่งยืน (sustainability) และการวัดคาร์บอนฟุตพริ้นท์ (carbon footprint)

เพื่อที่จะนำข้อมูลเหล่านี้มาพิจารณาว่า การใช้ชุดอุปกรณ์การทดลองเคมีแบบย่อส่วนของห้องดาวเคมีนั้น

สามารถเป็นทางเลือกที่เหมาะสมในการทดแทนวิธีการทำแล็บในห้องเรียนแบบดั้งเดิมหรือไม่

การสัมภาษณ์นี้จะถูกบันทึกไว้เพื่อการตรวจสอบในภายหลังโดยทีมงานของเราและรายงานจะถูกเผยแพร่ทางเว็บไซต์จุฬากับWPI พร้อมข้อค้นพบจากพวกเราและคำตอบที่ท่านได้ให้มา

เราจะลบข้อมูลการบันทึกและข้อมูลที่สามารถระบุตัวบุคคลได้ทั้งหมดหลังจากการวิจัยเสร็จสิ้น เช่น ชื่อ วันที่ และสถานที่ จะไม่ถูกเผยแพร่

สิ่งสำคัญที่ต้องทราบคือการเข้าร่วมของท่านเป็นไปโดยการสมัครใจและท่านไม่จำเป็นต้องให้ข้อมูลหรือตอบคำถามใดๆที่ท่านต้องการเก็บไว้เป็นความลับ เมื่อไหร่ก็ตามที่ท่านตัดสินใจที่จะไม่ดำเนินการต่อในการสัมภาษณ์

ท่านสามารถแจ้งให้เราทราบและเราจะยุติการสัมภาษณ์และทำลายข้อมูลที่ท่านได้ให้ไว้ในทันที

ท่านยินยอมที่จะดำเนินการสัมภาษณ์ต่อหรือไม่

- ฉันยินยอมที่จะให้สัมภาษณ์
- ฉันไม่ยินยอมที่จะให้สัมภาษณ์

Consent Script (Production engineer from Doing Science Co., Ltd)

You are being asked to participate in a research study concerning the use of the Dow Chemistry Classroom kits and their manufacturing process. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks, or discomfort that you may experience as a result of your participation. We will present this information to you so that you may make a fully informed decision regarding your participation.

We are students from Worcester Polytechnic Institute (WPI) and Chulalongkorn University (CU) who will be conducting this study. You will be asked a series of questions based on your experience in manufacturing chemistry kits. These questions will cover topics such as:

- The inspiration behind creating small-scale chemistry kits
- Incorporation of sustainability into their design and development
- Environmental impact goals from kits
- Waste management practices in the experiments outlined in the manuals
- Guidelines or recommendations for disposing of leftover chemicals or materials
- Use of reusable or recyclable components to minimize waste
- Integration of green chemistry principles into kit designs

The interview will be recorded for further review by our team, and the report will be published with our findings and your responses online. We will delete all traces of the recording after completing our research, and any individually identifying information such as names, dates, and locations will not be reported.

It is crucial to know that your participation is voluntary, and you are not required to share any information or answer any questions that you prefer to keep private. If, at any time, you decide not to continue, you may simply say so, and we will promptly stop the interview and destroy any information you've provided.

Do you consent to continue with the interview?

- ▪ I consent to give the interview.
- ▪ I do not consent to give the interview.

สคริปต์แสดงความยินยอม

เรียนถึงตัวแทนบริษัท Doing Sciences

ท่านได้ถูกเชิญชวนให้เข้าร่วมในการศึกษาวิจัยของทางมหาวิทยาลัย Worcester Polytechnic Institute (WPI) และจุฬาลงกรณ์วิทยาลัย (CU) เกี่ยวกับประสบการณ์ของท่านในการใช้ชุดเคมีแบบย่อส่วนและการผลิตชุดเคมีเหล่านี้

ก่อนที่ท่านจะตอบตกลง ท่านต้องทราบวัตถุประสงค์ของการศึกษา ขั้นตอนการปฏิบัติ ประโยชน์และความเสี่ยงหรือความไม่สบายใจต่างๆที่ท่านอาจประสบ ทางพวกเรามีหน้าที่ในการนำเสนอข้อมูลเหล่านี้เพื่อให้ท่านสามารถตัดสินใจในการมีส่วนร่วมในการสัมภาษณ์อย่างถี่ถ้วน

