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Implementation of green chemistry principles in circular economy system towards sustainable development goals: Challenges and perspectives

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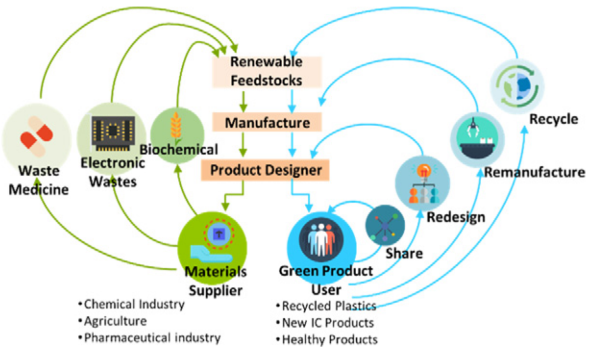
HIGHLIGHTS

- Prevention, assurance and sustainability are key indexes for green chemistry.
- International movement of green chemistry on policy implementation was reviewed.
- Integrated management and innovative technology of green chemistry were presented.
- Connection between green chemistry principles and circular economy was eatablished.
- Strategies on green chemistry principles towards circular economy were provided.

GRAPHICAL ABSTRACT



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ABSTRACT

Green chemistry principles (GCP) are comprehensively deployed in industrial management, governmental policy, educational practice, and technology development around the world. Circular economy always aims to balance the economic growth, resource sustainability, and environmental protection. This article offers a highlight on issues of significance within GCP and circular economy, and proposes the integrated strategies for GCP implementation from the aspects of governance, industry and education. At first, we developed a new categorizing system for GCP dividing to (i) pollution and accident prevention, (ii) safety and resource sustainability, and (iii) energy and resource sustainability. To assess the GCP practice towards the circular economy, the implementation of international movement of GCP in worldwide policy, especially those of Canada, China, Germany, Japan, South Korea, Sweden, Taiwan, United States and United Kingdom were reviewed. The policy implementation of GCP practices among governance, industries and education was analyzed. To integrate GCP into the circular economy concept, we also proposed five strategies of priority governance direction as follows: (i) establishment of cross-departmental collaboration, (ii) development of cleaner production and green product, (iii) provision of integrated chemical management system, (iv) implementation of green chemistry education program, and (v) construction of a business model. Finally, we discussed the prospects of disciplinary elements including the establishment of redesign-reduction-recovery-recycle-reuse (5R) practices for wastes reclamation, deployment

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of water-energy-food nexus with GCP to improve the food security and resource sustainability, and implementation of GCP in the green smart industrial park.

1. Introduction

1.1. Sustainable development goals (SDGs) and green chemistry

Sustainable development goals (SDGs), the collection of 17 goals proposed by the United Nations in 2015, aimed to improve the world welfare by tackling social, environmental, and economic sustainability. Among SDGs, clean water and sanitation (SDG 6), responsible consumption and production of resources (SDG 12), and actions against climate change (SDG 13) were related to the impacts of foul water, toxic waste, and climate change on the world welfare. Currently, 40% of world population is seriously impacted (negatively) by the water scarcity. Both leakage of toxic chemicals and global warming play a key role (negative) in causing water pollution and water scarcity. Therefore, the Paris Agreement, signed by a majority of the developed and developing countries (174 countries and European Union) in 2016, initiated the Green Climate Fund aiming at mitigating the greenhouse gas emissions (Seo, 2017).

Green chemistry principles (GCP) were created by Paul Anastas and John Warner, who had attempted to define a greener (or more environment-friendly) chemical process or product (Anastas, 2007). The concept was developed seeking the prevention of pollution before it would occur at its source by minimizing the use of hazardous chemicals. In general, GCP could highlight the design of safer chemicals, the use of catalysts rather than stoichiometric reagents, and the prevention of waste production (Anastas and Warner, 1998; Zhang, 2017).

According to GCP, the pollution prevention should be investigated on a molecular level and, hence, the reduction of pollution sources was emphasized in the entire life-cycle of a chemical. Green chemistry concepts stemmed from the United States' Pollution Prevention Act in 1990s (Nameroff et al., 2004). The This Act defines GCP as a source reduction, i.e., any practice that could prevent the hazardous chemical substances from being released into the environment and affect the public health (USEPA, 2017). An increase of energy efficiency and reduction of natural resource use for chemical synthesis are also addressed by the American environmental agency.

GCP could benefit human health, environment, and economic sustainability, which are highly related to SDGs and Table 1 shows how GCP are beneficially related to SDGs. Those principles might be the main source for achieving several SDGs including improved health and welfare, clean water, and clean-energy production and consumption. These SDGs were also interconnected to others such as SDG 11 (environmental benefits such as sustainable cities and communities) and SDG 14 (life below water). From the economic aspect, industrial innovation and infrastructure (SDG 9) and responsible consumption and production (SDG 12) would be the main objective, describing the contribution of GCP to the industry. The demand for chemicals in developed countries could promote the existing manufacturing to produce a surplus products to address the needs of the economic benefits in developing regions (Poliakoff et al., 2018). In order to achieve the SDGs which could integrate GCP and sustainability, the sustainable chemistry has been interested in the development of: new types of chemicals, a comprehensive evaluation framework covering the environmental, economic, and social aspects, and a long-term vision for sustainable development (Halpaap and Dittkrist, 2018).

Sustainable chemistry can be defined as a chemical-developing system in which safer and more environmental-friendly chemistry was applied to address the concern associated with the economic and social impacts of chemicals over their entire life-cycle (Marion et al., 2017). Covering a variety of fields including water, energy, food, climate, and population, sustainable chemistry could play an important role in human health and well-being of living species. However, green chemistry indeed aims to guide chemists to synthesize chemicals through environmental-friendly and highly efficient reactions, having a fundamental science involved in the SDG framework. In other words, to achieve SDGs effectively, GCP practice could represent a key performance indicator in evaluating the achievable objectives of SDGs.

1.2. GCP and circular economy concept

The concept of GCP has been holistically developed for preventing chemical hazards, reducing environmental impact, and enhancing economic benefits since 1990s. In the beginning, GCP have been proposed by the chemists and scientists who have designed the chemical processes and products. Although it is difficult to distinguish between green chemistry and sustainable chemistry (Sheldon, 2007; Watson, 2012), GCP are highly related to the benefits of chemical design (Anastas, 1993). Clean products or processes are essential in improving the quality of life during industrialization or urbanization. In order to implementing the green chemistry or sustainable chemistry, an internationally sound CMS should be established. In fact, several conventions related to management or prevention of toxic and hazardous chemicals have been proposed. They are (i) Dubai Declaration for necessity of sound chemical management; (ii) Basel Convention for control of transboundary movement of hazardous wastes and their disposal; (iii) Stockholm Convention for restraint of persistent organic pollutants; (iv) Rio Declaration on environment and development for avoiding environmental-quality degradation and natural-resource depletion; (v) Rotterdam Convention for responsibilities of hazardous chemicals importation; and (vi) Globally Harmonized System (GHS) of Classification and Labeling of Chemicals for classifying and labelling hazardous materials or chemicals. Abovementioned conventions encourage chemists to design chemicals in a greener way and to eliminate hazardous materials. For example, the Green Chemistry Institute was established as a non-profitable organization in 1997 to promote green chemistry technologies. It was noted that the total sales of chemicals were over 10,000 tons from 2011 to 2014 in China, Europe, Asia, and North America (Lozano et al., 2016).

A variety of chemicals, for example, pharmaceutical drugs, plastic polymers and silicon wafers have been developed in order to improve the quality of human life as well as the economic growth, while they increased the risk of toxicant dispersion and pollution and also threat to the environment. For the past three decades, the importance of balancing the conflict between the economic growth and environmental conservation has been emphasized. Therefore, GCP towards the sustainable development has been promoted (Lozano et al., 2018). As a strategic approach for the sustainable development, the implementation of "circular economy", a nascent concept to improve the resource and energy efficiency has been proposed by Leontief (Murray et al., 2015). The application of green chemistry concept could be a foundational component to achieve the circular economy rather than linear one (Smieja and Babcock, 2017). Based on the closing loops of renewable materials (Yuan et al., 2006), the transformation of waste materials for better utilization as well as for the system optimization could be achieved (Webster, 2013). Several studies performed by MacArthur Foundation have provided the various concepts of circular economy, for changing the economic model and thereby for promoting the more competitive resource and energy market. According to World Business Council for Sustainable Development (WBCSD), circular economy could identify the environmental priorities covering the information

Table 1
The relevant SDGs linked to the benefits of GCP application.

