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Green chemical engineering: challenges in chemical industrial processes for a better life

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Abstract. Almost thirty years away from sustainable development Rio summit, we still need to put a big effort in promoting and implementing industrial sustainable process. Green chemical engineering has been involved in industrial processes and chemical engineers are working to develop solutions for green and economic production of product using clean technologies, solving energy and raw materials shortage, sustainable water supply and wastewater treatment, carbon capture and utilization. This paper aims to highlight developments, challenges and best practices in green chemical engineering for both green product engineering and green process engineering. Incorporating the green engineering concept in the curriculum at university level to create a critical mass of engineers and scientists in green engineering is also included.

1.Introduction

One of the Sustainable Development Goals as Indonesia commitment by 2030 is “sustainable consumption and production’. It is related to green industrial process and product. Chemical products have contributed in supplying the needs and demands of our daily life. The products have been produced by chemical processes which consume huge amounts of natural resources and also generates unwanted by-products. It caused environmental pollution and the issue of climate change has been raised due to the rapid consumption of fossil-based energy. Nowadays, green chemical engineering which is a combination between green chemistry and green engineering has been involved in industrial processes to optimize the design of chemical processes and efficient use of materials and catalysts. As one of the most efficient means to achieve sustainable development in chemical industrial processes, green chemical engineering has been developed to address the needs of the green chemical industries and also for further studies on new technologies and processes. Green chemical engineering can be classified in two categories: green product engineering and green process engineering (Figure 1) [1]. Green product engineering includes the developments and use of new catalysts and renewable resources such as renewable energy and biomass. Green process engineering includes process intensification, new reaction media, energy conservation, CO_2 emission reduction, novel reactors and new separation techniques. Green product engineering has an objective to change or modify product designs by using non-toxic compounds or biodegradable materials during the production process. Green product engineering involves product lifecycle, from manufacturing process to distribution, from use to disposal or reuse and recycling. Green process engineering aims to reduce energy, water consumption and also undesired by products during the production process [2]. It includes reducing gas, energy or water emissions, improving resource and energy efficiency which involves in both novel separation technology and reactors design. Green process engineering will lead to sustainability of various competitive advantages and obtain both cost efficiency and profitability [2].