ในการสัมภาษณ์ครั้งนี้ พวกเราจะถามคำถามหลายข้อเกี่ยวกับประสบการณ์ของท่านในการผลิตชุดเคมีแบบย่อส่วน โดยที่คำถามเหล่านี้จะครอบคลุมหัวข้อต่างๆ เช่น:

- แรงบันดาลใจในการสร้างชุดเคมีขนาดเล็ก
- การประยุกต์คอนเซ็ปต์ความยั่งยืนในการออกแบบและพัฒนาชุดเคมีเหล่านี้
- ผลกระทบต่อสิ่งแวดล้อมจากชุดเคมี
- วิธีการจัดการของเสียในขั้นตอนการทดลองที่ระบุไว้
- แนวทางหรือคำแนะนำในการกำจัดสารเคมีหรือวัสดุที่เหลือ
- การใช้ส่วนประกอบรีไซเคิลเพื่อลดของเสีย
- การรวมหลักการเคมีสีเขียวในการออกแบบชุดเคมี

การสัมภาษณ์นี้จะถูกบันทึกไว้เพื่อการตรวจสอบในภายหลังโดยทีมงานของเราและรายงานจะถูกเผยแพร่ทางเว็บไซต์จุฬากับ WPI พร้อมข้อค้นพบจากพวกเราและคำตอบที่ท่านได้ให้มา เราจะลบข้อมูลการบันทึกและข้อมูลที่สามารถระบุตัวบุคคลได้ทั้งหมดหลังจากการวิจัยเสร็จสิ้น เช่น ชื่อ วันที่ และสถานที่ จะไม่ถูกเผยแพร่

สิ่งสำคัญที่ต้องทราบคือการเข้าร่วมของท่านเป็นไปโดยการสมัครใจและท่านไม่จำเป็นต้องให้ข้อมูลหรือตอบคำถามใดๆที่ท่านต้องการเก็บไว้เป็นความลับ เมื่อไหร่ก็ตามที่ท่านตัดสินใจที่จะไม่ดำเนินการต่อในการสัมภาษณ์ ท่านสามารถแจ้งให้เราทราบและเราจะยุติการสัมภาษณ์และทำลายข้อมูลที่ท่านได้ให้ไว้ในทันที

ท่านยินยอมที่จะดำเนินการสัมภาษณ์ต่อหรือไม่

- ฉันยินยอมที่จะให้สัมภาษณ์
- ฉันไม่ยินยอมที่จะให้สัมภาษณ์

Appendix D

Interview Questionnaires, Response, and Data Coding 1

Teachers' Interview

<table>
<tr><td>Code#</td><td>Question & Responses</td></tr>
<tr><td>1.1</td><td>How did you become a distinguished teacher? What are the training programs? How long did they take? Why did you do it?

Training along with adaptation and applied in her class, took 3-4 months.
The teacher participated in the program because she was interested in green chemistry and waste management.
The teacher became distinguished by designing innovative small-scale experiments, receiving the DOW-CST award, and being selected as a role model teacher at DCC. She attended training programs, including PACCON, to learn new techniques.
</td></tr>
<tr><td>1.2</td><td>Did the training cover waste management and green chemistry?

Yes, the training covered waste management and green chemistry. The teacher participated in training twice.
Yes, training was conducted twice for teachers, with Aj. Supawan present. Lab kits cannot be stored in the room due to space constraints, so small baskets are used. Small-scale experiments promote reusing and reducing waste.
The teacher's work highlights waste management and green chemistry, particularly in the precipitation of metals using tannins from natural fruits. The project also focused on sustainability by reducing waste and using locally available materials.
</td></tr>
<tr><td>1.3</td><td>Are the chemical resources for small-scale labs sourced locally, or do they require specialized suppliers?