Aspects	Key Factors	Related SDGs
Human Health	Enhanced safety for workers in the chemical industry	SDGs 3, 8 and 12
	Safer chemical products for consumers	SDGs 3 and 12
	Better food security	SDG2
Environment	Less exposure to toxic substances	SDGs 3, 6, 12 and 14
	Less release of hazardous chemicals to air	SDGs 3, 7 and 11
	Less release of hazardous chemicals to water	SDGs 3, 6, 11 and 14
	More innocuous products into environment	SDGs 2, 6, 9, 12 and 14
	Less harmful to plants and animals	SDGs 12 and 15
	Lower potential for global warming, ozone depletion, and smog formation	SDGs 11, 13 and 14
	Less chemical disruption of ecosystems	SDGs 12, 14, 15
	Less use of landfills	SDGs 11, 12
Economy	Higher chemical yields	SDGs 9, 12
	Fewer synthesis steps	SDGs 9, 12
	Reduction of wastes and lower treatment cost	SDGs 9, 11, 12
	Better performance of final products	SDGs 9, 12
	Reduced use of petroleum products	SDGs 9, 12, 13
	Reduced footprint of manufacturing plant	SDGs 9, 12
	Increased product values	SDGs 9, 12
	Improved competitiveness of chemical manufacturers	SDGs 9

about material flow, carbon, water and ecological footprints and could also develop an advanced concept that was able to change the businesses, government and the performance of societies (MacArthur et al., 2015). Kaur et al. (2018) reviewed the current trend of introducing the bio-based economy using green chemistry approaches to scale up the circular economic level. Waste management of bio-based plastics or polymers offers the advantages of resources sustainability instead of conventional treatment or disposal. Kirchherr et al. (2017) presented a conceptualizing framework of the circular economy, in which refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover (9Rs) were implemented to increase the circularity of the conventional linear economy. By reducing the use of resource and energy in chemical industry, circular economy provided a pathway for the sustainable development from the application of environmental assessment and demonstrate the recyclability of the new chemical product (Clark et al., 2016). The life of the future generation would be forced to be acknowledged (Bocken et al., 2017). It was suggested that the circular economy system for a chemical industry could be established on a multi-level scale by implementing the technological innovation, new business models, and stakeholder collaboration (Witjes and Lozano, 2016). For instance, a reliable and sustainable process for textile waste valorization by introducing the biological process with reclamation of sugars from biodegradable fibers and reduction of waste fiber disposal has been deployed in Hong Kong (To et al., 2019).

In this study, the innovative strategies and integrated management are considered as essential approaches to accelerating the development of GCP towards the circular economy. This work provides a comprehensive review of GCP practices related to government, and technical and academic activities. The promising concepts of "pollution and accident prevention", "safety and security assurance", and "energy and resource sustainability" are clearly defined on the basis of GCP. The strategies to implement green chemistry towards the circular economy including cross-departmental collaboration, cleaner production, chemical management system (CMS), green chemistry education program, business models, and smart technology were proposed. Finally, perspectives and prospects on green chemistry and circular economy such as redesign-reduction-recovery-recycle-reuse (5R) practices, integration of water-energy-food-nexus concept and GCP, and implementation of the green smart industrial park will be discussed.

2. International movement and barriers of green chemistry on policy implementation

Table 2 presents the international movement on policy-implementation of GCP practices in governance, industry, and academic aspects. The table shows the current practicable examples that could correspond to GCP; i.e., they could be utilized to easily announce and educate GCP to the public by the government. A selected nine countries (i.e., Canada, China, Germany, Japan, South Korea, Sweden, Taiwan, the United Kingdom, and the United States) for GCP were summarized as follows.

2.1. North America (the United States and Canada)

The development of green chemistry in the U.S. was discussed from a regulatory point of view. The U.S. Environmental Protection Agency (US EPA) formulated a series of procedures such as reporting, recording, and testing to refrain from using hazardous substances by following the Toxic Substances Control Act (TSCA) (Wilson and Schwarzman, 2009). The production, importation, utilization, and disposal of hazardous chemicals such as asbestos, radon, or polychlorinated biphenyls were stipulated by TSCA, which could be regarded as essential and legislative principles to emphasize the effective chemical management. Then, an evaluation system to regulate the new and existing chemicals (that have been used in the industry) has been established. The US EPA actually demanded the manufacturers to provide sufficient data about the potential exposure of hazardous chemicals. Due to sound scientific evidences and risk assessment on hazardous chemicals, manufacturers could support the recognition of those chemicals facing the uncertainty of regulatory (Matus et al., 2012a). It was suggested that the authority of clear, enforceable, and practical actions of a risk management was required. The study indicated that the risk management actions would be taken to promote the children's health, economic, popular equity, and social benefits (Matus, 2010).

The development of confidential business and information under TSCA could promote the manufacturers to design safer and more sustainable chemicals that can be produced at a lower risk and at a higher energy efficiency. By negotiating with local governments, the information about the share of chemicals that could protect the public health and safety could be received. Governmental promotion of the GCP could accelerate the development of greener products; for example, an environmental safety label could be attached to the antimicrobial goods so that the consumers could identify the non-pesticide products. The list of safer chemical ingredients built under the Safer Choice Program could provide the details of chemical ingredients or alternatives which were known as safer than traditional ones (Lavoie et al., 2010).

In order to manage the chemicals circulated in the market, the Canadian government announced the Canadian Environmental Protection Acts, the Canada Consumer Product Safety Acts, the Food and Drugs Acts and the Pest Control Products Acts for Human Health Risks Assessment, Potential Hazardous Chemicals' Assessment, and Chemical Wastes Prevention. Aforementioned regulations were regarded as the basis for chemical management and it could cover the monitoring, transport, counting and potential risks of all chemical substances (Zidek et al., 2017).

To promote the prevention of chemical wastes in the metropolitan regions, the national zero-waste council has designed a collaborative program on waste management to bridge the government leaders with the academia and non-profitable organizations. Several Canadian local government committees derived both academically and non-academically businesses to seek an integrated solution and to overcome a resource-constrained economy (GC3, 2015), when global competition in the industry towards more greener and safer chemicals is enhancing.

Table 2
International movement of green chemistry on policy implementation from the aspects of governance, industry and education.

Aspects	Countrlies	Policy Implementation
Governance	Canada	• The National Zero Waste Council has lead governments, businesses and non-government organizations to advance waste prevention with the Federation of Canadian Municipalities in 2013. • Government of Canada completed a triage of 23,000 chemicals that had been in commercial use during the previous two decades.
	China	• To develop green technologies, educational and research programs to enhance the content of green chemistry and green engineering both at the national and regional level over twenty years (Cui et al., 2011) • The 11th Five-Year Plan (2007–2011) included the energy policy to targeting for reducing the energy intensity of 20% since 2011, which will be the driving force of decreasing the energy consumption in chemical industry (Price et al., 2011)
	Germany	• The Federal Ministry of the Environment, Nature Conservation and Nuclear Safety has promoted the Sustainable Chemical Policy since 1999. • The "Roadmap for moving to a competitive low carbon economy in 2050" and the "Energy Efficiency Plan 2011" could contribute to a 25% reduction for greenhouse gases emission to conquer the climate changes.
	Japan	• The Japanese energy vision, "Long-Term Energy Supply and Demand Outlook to 2030" was adopted in 2015.
	South Korea	• The Ministry of Environment of Korea established the industrial-academic-governmental platform composed of different representatives in 2009. • The Act on Registration and Evaluation of Chemicals which mainly referred to EU REACH procedures came into force in 2015.
	Sweden	• Swedish Chemicals Agency established the restricted substances database to legislatively show the banning or restraining substances and export of various hazardous substances at the national level. (KEMI, 2016)
	Taiwan	• Taiwanese Environmental Protection Administration has initiated the long-term plans regarding standard registration for existing chemical substances since 2015. • In order to pursue the global trend of green chemistry and to reward parties who have been dedicated to the development of relevant improvement measures and promote green chemistry, Taiwanese Environmental Protection Administration has renamed "Regulations of Governing Rewards for Toxic Chemical Substances Operation". • Taiwanese Ministry of Labor established the Chemical Substance Nomination &. Notification followed by GHS to ensure the chemical security and safety.
	USA	• Through the Safer Detergents Stewardship Initiative, the Design for Environment Program was committed to the use of safer surfactants (Lavoie et al., 2012)
	UK	• The strategy of waste minimization, prevention, reuse, and recycling plays an important role in the efficient energy and resource management within the chemical industry (García et al., 2004). • The Department of Environment, Food and Rural Affairs in the UK invested more resources utilization projects which are estimated that could save up to 23 billion bonds for industries.
Industry	Canada	• The Canada Consumer Product Safety Act applies to suppliers of consumer products, including manufacturers, importers, distributors, advertisers, and retailers.
	China	• The Institute of Process Engineering has established the research and innovative greener chemical processes since 2001 (Ka et al., 2005).
	Germany	• The German government has introduced profitable projects and incremental investments on non-refillable beverage containers by transferring synthesis of chemicals and fuels from hydroxylation of linear alkanes or methane and unsaturated polyester resins
	Japan	• The foundation of Green and Sustainable Chemistry Network was establish in 2000 thereby taking place the research and development at the industry e.g., cell electrolysis, ion exchange membrane for sodium hydroxide production. • The process design comprising the environmental benign was also promoted by the Japan Association for Chemical Innovation.
	South Korea	• The Next-generation Eco-innovation project was launched to promote the related infrastructure and industrial facilities for green chemistry since 2011 (Lee and Park, 2015).
	Sweden	• Industrial investments for bioenergy show a positive trend focusing on manufacture chemicals or materials (e.g., organic products or nanoparticles), processes (e.g., producing methanol from wood) and feedstock (e.g., celluloses for textiles viscose) (Mossberg, 2013).
	Taiwan	• To introduce international exposure assessment technology for chemical grade management by establishing or upgrading the ISO45001 management system. • The establishment of a chemical investigation mechanism assisted in the high-risk chemical distribution in industrial areas, and control the potential of chemical hazards.
	USA	• PUMA have phased-out the usage of long-chain *per*- and polyfluorinated Chemicals since 2015 (ZDHC, 2015).
	UK	• Chemical Industry Association of UK has developed and promoted chemical products stewardship, which is a main responsible on chemical products in the industry to ensure that those hazardous chemicals can be treated appropriately throughout the entire life-cycle (CIA, 2015). • Chemical industries assist the National Health Service to support knowledge of healthcare for workers (DEFRA, 2013).
Education	Canada	• Green Centre Canada can promote the state-of-the-art facilities, highly experienced team of technical training, business model, and intellectual property professionals, and strong relationships with industries.
	Japan	• The Green and Sustainable Chemistry awards competition on the potential contribution of research including education, sports, culture, science, and technology has been developed since 2001.
	Germany	• Sustainable green chemistry has been developed in Germany among technical, environmental, economic and policy aspects since 2010.
	Sweden	• Swedish interdisciplinary research program "Greenchem" aiming to develop the application of renewable feedstock and biocatalysts and implement in various industrial sectors (Tufvesson and Börjesson, 2008). • The education program included the comprehensive chemistry course, laboratory experience and publication while the activities can be expended to research, workshop, technologies and policy aspects (Wang et al., 2018).
	Taiwan	• To develop the green chemistry education promotion program in the Universities to enhance people's environmental knowledge of green chemistry and further enhance their environmental skills and attitudes.
	USA	• Presidential Green Chemistry Challenge Awards was created by USEPA since 1995. • Green Chemistry Institute of ACS has conducted an industrial roundtable for the Pharmaceutical industry, to enable green and engineering into chemical businesses since 2005.
	UK	• The Green Chemistry Centre of Excellence in the University of York is an internationally-technology platform on sustainable chemistry research.