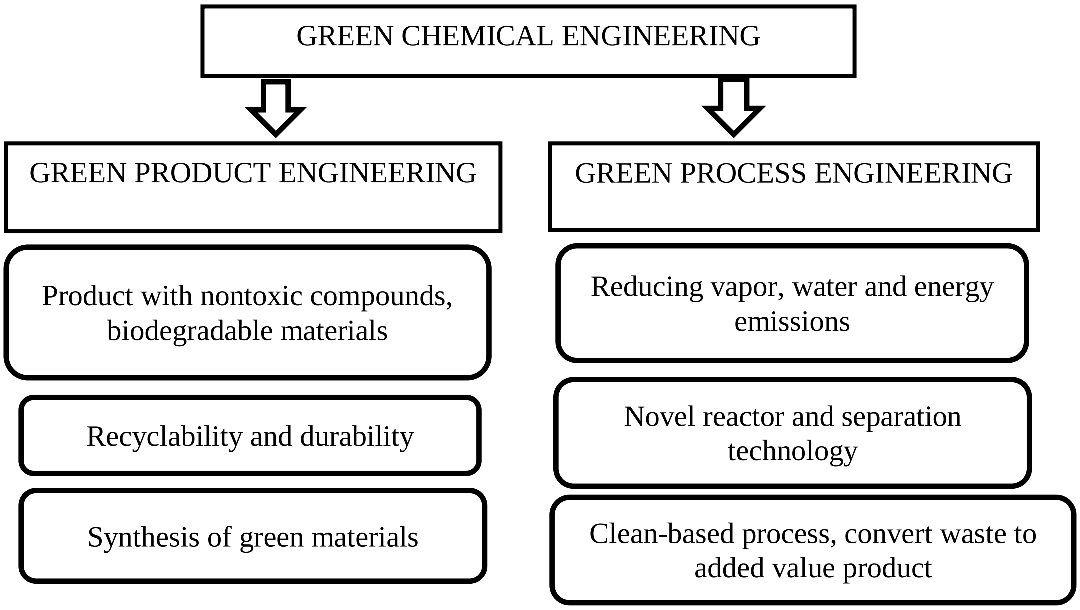

Figure 1. Green Chemical Engineering Concept

2.Green product engineering, challenges and best practice

There are three main focus areas of Green product engineering: 1) how to use alternative synthesis pathways which is more “green”, 2) the design of safer chemicals that are less toxic or safer with regards to hazard and exposure and 3) the use of alternative reaction conditions [3]. Figure 2 shows the ideal concept of green material synthesis which creates a lot of challenges in implementation, as 100% yield is unlikely to achieve. Identifying synthesis pathways requires creative thinking in chemistry and process design, since the pathways are big and large scopes. The applications in chemical industrial processes are so complex and the quantitative and qualitative design tools are not available. So, virtual reality powered by supercomputing and big data analysis is needed. Hence, a lot of research has to be conducted which make the tools emerge. It is a big challenge. An example of safer chemicals used is in the synthesis of adipic acid (Figure 3) which uses glucose as alternative of benzene [4]. The best practice of choosing alternative synthesis pathways is the synthesis of Ibuprofen, a pain reliever from 2-methypropylbenzene [4]. The synthesis involves Friedel-Crafts chemistry. The long steps reaction with acid catalyst ($AlCl_3$) lead to several by products and also the uses of many solvents (Figure 4). The new approach using recoverable Hydrogen Fluoride (HF) leads to shorter pathway and more “green”. As alternative reaction conditions, temperature and initial concentration are highlighted in this paper. Working on higher or lower temperature depends on the type,order of reaction and also activation energy in each reaction. The illustration of a parallel reaction for the first order reaction with reaction constant of kp and kw as seen in equations(1) and (2) shows that higher temperature is a better operation condition with Ep >Ew, the opposite is true for Ep <Ew. It can be explained by equation (3) which results in bigger ratio of kp/kw. The condition is also valid for first order series reaction as presented in equation (4). The notations in the equations are described as: A is frequency factor, Ep and Eware activation energy of P and W, R is a gas constant and T is absolute temperature. The notation of M, P and W represents raw material, product and waste (undesired product).

$$M \overset{kp}{\rightarrow} P \qquad (1)$$

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$$M \xrightarrow{kw} W \tag{2}$$

$$\frac{kp}{kw} = \frac{A_p e^{-(\frac{Ep}{RT})}}{A_w e^{-(\frac{Ew}{RT})}} \tag{3}$$

$$M \xrightarrow{kp} P \xrightarrow{kw} W \tag{4}$$

In the series and parallel reactions, the effect of raw material initial concentration can be sensitive. The rates of product and waste formation are expressed in equations (5) and (6) where [M] is the raw material concentration, n_p and n_w are the order of reactions. The ratio of these rates shows the selectivity to product formation.If$n_p>n_w$, the increase of [M] will increase product, but if $n_p<n_w$ the increase of [M] will reduce product and lead to the formation of waste.

$$rate\ of\ product\ formation\ = kp\ [M]^{n_p} \tag{5}$$

$$rateof\ waste\ formation = kw[M]^{n_w} \tag{6}$$

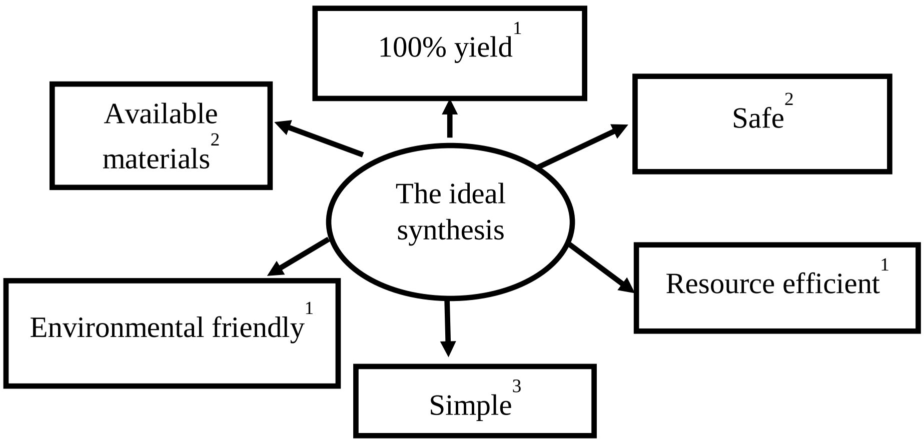

Figure 2. The ideal green product synthesis, where 1,2 and 3 indicate the aforementioned three main focus areas.