Chemicals ordered from suppliers, Dow-CST apparatus used, and chemicals shared among schools.
Chemicals are ordered separately, while Dow-CST provides apparatus. Some chemicals are shared, and additional boxes are borrowed when needed.
Some chemicals for small-scale labs can be sourced from local stores, such as potassium permanganate, while others are chemical-grade and stored in large school facilities.
The chemicals purchased depend on the type of experiments that will be performed. Most large schools have chemical-grade chemicals that are stored in their facilities. Some small-scale experiments do not require any high-concentration chemicals but can be found in any store such as potassium permanganate that can be bought for 15 THB.
</td></tr>
</table>

Code#	Question & Responses
1.4	What additional training or resources would be helpful to you in implementing more sustainable practices in your chemistry classes? ● Training to use fewer chemicals, safety, and easier control in small-scale labs. ● More training on using fewer chemicals, improving safety, and making experiments easier to control. Middle and high school students have different perceptions and usage patterns, so tailored resources would be beneficial. ● Additional training could help in refining small-scale experiments, especially in sustainable chemistry practices. The teacher emphasizes the need for better integration of small-scale chemistry concepts with traditional lab experiments.
1.5	Do you think small-scale labs are a sustainable alternative for the future of science education? Why or why not? ● Yes, they save the environment, are safe, and produce zero waste. ● Yes, they save the environment, ensure teachers' safety, and promote zero waste. They are easy to clean and cause no pollution. ● They require fewer chemicals, reduce glassware use, and lower costs while maintaining safety and repeatability. However, their success depends on teacher knowledge and the ability to adapt experiments. ● The teacher thinks that small-scale experiments can be a stable and sustainable option only when the teachers have sufficient knowledge that can be applied to real-world scenarios and the ability to make their own kits. It is also beneficial to have an advisor who can help provide a guideline on how to complete the small-scale kits.
1.6	Was the transition from a traditional lab to a small-scale lab smooth? What obstacles, if any, did you face? ● Yes, the transition was smooth with less time needed and increased student participation. Some challenges included budget constraints and the need for additional preparation. ● The transition was smooth, saving time and increasing student participation. ● The transition was challenging due to a lack of knowledge and resistance from those against small-scale labs. The teacher faced difficulties integrating small-scale principles into existing school experiments and had to go through trial and error.

1.7	Are small-scale labs easier or harder to maintain than traditional labs? ● Easier to maintain, not easily broken, and has no big storage issues. ● Small-scale labs are easier to maintain as they require fewer chemicals, use minimal glassware (reducing breakage risks), and have lower costs. Chemical storage is also simpler due to the lower quantities and concentrations used.
1.8	On a scale of 1 (not important) to 5 (extremely important), how important do you think sustainable waste management and green chemistry practices are? ● 5 for green chemistry, 4 for waste management, with emphasis on using fewer chemicals. ○ Level 5. It reduces chemical use, saves time, is easy to clean, and is safer. ○ Level 4. Teachers always emphasize students to use fewer chemicals. Kids always complain about why teachers are so strict on chemical usage. ○ Level 4. The way teachers dispose of waste is not that good. But for green chemistry, the teacher gives 5. ● If it belongs to Dow, it is good. However, some experiments are not related to the studies. So, the teachers have to design their kits. ● The teacher strongly values sustainable waste management and green chemistry, as shown in her focus on reducing waste, using local materials, and ensuring student safety with lower chemical concentrations.
1.9	Elaborate on the reason you gave your ranking. ● Less chemical usage, easy to clean, and safe for the students. ● The teacher supports green chemistry because it enhances sustainability, lowers costs, and makes chemistry more accessible while maintaining effective learning.
1.9.1	What would you like to see in the future regarding practices using the kits? ● Use small-scale labs instead of traditional methods. ● They should replace traditional labs entirely. ● The teacher would like to see more sustainable chemistry practices incorporated into small-scale kits, such as using biodegradable materials and natural products.
1.9.2	What would you like to see differently in your training? ● More focus on natural chemicals and sustainable practices. ● Future training should address ways to further reduce waste in small-scale experiments and provide better guidance on adapting traditional labs to small-scale methods.

<table>
<tr><td>1.10</td><td>Have you observed changes in student engagement or participation when using small-scale labs? What are the biggest benefits compared to traditional labs?
Students are more engaged, and safety is a key benefit.
Easy, less time.
Students can see precipitation, color change, bubbles, etc. This also hugely increases the students’ interest since there is fire involved.
Students hate complicated experiments, so they love small-scale laboratory kits.</td></tr>
<tr><td>1.11</td><td>Do you feel small-scale labs provide a safer environment for students and staff? Why or why not? Have there been fewer incidents or accidents in small-scale labs compared to traditional labs?
Yes, they are safer, with fewer incidents and better waste management.</td></tr>
<tr><td>1.12</td><td>What are your waste management procedures?
Have to pay to find some other company or charity to dispose of the waste.
Each year we have online “communications” to see who will be the leader in hazardous waste management.
Small-scale kits use fewer chemicals, just throw away the waste.
For a standard lab
Sometimes I drain it down the sink.
Otherwise, I will collect it in the box and wait for someone to help me dispose of it.
We keep the waste in the laboratory rooms.
Not sure what the last destination of the chemicals is.</td></tr>
<tr><td>1.13</td><td>What do you do with the boxes (small-scale kits) after they’re used?
Tell the students to clean up and pack it up again.
Reused it.</td></tr>
<tr><td>1.14</td><td>How do small-scale laboratories incorporate sustainability principles, and what further improvements can be made to enhance their environmental impact?
Concepts such as reducing waste are already ingrained in the principles of small-scale laboratories. It is up to the teachers to find better ways to make experiments even more sustainable such as using natural products that are biodegradable in their projects.</td></tr>
</table>