As a result, the Canada Consumer Product Safety Act has been formulated aiming at protecting human health suffering from hazardous substances in the consumer products (Zidek et al., 2017). The act indeed encouraged the use of alternative chemicals to the design and packaging procedure for reducing the environmental impact of the materials. For example, trichloroethylene and tetrachloroethylene which were consumed at more than 1000 kg per year in Canada is being avoided nowadays. The future priority for green chemistry promotion in Canada would be to achieve the higher performance, to formulate a more effective chemical management plan, to build an international green chemistry network, and to develop safer biodegradable chemical products.

2.2. Europe (the United Kingdom, Germany, and Sweden)

In the United Kingdom (UK), the research development on green chemistry towards sustainability has been established in the industries and university over several decades. For example, the green chemistry center of excellence could provide a technical platform for the education, training, and network of green chemistry and formulate a supply chain between the chemical producers, retailers, and consumers. In order to achieve the practical application of green chemistry from the social and environmental aspects, the chain of chemicals and food waste supply has been developed in the relevant industries. For instance, the chemicals from cereal straws could be extracted more feasibly than that of starch-rich wastes by supercritical CO_2, which could be used to produce adhesives for carpet tiles and other consumer goods (Pfaltzgraff and Clark, 2014). In other words, to increase the molecular life-time and potential reuse, biodegradability was regarded as an inevitable trend and an important characteristic of a greener product. For example, some poorly biodegradable compounds such as halogenated products (e.g., dichloromethane solvent) should be necessarily eliminated. By delivering the leadership and decision-making for accident control, hazards reduction and resource utilization, the industries could engage the professional groups in assuring the achievable green chemistry framework (HSE, 2017). On the other hand, the atomic efficiency for synthetic chemistry was observed as one of key factors for waste prevention and resource or energy sustainability, creating the concern of synthetic route, synthetic methodology, chemical process, and selective catalysis. The UK catalysis hub is devoted to increasing UK catalysis research portfolios under the national and international levels. The collaboration between chemists and engineers could contribute to the integration of an innovative solution for efficient catalysis product, thereby increasing the content of the atomic economy. The UK government also announced a zero-waste economic plan for chemical industries to improve the reuse and recycling of metals, textiles, constructions and biodegradable wastes for the circular economy. This action has been speculated as an effective waste prevention strategy for saving 30 Mt. of manufacturing feedstock in the UK by 2020 (Clark et al., 2016). Therefore, the UK government was promoting a circular society to reduce, recycle and reuse waste to achieve resources and energy sustainability, meanwhile, the GCP implementing on governance, industry and academy also presented superior contribution for accident prevention, safety assurance and hazardous material elimination.

The objectives of sustainable chemical policy in Germany were to avoid: (i) persistent or bio-accumulative toxin substances; (ii) carcinogenic or mutagenic toxic substances; (iii) hazardous substances entering into the environment via human activities (UBA, 2009). The ministry was required to understand the environmental impact and human health effect of the chemicals entering into the supply chain. This rule was also applied for the chemical and pharmaceutical processes to assure the safer chemical substances within the green chemistry concept. The relevant institutions of Germany on green chemistry are as follows:

(i) DECHEMA (Gesellschaft für Chemische Technik und Biotechnologie): To establish an evaluation framework for eco-friendly sustainability of a chemical product using GCP and to strengthen the application of green solvents and catalysts, such as ionic liquids and supercritical reaction materials;
(ii) German Chemical Engineering Association: To increase the safety requirements of chemical manufactures and transportation and to reduce the application of raw materials and energy;
(iii) German Federal Environmental Foundation: To promote the environmental protection programs in the chemical industry;
(iv) German Federal Environmental Agency: To develop an information exchanging network on chemistry, environment, and energy sectors (Steinhäuser et al., 2004);
(v) German Federal Institute for Occupational Health and Safety: To develop the chemical categorization scheme and to strengthen the inherent safety at work-places based on clear classification and labelling.

The aims of the above organizations are to establish the chemical management, to increase the inherent safety quality, and to build the technical and cleaner measures. Thus, the German Federal Environment Agency has launched the action plans for sustainable green chemistry including the resource-saving manner, avoidance or minimization of chemicals, comprehensive life-cycle assessment for chemical products and economic innovation since 2004. A comprehensive evaluation framework for a sound chemical management in Germany followed the REACH regulation to facilitate the development of non-hazardous alternatives and substances management. Interdisciplinary theoretical and work-sharing collaborations were essential for the establishment of sound chemical management and sustainable green chemistry. For example, the waste prevention program under existing chemical management framework ensured the resources materials to be more coherent and sustainable by waste utilization (Poliakoff et al., 2002).

In addition, the Germany government referred to the European union biodiversity strategy to 2020, aiming to increase the biodiversity for the environment and the biodegradation of chemical products. The important synthetic intermediates and commercial fragrances were obtained by the development of photoactivation and photooxygenations with the minimal fossil fuel consumption (Beach et al., 2009). For example, some derivatives from chitosan could be applied as ingredients both in cosmetic and pharmaceutical products (Luz et al., 2013). The toxicological test mainly on complexity assessment of lead chemicals for battery product has been developed in Germany over a decade. To further qualitatively and quantitatively evaluate its potential of molecular interaction, shape and conformation flexibility, and chemical and biochemical reactivity, the risk of hazardous release, bioaccumulation, biological activity, and uncertainty was analyzed at a multidimensional scale (Jakl et al., 2004; Jastorff et al., 2005). Moreover, the utilization of catalysis and enzymes as fertilizers and agricultural products could not only reduce the nitrous oxide emissions but also improve the green agriculture and food security (Schomburg et al., 2017). To substantially eliminate the discharged pollutants, the chemical industries have developed the monitoring programs to enhance the profitability of chemical processes (Duijm et al., 2008). The preventions for accidents and incidents were the fundamental elements for workers' security and safety in the chemical plants (Doytchev and Hibberd, 2009). The development of green chemistry or sustainable chemistry has been successfully deployed in Germany.

The Swedish government was promoting the chemical substance management within GCP at the domestic or international levels. Under the REACH framework, the Swedish textile industry was developing a list of restricted chemical substances on the basis of legislation. It could simplify the complicated procedure from passives to voluntary initiatives and provide a coherent communication pathway (KEMI, 2014). Furthermore, the Swedish government has promoted a long-term energy policy regarding the development of domestic renewable energy and renewable feedstock supply chain, which accounted for 28% use of renewable feedstock in 2009 (Dahlbacka, 2009). The Swedish government also provided the tax relaxation for the industries using ethanol and bio-diesel, which are unable to compete with fossil fuel without economic incentive (Dahlbacka, 2009). By improving cell or enzymes development, the industrial biotechnology could fulfill some GCP such as increasing energy efficiency, using renewable feedstock, preventing wastes, enhancing selective catalysis, and promoting biodegradable chemicals. In 2010, the share of biotechnology processes in the chemical industry was estimated 20%, which initiated the sustainable chemistry 2030 program in Sweden by leading a fossil-independent economy, enhancing the use of alternatives and bio-based feedstock, and establishing industrial symbiosis in 2030 (Grahn and Hansson, 2015). The potential biofuel production in Sweden has grown up, expecting 18 TWh per tons of fuel in 2023 (Grahn and Hansson, 2015). Currently, the Greenchem program in Sweden leads the vision and action plans towards green chemistry and circular economy: (i) the development and deployment of renewable raw materials and energy, (ii) the promotion of renewable chemical and material products for biodegradation, (iii) the application of renewable vehicle fuels, (iv) the enhancement of resource and energy efficiency (Greet Overbeek et al., 2016), and (v) strengthening of inherent safety on chemical processes and products (Abedi and Shahriari, 2005).