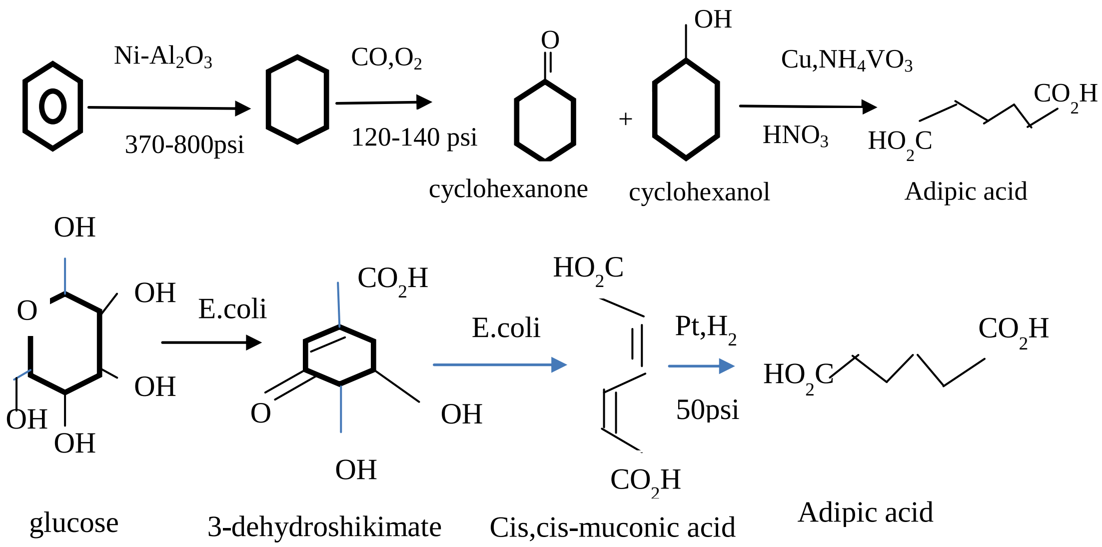

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Figure 3. Previous (above) and alternative synthetic (below) pathways for adipic acid synthesis

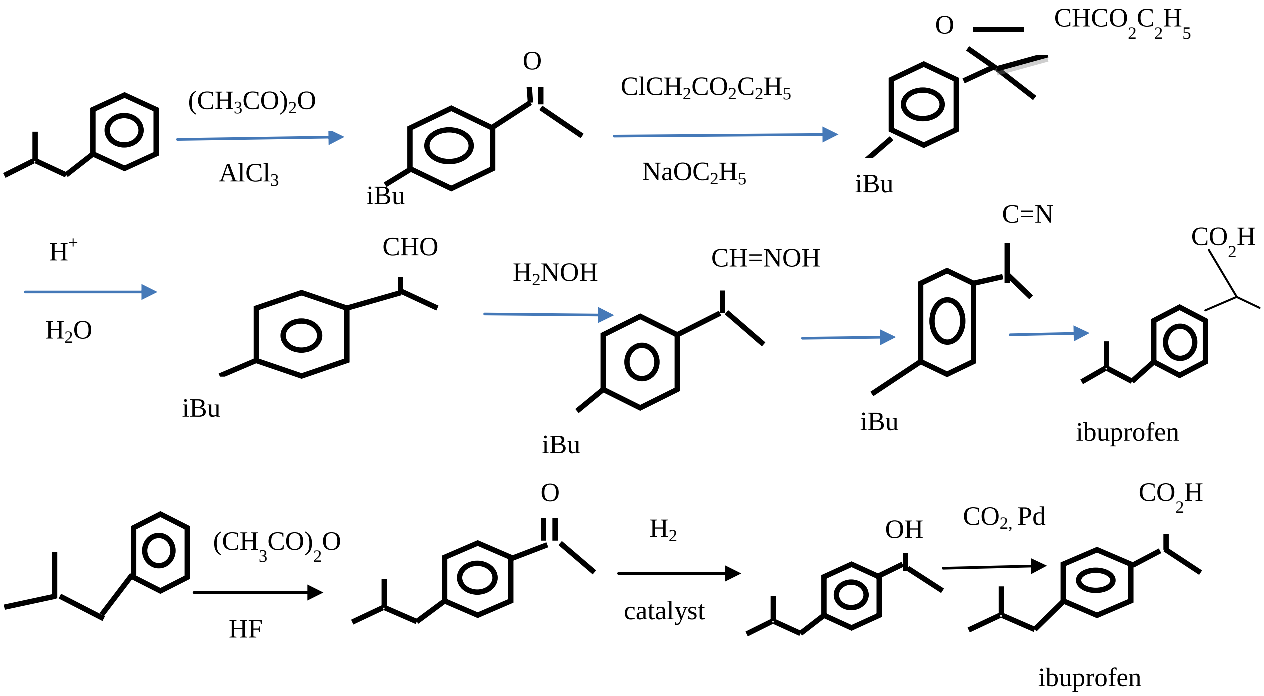

Figure 4. Previous (above) and alternative synthesis (below) pathways for Ibuprofen synthesis.

