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Using a hybrid of green chemistry and industrial ecology to make chemical production greener

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ABSTRACT

We proposed a model to extend green chemistry beyond the boundary of a single product by hybridizing it with the concept of industrial ecology in a chemical industrial park. The model works at three levels: single product, product food web, and infrastructure sharing. At the single product level, the core measures are cleaner production, the design of a green process that employs the "24 principles" of green chemistry and green chemical engineering in condensed forms, PRODUCTIVELY and IMPROVEMENTS respectively. The food web level is the key to extending the system boundary of a single product. At this level, collaboration among different firms in the chemical industrial park can be facilitated through designing, uncovering, and fostering horizontal and vertical integration among different stakeholders. Infrastructure sharing is an essential characteristic of eco-industrial development of chemical industrial parks. The model is exemplified in-depth in a typical Chinese chemical industrial park. We assessed the performance of disperse dyestuff manufacturing in the park and found that the park showed substantial reduction in its sulfuric acid consumption, water pollutants emission, and hazardous solid waste generation in disperse dyestuff production from 2011 to 2015. Integrating green chemistry and industrial ecology in the context of chemical industrial parks will be insightful for other chemical industrial parks aiming to facilitate green development.

1. Introduction

Sustainable industry is essential to addressing the challenges of climate change and resource deterioration. One of the targets proposed in the Sustainable Development Goals (SDG) is, by 2030, to "upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes" (UN, 2015).

China's chemical industry has undergone rapid development (Eissen et al., 2002). However, this industry is both energy-intensive and emission-intensive. Green chemistry is widely recognized as a key strategy that can facilitate the sustainable development of the chemical industry (Anastas and Lankey, 1998). It is characterized by dual twelve principles that fall into two general categories in condensed forms: PRODUCTIVELY (Tang et al., 2008) in green chemistry and IMPROVEMENTS (Tang et al., 2008) to Green Chemical Engineering. Myriad methods of green synthesis have been devised, and several have been honored with the "Presidential Green Chemistry Challenge Award". In most cases, Green chemistry targets the synthetic process of a single product by designing novel methods of synthesis; it aims to enhance selectivity, improve the conversion rate and yield of core reactants, and decrease wastes, and it aims to achieve all of this simultaneously whenever possible. In general, diverse reactants and auxiliary materials are used in a synthetic reaction; however, many of these components, particularly the auxiliary materials, generally become waste. This can be partially proven by the high E factors of 5–50 and 25–1000 (Sheldon, 2007) for fine chemicals and pharmaceuticals, respectively; these high E factors are due to the multi-step synthesis and diverse material inputs in the synthesis and intensive work-up processes. There are some limits on Green Chemistry's ability to decrease the E factor because it only targets single products.

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Graedel first introduced the idea of Green Chemistry in an industrial ecology context in the inaugural issue of the Green Chemistry Journal and proposed the expansion of green chemistry from merely green synthesis to the greening of entire life cycles (Graedel, 1999). Anastas proposed the methods and principles by which each process in product synthesis could be analyzed "through life cycle analysis (LCA), which combined with the Green Chemistry theory closely, to enhance the whole process's environmental benefits" (Anastas and Lankey, 2000). In 2001, Graedel made further progress in the practice of green chemistry and proposed a method of achieving the optimal state of an entire system in the context of the environment. Graedel's green chemistry system was based on "products, enterprises, infrastructures, and social level promotion" (Graedel, 2009).

This study proposes a model of how to apply green chemistry beyond the limits of a single product by creating a hybrid system with the methods of industrial ecology in the context of a chemical industrial park; the goal is to improve the material efficiency of chemical production. A typical Chinese chemical industrial park is used as a case study. The underlying idea is to enlarge the traditional product-specific boundary of Green Chemistry and create a boundary based on systematic thinking.