2.3. East Asia (China, Japan, and South Korea)

The regulation of imports and exports for toxic chemicals and new chemical substances management in China began in 1994 and 2003, respectively. China also joined the international treaties including the Rotterdam Convention for Pesticides and Hazardous Chemicals and the Stockholm Convention for the Persistent Organic Pollutants (Wang et al., 2012). To propose an innovative solution for dealing the conflicts between economic growth and environmental protection, the green chemistry and green engineering were important concepts to systematically evaluate the chemical process and products in the entire life-cycle (Matus et al., 2012b). The green chemistry and green engineering community were highly developed in an academic-industrial community which could extend the engaging work in different sectors. Nearly 20–25% of the research subsides in chemical engineering for green chemistry projects was accounted for organic and physical chemistry.

In 2007, China chemical management was insufficient including the non-clear national policy, incomplete laws and regulations, inadequate administration and capacity building, lack of public participation and absence of technology supports, reported by China council for the environment in 2006 (Hu, 2007). The Ministry of Environmental Protection launched the first long-term plan for chemical management in 2011. Green chemistry could contribute to the scientific methods for higher energy efficiency, pollution prevention, and better economic benefit. Therefore, the economic incentives, policy drivers, and technology development related to green chemistry have been implemented in China. It was demonstrated that the governance priorities would emphasize green energy for improving the energy efficiency and thereby supporting the novel green chemistry and engineering research.

Japan has focused on the development of technology in the green chemistry field since two decades ago. Information system, educational program or workshop, and international activities were built to encourage individual institute or company to compete the green and sustainable chemistry award. To promote the management of chemicals more effective, the Japanese government has constructed the information platform. The inter-ministerial GHS committee was launched in 2001, transferring the United Nation Standards to Japan. The surveys on chemical substance practices for hazardous materials listed in the Pollution Release/Transfer Register was conducted on the basis of the domestic chemicals database. By establishing the GHS domestic laws, the classification of chemical substances, the implementation of exchanging information and the quality of industrial safety and health could be promoted. The related regulation such as the Chemical Substance Control Law was improved and modified. The Chemical Substance Control Law stipulated the existing chemical substances via monitoring and reporting. In addition, the new chemical substances would be reviewed by priority toxin assessment. In addition, the strategic energy plan was initiated to reduce the energy consumption in the chemical industry. The policy makers and industries focused on the resource cycle for chemicals. For instance, the Chiyoda's CO_2 reforming process was well developed to convert CO_2 to synthesis gases to be used in conventional steam-reforming processes (Yagi et al., 2005).

In Korea, in order to strengthen the regulation on hazards and risk controls as well as to improve the chemical management system in chemical industries, an integrated approach for chemical management combining GCP was proposed. The "health and environmental protection" and "improvement of the chemical industry competitiveness" were two objectives for a sound chemical management. Accordingly, moving green chemistry to a direction of "green shift" in various regions included the reducing risk of hazardous chemicals, managing people's health, alleviating the environmental impact, and building the communication and cooperation system. The project of next generation eco-innovation was a comprehensive research providing green chemistry support system and related chemical information to organization, company and government. Meanwhile, the transformation of chemical techniques and assessment of international chemical regulations could support the small and medium businesses. The authorization of the Ministry of Environment would implement the evaluation and risk assessment of registered hazardous chemicals under "Act on the Registration and Evaluation of Chemicals" (K-REACH). Similar to REACH, the registered chemicals which were designated as banned or permit-required shall be substituted by alternative materials or technologies to eliminate their hazardous impacts on the environment, economy and society. In addition, the current existing toxic chemical act is focusing on the control of hazardous substances and the prevention of chemical accidents as well. Above descriptions conveyed that South Korean government was developing a sound chemical management towards a green chemistry framework.

In Taiwan, the promotion of GCP practice has been deployed at governmental, industrial and educational field. For example, Taiwanese Environmental Protection Administration has planned a long-term project to manage the existing and high-concerned chemicals followed by the GCP. The international exposure assessment technology for chemical grade system was also developed to reduce the high-risk chemical distribution in industrial areas. In addition, a green chemistry educational program was implemented in the colleges to strength the professional knowledge of green chemistry.

3. Promising vision for GCP: prevention assurance sustainability (PAS) principle

Green chemistry and sustainable chemistry have mainly focused on designing safer chemicals, utilizing renewable feedstock and increasing energy efficiency towards the sustainable development. As shown in Fig. 1, novel definitions of GCP were proposed as follows; (i) pollution and accident prevention, (ii) safety and security assurance, and (iii) energy and resource sustainability. By integrating the last word of each part, the prevention-assurance-sustainability (PAS) principle was developed. The current implementation level of GCP could be easily indicated in the PAS, which could be commonly applied for further comprehensive evaluation. The PAS was created from three round structures, which indicated the cross relationships between GCP. The cross-sections were estimated as GCP #5, #9, and #10, meaning that the implementation and application could be integrated into various regions. The middle part was the core issue of PAS combining all GCP. Although each GCP would not be located at the specific position in the PAS circle, it could be a promising idea to gain a better understanding of the green chemistry.

3.1. Pollution and accident prevention

GCP #1 (Waste Prevention), GCP #3 (Less Hazardous Chemical Synthesis), and GCP #8 (Reduce Derivative) were the main aspects in the "Pollution and Accident Prevention." The definitions of GCP #1, #3 and #8 represent the prevention of waste production, elimination of non-toxic substance to human or environment, and minimization of the unnecessary derivatization in the chemical process. The essential element of a waste prevention level is to measure the content of wastes discharged from the chemical process by using the metrics including the E (Environmental)-factor (kg wastes/kg products) (Sheldon, 2007). It was defined as the mass ratio of waste to desired outcomes and Sheldon firstly organized the *E*-factor in the chemical industry in 1992 (Sheldon, 1992). The higher E-factor represented more wastes and thereby contributing to more negative environmental impacts. The ideal E-factor equals to zero, achieving the goal of zero waste in the plants. Other mass-based metrics to quantify the environmental impact of chemical wastes included the reaction mass efficiency, effective mass yield, waste water intensity, solvent intensity, and mass intensity (Constable et al., 2002; Curzons et al., 2001).

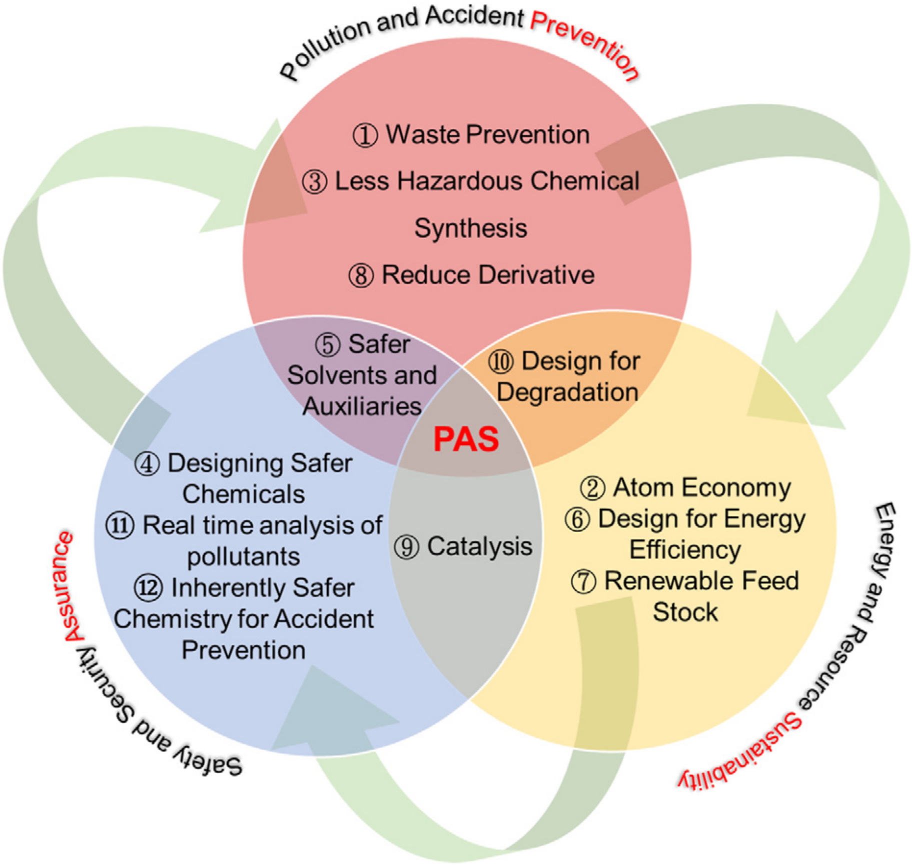

Fig. 1. The framework of Prevention-Assurance-Sustainability elucidating green chemistry principles.

Due to the diversified definition and metrics, the Green Chemistry Institute of Pharmaceutical Round Table redefined the Process Mass Intensity (PMI) metrics, thereby involving the water, solvent, and materials utilization. PMI could be the benchmark of the environmental footprint and the green content in the process, which were widely utilized in the pharmaceutical industry (Jiménez-González et al., 2013; Jimenez-Gonzalez et al., 2011).