One example of green products is biodegradable plastic which is bio-based and biodegradable. The product is made from starch, vegetable oil and other materials from nature without polyethylene and polypropylene .It dissolves in hot water and is degradable after 2 months by composting system.

3. Green process engineering, challenges and best practice

Green Process Engineering involves the design, commercialization and use of processes to limit environmental burden by minimizing pollution at the source and risk to human health and the environment. It also contributes to the technological modernization of the economy. The criteria for Green Process Engineering can be categorized into two: 1) it must be based on new technological knowledge, 2) it must be able to be implemented. The significant opportunities are in the development of advanced materials, growth renewable energy, whereas the barriers are the difficulty in quantifying the true costs of waste and the potential savings offered by Green Process Engineering leading to the availability of comprehensive proof of good environmental and economic performance of proposed green chemical processes. Many research and manufacturing firms have started to tackle this problem. The best practice in Green Process Engineering discussed in this paper are :1) VOCs (volatile organic compounds) recovery from printing process and 2) water reduction in a process of recycle polypropylene (PP) woven sack to make polypropylene pellet for PP rope. There are two VOC recovery processes in printing industry that will be discussed in the paper [5]. The first process is considering to treat the VOC, while the second process is a new development to recover the VOC. The new technology of VOC recovery in printing process is a parallel system of advanced materials as adsorbents. Ethanol is used extensively in the printing industry. The major component of volatile effluents in printing industries are ethanol (30-50 wt%) and ethyl acetate (10-15 wt %). The flow sheet in Figure 5 shows the VOC which was treated using incineration leading to energy and CO_2 emissions. The green process engineering tried to solve the incineration process with other green VOC recovery technology (Figure 6), the dotted rectangle is the challenge for green process engineering to develop new technology in a green separation process. The new development green process engineering for such issue is presented in Figure 7 by using advanced materials which have been developed in emerging catalysis and separation applications.

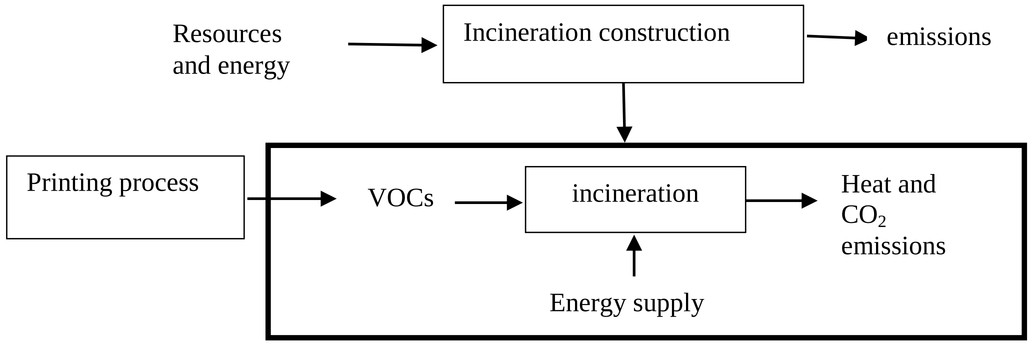

Figure 5. Diagram of incineration for VOC treatment in printing process, the box with solid line is the system

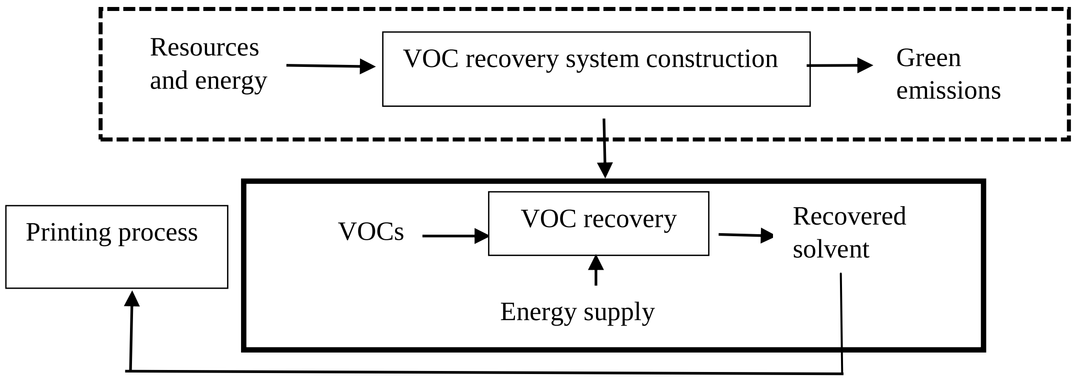

Figure 6. The concept of green process engineering in VOC recovery by designing green separation process.