1.15	How do you apply green chemistry in your classroom? ● Adapt an eggshell into some experiments such as back titration. ● Using flowers to be a natural indicator in titration experiments such as butterfly peas.

Appendix D. The table consists of question sets, responses, and the code for the interview with teachers from Prachinratsadorn-Amroong school.

Appendix E

Interview Questionnaires, Response, and Data Coding 2

Lab Technicians Interview

Code#	Question & Response
2.1	In general, how is laboratory waste managed? ● Waste is categorized by the SHECU table which is printed out and placed in corners of the laboratory room for students to follow the guidelines, separating waste into the right waste container. At the beginning of each class, professors will brief students about how to clean and manage waste from each experiment.
2.2	How is chemical waste collected and stored before disposal? ● For example, titration experiments will produce waste that is or can be neutralized which will be drained down into the sink while other waste must be separated and categorized into waste containers before sending to the waste disposal company.
2.3	Are there any initiatives to minimize chemical waste generation? ● There are uses for small-scale laboratories instead of doing traditional experiments to reduce the time and waste produced. Students can understand the concept faster by experimenting with the same chemicals but using approximately 10 times fewer chemicals.
2.4	Do you think there are areas where waste management can be improved >> if so, what are the challenges? ● Changing to alternative chemicals such as natural chemicals and indicators. To follow the green chemistry principles, use less hazardous chemicals to prevent health risks and provide eco-friendly solutions. The waste disposal process won’t require energy emissions (ex. landfill, burning fuels). Which are factors that have been creating a carbon footprint.

Appendix E. The table consists of question sets, responses, and the code for the interview with lab technicians from Chulalongkorn University

Appendix F

Interview Questionnaires, Response, and Data Coding 3

Doing Science Interview

Code#	Question & Response
3.1	Do you address waste management in the experiments outlined in your manuals ● Doing Science is not responsible for making waste management outlines for customers. The company assumes that most of its customers (schools) have a waste management process of their own.
3.2	What inspired you to create small-scale chemistry kits? ● The production engineer only accepts the order/request/draft of the whole kit. She has no idea about inspiration as she doesn't design the kit
3.3	Any positive or negative feedback about the kits from the customers ● Most feedback is positive, and the most common negative feedback is that some powder bottles of chemicals were spilled during transportation
3.4	Do your kits include reusable or recyclable components to minimize waste? If yes, can you describe them? ● Almost every part of the kit is reusable as the kit itself aims for 20-30 uses per kit before the chemical runs out. ● If the kit is being stored properly, the plasticware inside should be able to last for around 3 months

Appendix F. The table consists of question sets, responses, and the code for the interview with the production engineer from Doing Sciences Co., Ltd.