However, the E-factor has been used for cleaner process design for zero waste discharge, which is the primary driving force to develop green chemistry (Sheldon, 2017). The quantitative waste reduction could not be immediately reflected (Jimenez-Gonzalez et al., 2011) due to the fact that PMI would further concern about the cost of raw material-input and process design. In our opinion, the waste prevention would be the main criteria in GCP. The cleaner and greener process could ensure the safer workplace due to low occurrence rates in waste treatment. Furthermore, GCP #5 (Safer Solvents and Auxiliaries) and #10 (Design for Degradation) were linked for pollution and accident prevention, and these two principles required to be firmly assessed via lifecycle approach. The solvents and mass separation agents could provide the energy and materials transfer in the process. In other words, the wastes reduction via safer and greener degradation design could be achieved by using the suitable auxiliaries in the chemical reaction.

3.2. Safety and security assurance

GCP #4 (designing safer chemicals), #11 (real-time analysis of pollutant), and #12 (inherently safer chemistry for accident prevention) are the critical elements for “Safety and Security Assurance”. It meant designing safer chemicals products and processes by reducing the hazards and toxicity and the assurance of worker's security by preventing accidents. For chemical substance management, minimizing the toxicity and maintaining the efficacy might be significant challenges for the design of safer product and processes. Usually, designing safer chemicals required understanding the chemical, toxicity, and physical characteristics and associated risks. Anastas and Warner (2005) clearly defined the hazards of different levels for chemical manufacturing sectors and proposed some advantageous methods for developing the design of safer chemicals viz. (i) better technologies for the hazard treatment at a molecule level, (ii) enhancement of toxicity tests to decrease the hazard, (iii) financial benefits of more favorable hazard elimination, and (iv) lower environmental impacts (Anastas and Warner, 2005). However, safer design could not be achieved without the knowledge of chemical structure. The real-time monitoring system for process analysis was necessary to determine hazards or toxicity of the chemicals. The monitoring method could be divided into in-line, on-line, and at-line in a chemical plant. Such analysis could not only instantly detect the changes of parameters (e.g., pH value, gas flow rate or temperature) prior to the process become unstable but also precisely prevent the leakage of hazardous chemicals.

The real-time monitoring technology played a vital role in accident prevention and safer workplace. GCP #12 was the essence of green chemistry, contributing to safer and healthier chemical products and processes. Toxin releases, risk explosions, and fire occurrence were the three major concerns when considering the safety and health in a chemical plant (Sneddon, 2016). Therefore, by involving the engineering control (i.e., green engineering) into GCP, the elimination of unwanted chemical substances could be achieved.

3.3. Energy and resource sustainability

Promoting the value of energy and resources is the key issue for sustainable development. Among GCP, minimizing the energy consumption and maximizing the energy intensity is the primary target. In other words, the most manufactured goods could follow this golden rule in GCP #6 (design for energy efficiency) at a single chemical process along with their production route (IEA, 2013). From a life-cycle point of view, wasted-energy stream could be utilized for cooling, heating and work, creating huge opportunities to reduce energy consumption.

Most energy consumptions were occurred in chemical separation and purification. Renewable feedstocks attracted higher interests for reducing environmental issues, promoting economic growths and increasing energy diversity in decades (BR&Di, 2006). The development of fuels, chemicals, and materials from renewable feedstocks had several significant advances. For example, biodiesel could be produced from plant oils and algae. Bioethanol and butanol could be generated from sugars and lignocellulose, thereby producing bioplastics, foams, and thermosetting materials. Therefore, GCP #7 (use of renewable feedstock) represented that chemicals and materials from renewable feedstock could contribute to the better and brighter chemical process with a higher energy efficiency and a lower environmental impact.

However, the entrepreneur always looks forward to the cross-discipline economic incentives. GCP #2 (atom economy) could elucidate the efficiency of a chemical reaction by calculating the product yield, representing a green paradigm shift in terms of the content of reactants converting into the desired products (Trost, 1991). The key element to achieve a better atom economy is reaction catalysis which could provide an alternative pathway involving lower energy transition and activation barriers (Rothenberg, 2008). Atomic economy, as the intrinsic efficiency of a balanced chemical reaction, could also identify the conceptual design for chemical synthesis in green chemistry and the idea of 100% atomic economy would be an ultimate goal for the greenest process (Dicks and Hent, 2015). On the other hand, the design of resource efficiency is another essence in GCP #2. Some critical issues including climate change, clean energy, industrial innovation, and circular economy are substantially connected to GCP #2, #6, and #7, when people have raised the interest in the green economy and sustainable development. Model transformation from the linear flow of resource utilization to the greener and circular one could seek a higher resource efficiency via the redesign of product and processes (European Commission, 2011). However, the development of a circular economy from a traditional linear economy has been facing barriers and challenges from regulatory, institutional and financial aspects. However, the economic assessments should establish 'take-make-use-dispose' production chains to include the cost-effectiveness and social acceptance for resource utilization/depletion, waste management plan, and environmental pollution control (Sheldon, 2016). To sum up, the shift towards the energy and resource sustainability required (i) accelerating the GCP practice, (ii) improving the energy and resource efficiency, and (iii) developing sustainable production chain via redesign and regeneration.

3.4. Summary of prevention assurance sustainability (PAS) concepts on green chemistry

The definition of PAS principle clearly depicts the green chemistry by integrating the 12 GCP. The green chemistry is a dynamic area, where transformative changes depend on various sectors and factors such as environmental issues, labor security, availability of energy and resource, chemical synthetic process, and economy. In the chemical or pharmaceutical industry, green chemistry or sustainable chemistry could represent a wide range of cross-disciplines. Considering the 12 GCP in PAS circle, GCP #5, #9, and #10 can represent the definition in both two areas. For instance, safer solvents and auxiliaries (GCP #5) can present not only the lower environmental impact from the life-cycle point of view but also the better process safety. It is noted that choosing the appropriate solvents and auxiliaries means achieving the optimization of chemical process and reduction of toxic and polluted by-products (Jessop, 2016). Catalysis (GCP #9) can depict the energy requirement by minimizing the enormous amount of wastes. Moreover, to fulfill the commercialization, the design for the degradation of the chemical product (GCP #10) via biodegradation, hydrolysis, and photolysis is necessary for lifetime and end-of-function consideration (Scott and Lee, 2016). Therefore, the PAS principle would create the cross-disciplinary ranges for prevention, assurance, and sustainability to increase the understanding of policy implementation and public awareness for GCP.

4. Strategies on implementation of Green Chemistry principles towards a circular economy

Integration of GCP in the circular economy can facilitate the development of sound chemical management. The achievable GCP practice can generate a circular economy to build a strong connection between producers, manufacturers, consumers, and designers. Fig. 2 shows the three stages of integrated GCP and a circular economy under PAS principle. For the feedstock extraction, the recycling and reclamation of renewable feedstocks could fulfill the GCP #1, #2, #3, #4, #5, #6 #8, #11, and #12 efficiently. The rethinking of recirculation of the chemicals with a life cycle assessment cannot only reduce the environmental impact but increase the social economic benefits (Linder, 2017). The feedstock utilization plays an important role in the manufacturing of the products and design. Some defective products are considered for reuse or recovery by contributing the prevention of wastes. At this stage, the chemical product designers have to increase the use of safer and more energy efficient solvents and auxiliaries. Finally, the environmental and economic benefits of chemicals related to the services or goods have to be constructed by establishing a comprehensive business model. Both energy efficiency and chemical safety are the major concerns for the PAS principle. To achieve GCP practice in a circular economy, the strategies of priority governance direction (PGD) could be integrated into (i) cross-departmental collaboration, (ii) development of cleaner production technology, (iii) establishment of integrated chemical management, (iv) implementation of green chemistry education, and (v) construction of a business model and supply chain, as described below.

4.1. Establishment of cross-departmental collaboration

Development of green chemistry requires effective governance, policies, frameworks and tools under a cross-departmental collaboration. The promotion of GCP practice in an environmental agency can focus on the environmental protection, safer chemical substances, and pollution prevention and reduction. Other assignments such as management of industrial chemicals, labor security, real-time monitoring system, and green chemistry technology can be classified to the industrial or economic department. To clarify the responsibility attribution to GCP deployment, the policy frameworks within an individual authority would be established under strong policy incentives and a clear regulatory framework (Scruggs et al., 2014).