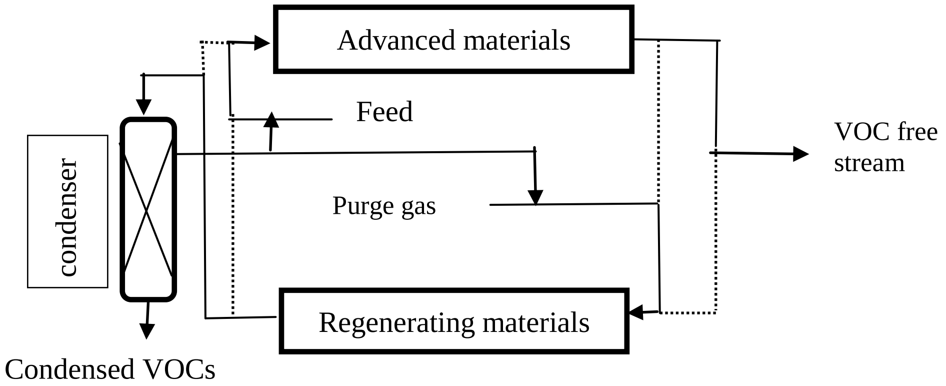

Figure 7. Green separation process for VOC recovery in printing industry.

The other best practice for green processing engineering is the water reduction in a recycle process of polypropylene (PP) woven sack to make polypropylene pellet for PP rope. The project has been conducted in East Java, Indonesia. The process diagram is presented in Figure 8. We changed the angle of the conveyor to reduce water loss in rinsing and transporting processes. Consequently, there was 54.17 % reduction of water losses from the initial water outlet flowrate of 0.51 m^3/minutes. Hence wastewater treatment in the process is more economically efficient.

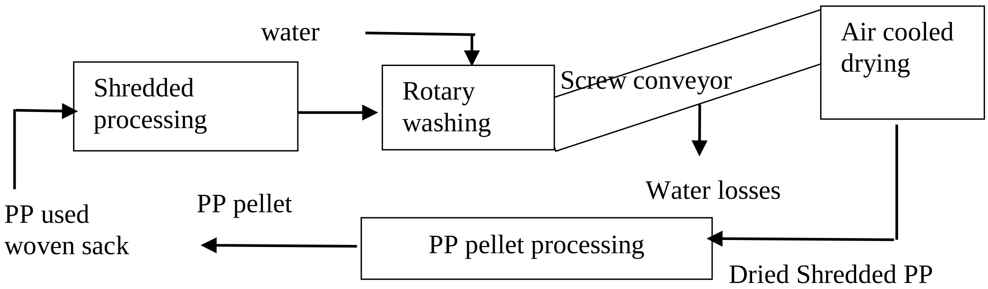

Figure 8. Schematic diagram of recycle PP woven sack processing

4. Incorporating the green engineering in the curriculum

Since green engineering principles should be used by all engineers, incorporating the concept to undergraduate curriculum is important. Integrating green engineering concepts into various chemical engineering courses is challenging. We propose to incorporate the concept in material and energy balances, thermodynamics especially in single phase and multiphase systems, reaction engineering, separation process, and process design courses. The material and energy balance course is an initial place to put the green engineering concept in chemical engineering. Table 1 shows some conceptual green engineering topics proposed in material and energy (M&E) balance course.

Table 1. Conceptual green engineering topics in M&E balancescourse [6]

Green engineering topic	M&E balances topic
Balances on recycle operation in green engineering process; green chemistry in stoichiometry; combustion process and environmental impact	Fundamental of material balances
Various form of energy in a green engineering process	Energy and energy balances
Use of heat capacity and phase change calculation; recovery of energy in process-energy integration; mixing and solution issues in green engineering	Non reactive process balance
Energy use in green chemistry reaction, combustion process; overall mass and energy balances in green engineering on an overall plant design basis	Reactive process balance

5.Conclusions

Engineering solutions to promote green engineering are required to adapt consumer demands and minimize environmental impact. We can put together the concept of green chemistry and green engineering at the earliest stages to make an effective strategy for minimizing waste, maximizing efficiency and increasing profitability. The need to incorporate green engineering concept in the curriculum at university level to create a critical mass of engineers and scientists for future development and challenges is inevitable since the multidisciplinary approach in solving a complex problems is needed.

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