Industrial ecology is a subject concerning the flows of materials and energy in industrial and consumer activities, the effects of these flows on the environment, and the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources (Lifset and Graedel, 2010). Industrial Ecology can operate at different levels, including the firm level, inter-firm level, and regional/global level (Lifset and Graedel, 2010). An eco-industrial park is an important experimental field for industrial ecology and operates at the inter-firm level. As common feature of the global landscape, an industrial park is "*a large tract of land, sub-divided, and developed for the use of several firms simultaneously, distinguished by its shareable infrastructure and close proximity of firms* "(UNEP, 1997). An eco-industrial park is a type of industrial park that fosters an industrial ecosystem within an industrial park. In such a park, the key feature is that "*effluents of one process serve as the raw material for another process*" (Frosch and Gallopoulos, 1989). One popular definition of an eco-industrial park (EIP) comes from the Environmental Protection Agency (EPA) (Chertow, 2000a,b), which defines the park as "*a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues including energy, water, and materials. By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize if it optimized its individual performance only*". EIP development is currently being intensively discussed and piloted in China (Shi et al., 2012a, 2012b) and around the world; the most recent review can be found in ref (Chertow and Park, 2016). Chemical industrial parks are common in the development of the chemical industry around the world. There are already many well-developed chemical industrial parks, including those in Germany (Graedel, 2009; Anonymous, 2011), the Singapore Petrochemical Complex on Jurong Island (Yang and Lay, 2004), and the ARRR cluster in Europe (EPCA, 2007). China has approximately 500 chemical industrial parks, which, collectively, play a crucial role in facilitating the development of the chemical industry (Tremblay, 2001; Fringuelli et al., 2010).

In chemical industrial parks that specialize in petrochemical production, efficient use of both materials and energy can be improved by the integration of materials, products, and energy (Sterr and Ott, 2004). This integration is partially responsible for the small E factor of petrochemical production, which is generally below 1.0 (Sheldon, 2007). However, fine chemical products, such as dyestuffs and intermediates of pharmaceuticals, require multistep synthetic processes and diversified production volume, and thus these products have much higher E factors (Sheldon, 2007). We propose that, in a fine chemical industrial park, there is great potential to improve the material efficiency of chemical production by extending the system boundary of single chemical production and integrating it into the industrial ecosystem.

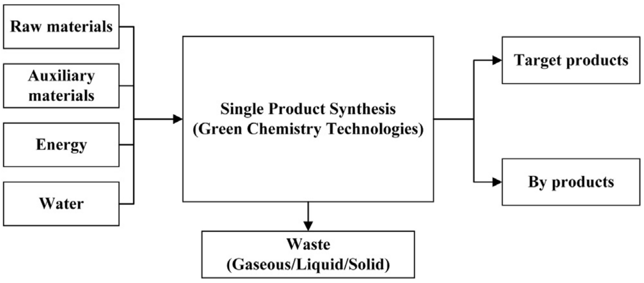

Fig. 1. Schematic diagram of the production of a single product.

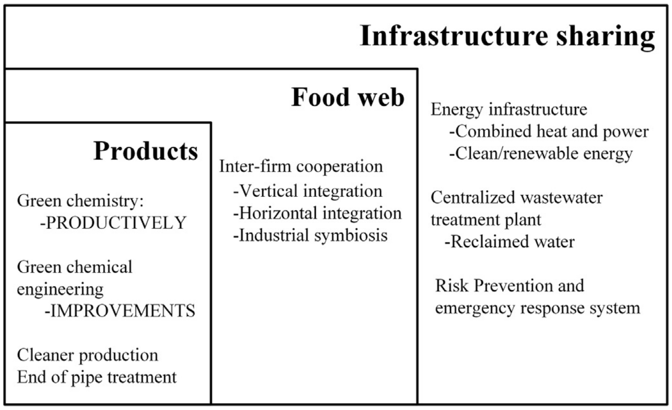

Fig. 2. Conceptual model of a hybrid of green chemistry and industrial ecology in the context of a chemical industrial park.

This paper is organized as follows: Section 2 introduces the models and provides a brief introduction to the fine chemical industrial park that is used as a case study; Section 3 presents the practices of green chemistry in the park; Section 4 illustrates the park's performance in hybridizing green chemistry with industrial ecology, and Section 5 presents conclusions.

2. Methodology

2.1. *A conceptual model of a hybrid of green chemistry and industrial ecology in the context of a chemical industrial park*

Fig. 1 illustrates the conceptual model of green chemistry at the single-product level, and the process of synthesizing a single product is defined as the system boundary. In a single-product model, the inputs include raw materials, auxiliary materials, energy, and water; the outputs are the target product(s), byproduct(s), and wastes (gaseous/liquids/solid wastes). The application of green chemistry technologies at the single-product level can, to some extent, improve the efficiency of core materials. But, inevitably, some auxiliary materials and by-products cannot achieve full atom economy because they are not combined in the structure of the final products.

Fig. 2 illustrates the conceptual model of a hybrid of green chemistry and industrial ecology in the context of a chemical industrial park. It is derived from in-depth observation of the greening practice implemented in the chemical industrial park under consideration in this study and some other chemical industrial parks in China (Ding and Hua, 2012; Yune et al., 2016). The model aims to