Fig. 3 shows the governmental framework of green chemistry and the circular economy in Taiwan. Normally, the environmental protection agency (EPA) charges on waste prevention and less hazardous chemical synthesis. EPA and the Ministry of Economic Affairs could establish a platform for less hazardous chemical synthesis and design for energy efficiency. The Ministry of Economic Affairs could also collaborate with the Ministry of Finance for a green chemistry business model related to the atomic economy. Regarding to safer solvent, auxiliaries, and chemicals, the Ministry of Labor, the Ministry of Finance and the Ministry of Health and Welfare could propose some policy implementation for labor security and insurance and the toxic chemical management to assure the safety performance. In addition, the education and research development is under the governance of the Ministry of Science and Technology and the Ministry of Education. In this part, the catalysis, reduced derivative, and design for degradation are required to concentrate on the basic research and educational project in the

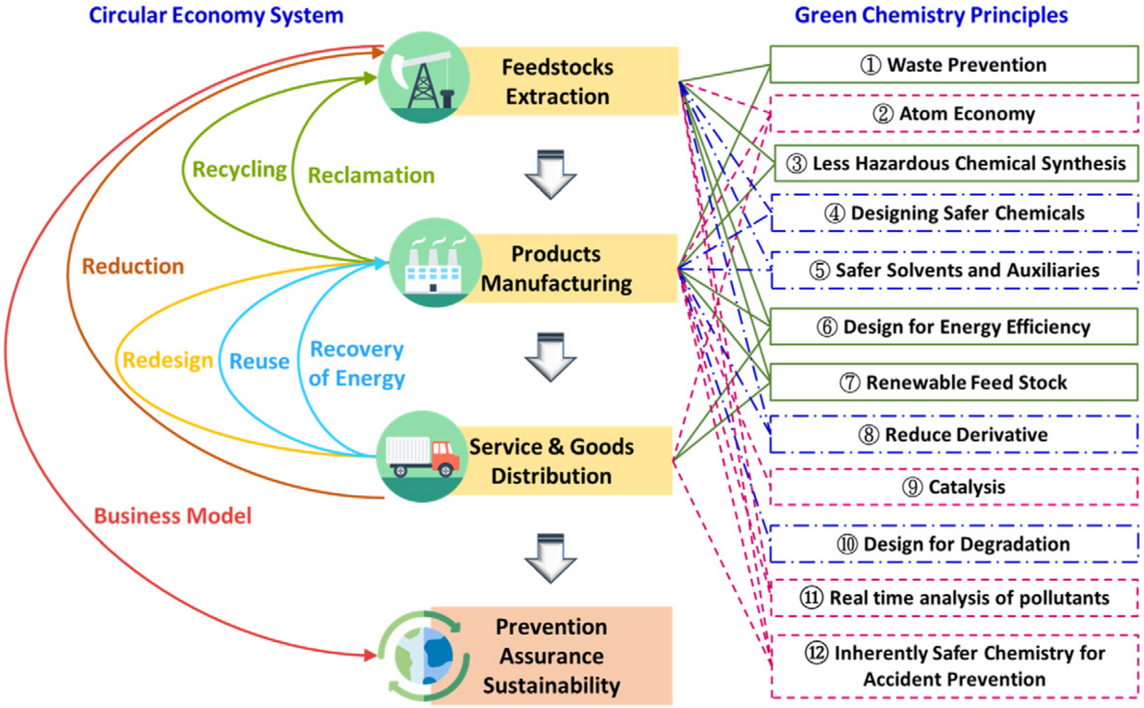

Fig. 2. The structure framework of green chemistry principles and circular economy in the entire life cycle.

universities. Moreover, the renewable feedstock sources for green chemistry are generated from agriculture and biotechnology, which is under the guidance of agricultural sectors. The related authorities might propose the clear objectives and sound plans on GCP practice. Each sector had to keep reviewing the national policies to ensure long-term reliability, security and sustainability. Therefore, a cross-department collaboration framework could be consistently established following the PAS principle.

4.2. Development of cleaner production and green products

The integration of green chemistry and cleaner production results from the innovative engineering design of scalable processes, products, and systems. Anastas and Zimmerman (2003) proposed 12 green engineering principles (GEP) that were not only a framework bridging between designers, producers, and consumer but also a methodology for green design and sustainability. GEP can provide a useful tool to optimize the entire process from the molecular to system level. The use of materials and energy in the entire system have to consider their life cycle and natural inherency in order to make products more environmental-friendly. For example, Hong and Chen (2017) reviewed the strategies of waste polymer recycling towards a green polymer product. The suitable depolymerization process can reclaim the biomaterials such as amino acids, carbohydrates and nucleic acids and the application of recyclable polymers should concern the high cost and energy consumption issue.

Table 3 illustrates the cross-connections among green engineering, green chemistry, and PAS principle. For example, GEP #1 refers that energy and materials inputs or outputs will be inherent and nonhazardous, which are similar to GCP #1, #3, and #8. Although only GEP #7 can be classified into the safety and security assurance in the green engineering framework, the systematic integration of those GEP is an essential approach for accomplishing the cleaner production. It should be noted that, however, green chemistry and green engineering are only generated as part of the scientific solutions for cleaner production. It would inevitably create strong interaction with end-users and markets. GCP and GEP can be emerged as a tool or a guideline to reconcile the real situations for the production of cleaner chemicals to reduce the hazards and wastes associated with the chemical enterprise and consumers. Integration of green chemistry and green engineering towards prevention-assurance-sustainability can simultaneously accelerate the economic growth and the reduced environmental and social impacts.

Furthermore, a sustainable or green product indicates the development of products aimed to comprehensively improve the environmental and social quality (Seuring and Müller, 2008). In order to develop and deploy the green products, some useful analytic tools such as design for environment and design for disassembling and life-cycle approach have been used (Albino et al., 2009; Kara et al., 2014). Green design can define the combination of modern science and technology via innovative ideas for eliminating the ecological and environmental destruction (Zhang, 2017). Krishnan and Zhu (2006) proposed the development of intensive products by determining the product quality in the R&D process, and the equipment and facility could identify the greenness level of different industries. The main fixed-cost can be attributed to the functional design in the greenness level rather than the variable cost. For example, the investment in the chemical processing or production is the major cost in chemical industry while the distribution or treatment cost sometimes accounts for only a small proportion in the entire life cycle. In the pharmaceutical industry, the greenness level depends on the product or design processing that can reduce the main source cost and the distribution cost of products. On the other hand, raising the pollution tax can encourage the implementation of the green product (Eichner and Pethig, 2003). Regarding to assessment, the application of multiple life-cycle analysis, fuzzy logic tools, analytical network processes, and a decision-support model for performance evaluation of green product or design would involve the supply chain, markets, and economic factors (Wang et al., 2017). Therefore, to foster the development of green chemical products, the priority research direction could focus on policy measures, marketing strategies, functional design, purchase-behavior, and integrated chemical management system.

4.3. Provision of an integrated chemical management system

The integrated chemical management system (ICMS) is defined as a cross-disciplinary coordinated framework to manage chemicals for risk

Fig. 3. Governmental framework for GCP-based green chemistry and circular economy exemplified by Taiwan government.

minimization, hazardous pollution reduction, and precautionary mechanism assurance (Cousins et al., 2016). The key components such as real-time monitoring, centralization of chemical storages, workplace training, and chemistry education can be included. The GCP practice can result in successful integrated chemical management. Due to numerous instruments and processes in chemical industries, strategic approach for developing the ICMS would assess the content of material/energy flow, the entire life cycle of products or processes, the performance of multi-sectoral and international cooperation, and the finance. The ICMS would be designed as “fit-to-purpose” application that can be suitable for various sectors in the real world. For instance, the idea of coupling industrial ecological park to green chemistry, which would facilitate the greener process and integrated chemical management, was proposed in Shanghai (Yune et al., 2016). In this case, the integrations of (i) product, (ii) public utilities, (iii) logistics, (iv) environmental protection and safety system, and (v) public and service management were applied to the establishment of chemicals supply network. The ICMS can provide a symbiotic network-approach for the determination of chemicals and by-product values, such as catalyst recycling, acid or base recovery, reclamation of wastewater and utilization of waste-heat or pressure from a different process.

In order to confirm the systematic development of ICMS, the GCP practice framework would be implemented for the defect of regulation on prevention of chemical hazards, pollution, and leakages in the different sectoral areas. As shown in Fig. 4, the framework of GCP practice on an ICMS is suggested to follow the Plan-Do-Check-Action (PDCA) principle. The four stages of PDCA principle comprised: (i) development of design and planning, (ii) deployment and implementation, (iii) performance evaluation and impact assessment, and (iv) response and rolling amendment. In the beginning, the long-term goals and vision are established to identify the domestic capacity of key technologies and build up the new market mechanism. In the second stage, the practical financial and business model should be established through the development of the cross-departmental cooperation. Also, the research on innovative technologies for cleaner production has to be deployed. It is noted that some crucial elements, including the participation of local communities and non-government organizations for consultation and cooperation, should be involved. Then, the management plan can be assessed for performance and impact of current chemical-related activities. In this stage, the evaluation on the level of the public awareness and knowledge of green chemistry is an important measure. The educational workshop and electrical announcement for the policy implementation might be conducted via clear documents or video materials. The information technology (such as a real-time monitoring system) can also play an important role in the establishment of performance indicators, accurate and precision measures and appropriate analytical methods. Finally, the response and rolling amendment action such as risk assessment, modification of the proposed plan and establishment of green commerce council are necessary for a complete ICMS.

4.4. Implementation of green chemistry education program

Green chemistry education is essential for sustainable development. A dynamic cross-disciplinary education framework transforms science, engineering, and technology to sustainability consciousness by serving GCP. Collins (1995) proposed a strategic education program, so-called “Chemistry and Sustainability (C&S)”, to reflect the educational framework based on the science, engineering, and technology for the

Table 3
Cross-connection among GEP, GCP and PAS principle.