Appendix G

Classroom Observation Key Questions, Observation Notes, and Data Coding

Classroom Observation

Code	Questions & Interpretations
4.1	Did students obtain comparable results during the experiment? ● In the electrochemistry experiment, students received similar results in the first half of the experiment. However, in the second half of the experiment, students who were using the small-scale chemistry kits did not achieve the result of a lightened lightbulb. Conversely, students using large-scale experiments were able to reach the experimental outcome.
4.1.1	How do large-scale and small-scale results compare? ● The results of large-scale chemistry experiments were easier to observe compared to smaller-scale chemistry kits.
4.1.2	What are the similarities or differences in the time required to conduct large-scale chemistry experiments versus small-scale chemistry experiments? ● Small-scale experiments require less time than traditional due to the number of chemicals used for reactions to occur and the size of the equipment is smaller which makes them easier and faster to clean. ● Small-scale experiments tend to react more quickly because of the higher surface area and volume ratio, which efficient for time-limited labs
4.2	What are the observed waste disposal procedures in classrooms? ● There are no disposal procedures for getting rid of chemicals. ● Students clean their own materials. This assists in lab work; and also teaches students proper lab maintenance and the importance of cleaning them after the experiment
4.2.1	Where does the waste go? ● For small-scale, waste and equipment are wiped with tissues and trashed in a bin, while traditional have jars to separate chemicals. ● The black garbage bag is used for general waste. ● Clean-up procedure: waste is usually disposed of in trash bags. ● During clean-up procedures, waste is usually disposed of in trash bags. ● For an electrolytic cell experiment, a plastic container is used for waste.
4.2.2	Is water used to clean out chemicals from materials? ● For small-scale kits, students used water to clean after wiping with tissues. For traditional labs, water was used after pouring chemicals separately into a container.
4.2.3	How are tissues used during the disposal process? ● Tissues are used to wipe chemicals during disposal procedures.

4.2.4	What excess material is recycled? (i.e. kits, chemicals, materials within kits, etc.) ● For the electrolytic cell experiment, we learned that the small-scale chemistry kits remain on the group tables. The materials within the kits are replaced with the appropriate materials and apparatus needed for the next experiment. ● In addition, we learned that a cup of water and a pipette also remain on the table and are reused for each experiment. ● In the metal and ion metal reaction experiment, metals are reused for future experiments.
5.1	Are students working collaboratively? ● For the majority of the classroom observations, we interpreted that students were effectively collaborating with each other. ● Teachers gave students time to prepare encouraging independent thinking and teamwork; discussing roles ahead, so they could work more efficiently and develop collaboration skills ● Inefficient teamwork, only one student doing the writing, others observing with lots of downtimes
5.1.1	Are students engaged while experimenting? ● Students are engaged as they conduct their experiment. ● Students seem happy to perform the experiment. ● Continue engagement!! Even after the lab, students remain in observation which enhances their scientific thinking. ● High engagement!!! Students take pictures and record as they conduct experiments. This can indicate that students find the experiment interesting.
5.1.2	Did students present/report their findings? ● Yes, students presented their findings. ● The presentation allows students to practice presentation skills in finding science. In addition, this will help students better understand the concept of electrolytic cells. ● Individual reports ensure that each student reflects in the experiment independently >> reinforces their understanding and analytical skills than done in group work. ● Short presentations promote active participation and communication skills>> also allow students to compare their group with other groups.
5.1.3	How are the students' demeanors post-experiment? ● Students really enjoyed the lab and continued investigating for leisure. ● Students feel comfortable admitting mistakes which help them to learn from others rather than feeling disappointed>> This encourages honesty and self-reflection. ● Give time for discussion to ensure that students reflect on their results, verify data, and collaborate to understand the results better before presenting>> Encourage critical thinking and teamwork
5.2	How engaged are the teachers with the students? (i.e. demeanor, while conducting

	experiments, answering questions, interest in students' success, etc.) ● The teacher ensures that all students can follow the lesson. ● When out of time or have mistakes and errors, the teacher explains the reason why the student made this mistake, and where it came from. ● Rather than just correct mistakes, teachers ensure that students understand the cause of error >> This fosters critical thinking and helps prevent repeat mistakes in the future.
5.3	Do teachers reinforce safety when handling materials and chemicals? ● Teachers briefed students about safety at the beginning of their class and after discussing the results they guided their students again.
5.3.1	Do the teachers or lab procedures mention waste procedures? ● The teacher briefed the students at the beginning of the experiments and after finishing the experiments they briefed the students again. ● The lecture was explained in an easy way to understand and not too long and the teacher also told the students how to clean after finishing.
5.4	Are there any implemented sustainability practices in these classrooms/experiments? ● Less water usage. Water sources come from alternative sources. ● Some materials are reused (i.e. water and metals) ● Focus on lab safety sustainability; Teach waste disposal procedures ahead to ensure that students are aware of responsible chemical management and reduce environmental impact
5.4.1	How sustainable is a large-scale laboratory versus a small-scale chemistry kit? ● Despite small-scale laboratories proven to take half the time compared to doing the experiment traditionally, easier to understand (by comparing the time it takes for the flowcharts to be completed as well as the fewer steps stated), and producing much less waste (disposing of those wastes by simply wiping the chemicals with tissue; whereas in the traditional method, the chemical wastes had to be separated into groups which then had to undergo further disposal). One or more students were still more inclined to experiment traditionally. ● While small-scale experiments are more sustainable, larger scales may still be preferable for the lab because of ease of handling. Both take similar time indicating that small scale does not speed up the process but serve other benefits such as reduced waste and easier cleanup
5.5	Are there any green chemistry practices in the laboratory? ● Students conducted experiments in groups, used chemicals as necessary, and did real-time analysis.