GEP	Related to GCP	Related PAS Practice
1. Inherent rather than circumstantial	1. Waste Prevention 3. Less Hazardous Chemical Synthesis 8. Reduce Derivative	• Pollution and Accident Prevention
2. Prevention instead of treatment	1. Waste Prevention	• Pollution and Accident Prevention
3. Design for separation	9. Catalysis 10. Design for Degradation	• Pollution and Accident Prevention • Energy and Resource Sustainability
4. Maximize mass, energy, space, and time efficiency	6. Design for Energy Efficiency	• Energy and Resource Sustainability
5. Output-pulled versus input-pushed	9. Catalysis	• Energy and Resource Sustainability
6. Conserve complexity	2. Atom Economy 7. Renewable Feed Stock	• Energy and Resource Sustainability
7. Durability rather than immortality	4. Designing Safer Chemicals	• Safety and Security Assurance
8. Meet need, minimize excess	3. Less Hazardous Chemical Synthesis 8. Reduce Derivative	• Pollution and Accident Prevention
9. Minimize material diversity	10. Design for Degradation	• Pollution and Accident Prevention • Energy and Resource Sustainability
10. Integrate local material and energy	7. Renewable Feed Stock 9. Catalysis	• Energy and Resource Sustainability • Safety and Security Assurance
11. Design for commercial "afterlife."	2. Atom Economy 6. Design for Energy Efficiency	• Energy and Resource Sustainability
12. Renewable rather than depleting	7. Renewable Feed Stock	• Energy and Resource Sustainability

chemistry field towards sustainable development. In principle, the objectives of C&S curriculum for students include; (i) how sustainability ethics can be applied for chemistry; (ii) framework for strategic sustainable development (Robèrt et al., 2013); (iii) the applications of green chemistry principles; and (iv) the relationship between environmental sustainability and chemistry science. The C&S course materials in green science and technology should be implanted for schools and the public, including on-line videos (Collins, 2015). The C&S program can translate into an appropriate subject and the essential element for the green chemistry education. Although it is not easy to present all elements of sustainability to students, better delivery of the key concepts can be achieved via critical discussion and thinking. Reasonable assertion of sustainability would then be held for the entire civilization.

Oher examples of nontraditional green chemistry courses were launched at Westminster College. On the basis of green chemistry concepts and their inherent necessity, undergraduate students could learn how to apply GCP practice in chemical industry through case-study discussion, journal articles, and a final project in a green chemistry educational module (Kennedy, 2015). This dynamic design creates a novel educational approach to real applications of green chemistry. The green chemistry concept also should be educated in high schools or technical schools. For instance, the Green Chemistry Creativity Competition has been organized for high school students in Taiwan over a decade. Students are challenged to propose innovative ideas of experimental designs based on GCP, such as reduction of derivatives or wastes, energy efficiency, and utilization of renewable feedstock. Aforementioned are good educational models and experiences for green chemistry education framework. Excellent curriculum objectives, course logic content, teaching method, competitive activity and teaching quality could provide an appropriate dynamic modification for educators.

4.5. Construction of business models: waste-to-resource supply chain

The movement of chemical industries towards a circular economy implies an important change in the modes of traditional chemical businesses. Normally, chemical suppliers want to increase their sales volume and satisfy the consumers' demand with more products sold to raise the revenue. This traditional business model is not only generating negative environmental impacts but also accelerating the resources and energy consumption. To change this culture and operation mode, a revolution is required. A new business model named Chemical Leasing (ChL) can provide an approach to sustainable development (Geldermann and Hesse, 2010), which has been implemented since 2004 in Europe. United Nations Industrial Development Organization

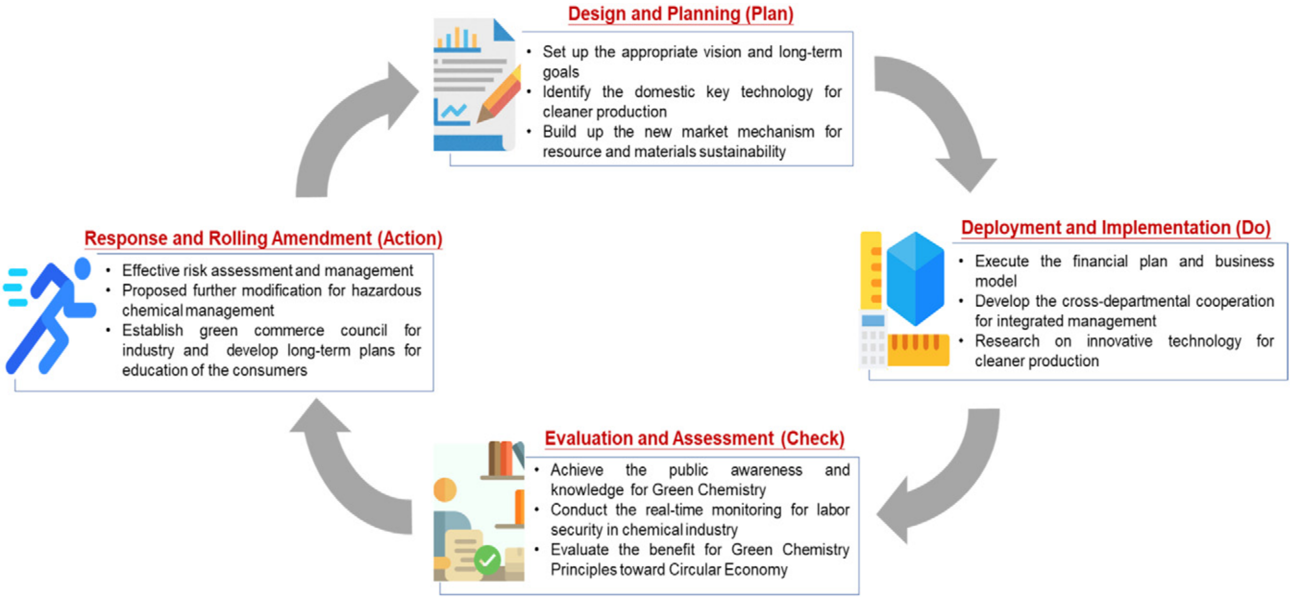

Fig. 4. ICMS for the chemical industries in accordance with PDCA principle.

(UNIDO) defines ChL as a service-oriented business model transferring from the enhancement of chemical sales volume to a high-efficiency value approach. The producer can sell the chemical's functions and service to fulfill the consumers' demand without raising the payment per volume (Schwager et al., 2016; UNIDO, 2016). ChL is a practical and economical approach, demonstrating the minimization of chemical hazards and pollution and providing an economic incentive for the development of different marketing plans. The responsibility of the chemical suppliers or service providers includes the management of the entire life cycle, reduction of the risks of hazards, and assurance of human health. A successful ChL practice can broaden the social responsibility of incorporating environmental, social, and economic aspects (Moser et al., 2014). The participating companies can improve their performance in environmental protection, social image and economic benefits by planning the proper benefit sharing, regulating the quality standard, and remaining the mutual trust with the customers (UNIDO, 2015).

ChL has already been successfully demonstrated in various industrial sectors, such as agricultural and color industry (Wang et al., 2012), oil & gas upstream industry (Matus et al., 2012b), and car manufacturing, textile, petrochemical and printing industries (UNIDO, 2011). It is a key solution for chemical-related industry to contribute to the circular economy system (European Commission, 2014; European Commission, 2018). However, the ownership, partnership, and responsibility in ChL projects for waste treatment and resource distribution have not been completely addressed. ChL is also facing some challenges including the technology to transform a vendor to service supplier, the readjustment of user habits in terms of contracts, accounting, and responsibilities (Lozano et al., 2014), and finally the legislation, knowledge, and public acceptance (OECD, 2017). To identify the feasibility of a ChL model, a comprehensive performance evaluation program using numerous effective methodologies such as Delphi method (Heintz et al., 2014) and an analytical hierarchy process (Kim et al., 2015) is required to facilitate the chemical management.

Besides a successful business model, the accomplishment of the circular economy system is required for the establishment of waste-to-energy (WTE) supply. To build WTE supply chain, “5R practices,” principles (Pan et al., 2015) i.e., reduction, reuse, recycling, recovery (energy), and reclamation (land) were also necessary, which were highly related to the circular economy concept. The WTE supply chain can provide a simultaneous method tackling the issues in energy demand, resource efficiency, waste prevention and chemicals management. The WTE supply chain could also offer a multi-waste treatment pathway for different types of chemical wastes.

In order to systematically develop a holistic chemical management plan over their entire lifecycles, policy makers should consider how to connect the business model (i.e., ChL model) and the industrial supply chain (i.e., WTE supply chain). As shown in Fig. 5, the green chemistry can be implemented by connecting the WTE supply chain based on the fundamental chemical consumption to a ChL model. The effective circular economy system in chemical industry should be based on GCP to achieve PAS principle. The concept of PAS principle involves the resources and energy utilization for the development of the WTE-supply chain. Consequently, good practices of a business model, wastes to resources supply chain, policy framework, comprehensive educational system and technologies development can be supported.

5. Perspectives and prospects

The conventional chemical industry is reproved for environmental quality degradation and natural resource depletion due to its anthropogenic activities. The GCP was an essential component of the transition from a linear economy to a circular economy by effectively utilizing the natural resources and energy towards sustainable development. The perspectives and prospects on the GCP towards a circular economy include 5R (redesign, reduction, recovery, recycle, and reuse) practices of the circular economy, establishment of water-energy-food (WEF) nexus with GCP and development of green smart chemical industry.

5.1. Establishment of 5R practices for waste reclamation towards circular economy

In order to develop a circular economy in chemical industry, the framework of sustainable material management (SMM) can be applied for resource and energy recycling (e.g., chemical wastes and waste energy). As a systematic approach, SMM seeks to promote the sustainable use of materials and products over the entire lifecycle to reduce environmental impacts while considering the economic benefits. To integrate GCP and the circular economy, the substantial business model with a high efficiency and sound management is necessary. To increase the efficient application of resources under the SMM framework, the comprehensive planning, strict evaluation system and effective management programs should be implemented, e.g., the green “servicing” business models, including goods rental, goods share and service guarantee for waste prevention. The extended producer responsibility for multi-scale analysis would be taken into account to manage materials and products on a life-cycle basis. In addition, the green design and green supply chain can promote the development of the high value-added product. The national governance framework for a new waste management policy at each stage of products and service would be specifically stipulated.