Appendix G. The table consists of key questions, observations, and the code for classroom observation.

Appendix H

Project Gantt Chart

Actions	Week						
	1	2	3	4	5	6	7
Meeting with Sponsor	■						
Meeting With Expert	■	■		■	■		
Interviews		■	■	■	■	■	
Ethnography			■	■	■	■	
LCA		■	■	■	■	■	
Recommendations						■	■
Write Final Paper	■	■	■	■	■	■	■
Archival Research	■	■	■	■	■	■	■
Submission							■

Appendix H. The table of the Gantt Chart shows the progress of the team within seven weeks.

Appendix I

Group and Individual Authorships

Tanat "Brio" Boonratanakornkit

Brio led the interview sub-team on the data collection. He contributed to this report by developing question sets and consent forms for interviewing teachers at Prachinratsadorn-Amroong School. He also analyzed classroom observation results and summarized the findings. Additionally, he played a major role in collecting all necessary references using Zotero software. Brio was the primary author of the appendix and co-authored the conclusion section with Connor. Finally, he served as the primary editor for the overall report, mainly focusing on grammatical accuracy and proper sentence structure.

Bridikul "Ronnie" Bridhikitti

Ronnie was part of the interview sub-team for data collection. He and Tonkla hosted the interviews and analyzed the notes to extract findings. He was the primary author of the introduction, sponsor background, and recommendations sections of the report, collaborating with Tonkla. Ronnie also represented the team in communications with our project advisor, Professor Dr. Supawan Tantayanon.

Jirachaya "Amy" Kaemavichanurat

Amy was part of the lab manuals sub-team led by Samyra. She translated lab manuals provided by teachers at Prachinratsadorn-Amroong School. Amy was the primary author of the recommendations section, working with Ronnie. She also served as the primary editor for the overall report.

Samyra Guerrier

Samyra led the sub-team for translating and analyzing lab manuals. She researched various case studies of small-scale kits and provided background information on traditional laboratories. She is the primary author of the literature review section and co-authored the appendix section with Brio. Thus, she identified limitations and gaps in small-scale kits in the literature review section. Samyra also analyzed classroom observations and summarized the findings with Brio. She represented the team in communications with sponsors, LCA experts, and advisors via email.

Declan Reilly

Declan was the primary author of the findings, limitations, and ethical concerns sections. He also served as the primary editor for the overall report. As part of the LCA sub-team, he outlined the LCA process and worked on its calculations and findings. Additionally, Declan represented the team in presentations to advisors and was responsible for team organization and management with Connor.

Connor Tam

Connor was the primary author and editor of the methodology, literature review, and conclusion sections. As the leader of the LCA sub-team, he wrote about green chemistry and worked on LCA calculations and findings with Declan and Tannie. He also drafted observation guidelines for the team. Connor, along with Declan, facilitated meetings and managed the team's workflow, ensuring a safe and comfortable work environment.

Apichai “Tannie” Wejsuwan

Tannie coordinated with Dr. Panawan Vanaphuti to schedule the team’s titration lab. He led the team during titration experiments and, as part of the LCA sub-team, calculated LCA and conducted database research. Tannie also served as the primary editor of the report and was the primary author of the bibliography and discussion sections.

Tathata “Tonkla” Youngsuksathaporn

Tonkla represented the group in communications with LCA experts and interviewees, including teachers from Prachinratsadorn-Amroong School, lab technicians, and the production engineer from Doing Science. She assisted Brio and Ronnie in hosting interviews and analyzing the findings. Tonkla was the primary author of the introduction, sponsor background, findings sections and co-authored the appendix section with Brio.

The Collective Team

In addition to their contributions, all team members collaborated on setting and refining the goals and objectives. The team conducted titration experiments to obtain results for the report, interviewed teachers, and observed classrooms at Prachinratsadorn-Amroong School.