5.2. Development of water-energy-food (WEF) nexus framework with GCP towards sustainability

The critical connection of water resource, energy efficiency and food production could be affected in chemical manufacturing process. WEF nexus with GCP would be considered for the future development of circular economy in the chemical industry. Due to the inextricable relationship between water, energy and food, the chemical manufacturing processes have some impacts on each part. For instance, the resource recovery from wastes food supply chain could produce bio-based chemical and bioenergy (Avtar Matharu et al., 2018). Fig. 6 shows the relationship between WEF nexus and the PAS principle, water supply, food security and energy efficiency could be connected based on concept of PAS. The water resources and water reclamation were grained to lead a great concern in the chemical and agricultural sectors. The huge amount of water utilization could cause an insufficient water supply. Similarly, the amount of energy to produce water, chemicals and food could be a significant issue. The energy efficiency could affect the quality and quantities of water, chemicals and food. Higher energy consumption could reduce the resources efficiency, resulting in impacts on environmental pollution and climate change. The implementation of GCP with green process engineering (including maintenance) could enhance energy-resource efficiency, water reclamation effectiveness and food-security assurance by forming WEF nexus. Thus, integrating GCP practices into several sectors is a green option for water resources and food security to achieve sustainability. Also, GCP practices could connect to potential business markets, including food/agriculture, cities, and energy/materials. The decision-making criteria of GCP with WEF nexus framework are crucial in the establishment of inter-sectoral collaboration, soundness of chemical management, promotion of cleaner production technology and educational program, and integration of smart technology.

5.3. Implementation of GCP and smart technologies for green smart industrial park

Recently, the concept of “green smart industrial park” has been proposed, which is defined as an industrial park equipped with information and communication technology (ICT) services. Different from the traditional management system in the chemical industry, the green smart industrial park emphasizes the industrial information system and service

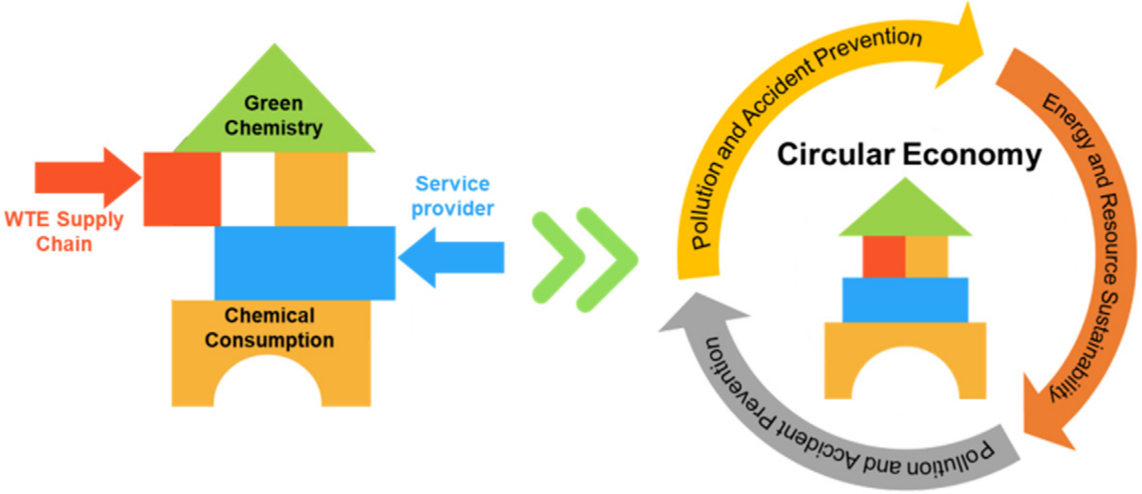

Fig. 5. Integration and establishment of green chemistry framework towards circular economy.

based on the individual requirement under various departments. The traditional chemical industries are running on the road of Industry 4.0 which can build incremental profits and benefits and generate a new income stream. This basically requires the development and application of Industrial Internet of Things (IIoT) which integrate many industries including manufacturing, chemicals, oil and gas, agriculture, transportation and mining. Most importantly, the sensing technologies or digital technologies are deployed to measure the operational and environmental parameters to assure the safety and efficiency (Zhou et al., 2017). Hazards or operation parameters in chemical processes such as carbon monoxide concentration, methane concentration, temperature, pressure, pH value and energy consumption can be real-time monitored (Chen et al., 2016). The combination of IIoT and Big Data analysis can provide an innovative solution to chemical industry. With the advance of IIoT system, the chemical industry can raise the asset intensity to optimize the maintenance procedure by using a predictive model. The continuous data-collection on critical equipment such as turbine, compressor, boiler and packing tower can predict the possible breakdowns, avoid the potential accidents, and reduce the operational risk. The dynamic energy consumption target also can be established under optimal operation condition. The higher energy efficiency, better pollution prevention and well accidents avoidance can be accomplished under a predictable model in the future (Stefan Van Thienen et al., 2016).

To implement a circular economy in the industries, the smart industrial parks were also proposed recently. Smart circular economy industrial parks could provide the practical management of intelligent distribution or architectures, supporting the industrial process and increasing the product service to consumers (Song et al., 2014). This original concept is called "eco-industrial park" (Côté and Cohen-Rosenthal, 1998), where it is developed not only to minimize the environmental impacts and additional costs but also maximize the energy and resource efficiency and service quality. Accordingly, GCP can be involved in the integration of smart technologies

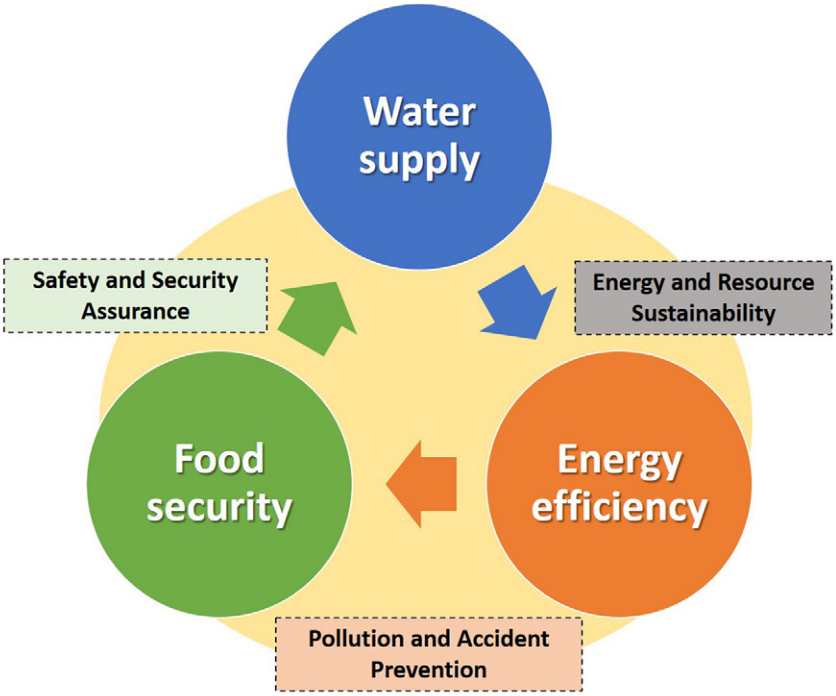

Fig. 6. The relationship between water-energy-food nexus and the PAS principle.

and circularity concept and thereby building a smart industrial park. This formulated model has to be comprehensively evaluated by ecological network analysis and life cycle assessment (Martín Gómez et al., 2018).

6. Summary

Green chemical principle practices and circular economy framework have been developed in the governmental, industrial, and educational fields around the world. The circular economy concept would be integrated in order to effectively achieve practical GCP in industries. On this basis, we have provided a PAS (i.e., Prevention, Assurance, and Sustainability) principle to clearly elucidate the GCP. The structure of PAS is linked to a circular economy in the entire life cycle. International movement on the implementation of GCP is also reviewed. U.S and European countries have constructed sound chemical management and regulation over a decade, e.g., TSCA and REACH. To achieve an effective pathway on GCP practices towards a circular economy, the strategies of PGD have been proposed as follows: (i) strengthening of cross-departmental collaboration, (ii) developing cleaner production to green products, (iii) building integrated chemical management system, (iv) implementing green chemistry education, and (v) establishing business model linked to waste-to-resource supply chain.

The future research and governmental works on sustainable and green chemistry connecting to circular economy would focus on the implementation of GCP into cross-disciplinary fields, such as 5R practices and sustainable material management, WEF nexus, and green smart chemical industry with IIOT technologies. They can enhance and upgrade the partnership between feedstock producers, existing chemical manufacturers, recycling sectors, and consumers. It is noted that, additionally, a novel business model will be imposed on multi-sectors plans to ensure energetics development of GCP practice. The vision of scientists in the field of material sciences and energy system would be changed to face the evaluation of huge data collection (i.e., big data analysis). It has been observed that applying new solutions to scientific problems of GCP implementation would be accelerated by transforming an integrated approach to a circular economy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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