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Development of a system dynamics model for polycyclic aromatic hydrocarbons and its application to assess the benefits of pollution reduction

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A B S T R A C T

A dynamic multimedia transport (DMT) model for polycyclic aromatic hydrocarbons (PAHs) was constructed using the system dynamics software STELLA to simulate the transmission and flow of PAHs in different media. Humans are primarily exposed to PAHs via ingestion. Thus, this study used the DMT model to simulate the concentrations of PAHs in food media and the human body and assess the risk of harm to humans. On the basis of the hypothesis of PAH reduction in the Taiwanese steel industry, two scenarios were used (cases I and II), and integration indicators such as the Air Resource Co-Benefit Model of air pollutants, greenhouse gases, and PAHs reduction was established for the cost–benefit analysis of the reduction scenarios.

This study not only established Taiwan's PAHs dynamic multimedia transmission model successfully but also performed a reduction scenario on the steel industry. In the year 2025, the total costs for cases I and II will be USD 690 and USD 694 million per year, respectively, and the total benefits will be USD 492 and 1669 million per year, respectively. Therefore, case II is preferable to case I in terms of benefit ratio (2.40 vs. 2.35, respectively).

1. Introduction

No study has indicated that acute or short-term exposure to polycyclic aromatic hydrocarbons (PAHs) causes human harm. However, animal experiments have shown that long-term chronic exposure to PAHs with four to seven rings poses hazards to health, with benzo(a) pyrene (BaP) being the most powerful carcinogen (Grimmer, 1983). Existing studies on the dietary intake of PAHs differ in methodology with analyzed foodstuffs and PAHs (Domingo, 2017). Humans are exposed to PAHs primarily via inhalation (Guille´n et al., 1997; Scherer et al., 2000; Falco´ et al., 2003; Moon et al., 2010; Bolden et al., 2017; Heindel et al., 2017; Hallak et al., 2018). PAHs, which are toxic, carcinogenic, and mutagenic to all organisms, including humans (Nacci et al., 2002; Armstrong et al., 2004; Moon et al., 2010; Guo-liang Li et al., 2014; Agudelo-Castañeda et al., 2017), are ubiquitous environmental pollutants that occur primarily because of anthropogenic activities. The main source of PAHs is the combustion of fossil fuels (Christensen and Bzdusek, 2005; Moon et al., 2006, 2010; Keita et al., 2016; Llamas et al., 2017; Gope et al., 2018). Tuominen et al. (1988) and Bandowe and Meusel (2017) reported that low-molecular-weight PAHs do not have serious mutagenicity but may have some strong oxidizing agents (e.g., nitro-PAHs) due to photochemical reaction, thus resulting in higher carcinogenicity. PAHs enter the body and are transformed into carcinogenic precursors by cytochrome P450 metabolism; these precursors then combine with DNA, thus causing genetic replication defects and malignant tumors (Cavalieri and Rogan, 1995; Nebert and Dalton, 2006; Das et al., 2017). Therefore, it is important to reduce PAH emissions to safe levels.

Some multimedia mass-balance models have been recently developed to predict the fate and behavior of chemicals released into the environment (Mackay et al., 2009; MacLeod et al., 2011; Kim et al., 2017). These models include the EQuilibrium Criterion (EQC) model, the Risk Assessment, IDentification And Ranking model, and ChemCAN (Kim et al., 2013). Such models provide a powerful framework for understanding the behavior of chemicals in the environment (MacLeod et al., 2011) and have been adopted by industry and government agencies to support decision making (MacLeod et al., 2010). For example, the California Environmental Protection Agency in the United States sponsored the development of CalTOX, a multimedia contaminant fate and exposure model for assessing hazardous waste site; the System for the Evaluation of Substances of the European Union was built upon a multimedia chemical fate model; the US Environmental Protection Agency (EPA) developed a number of models to aid in decision making (CEMC, 2010); multimedia models were incorporated into the EPI Suite collection of exposure assessment tools (MacLeod et al., 2010); and multimedia models are used to develop strategies for

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reducing the levels of high-priority contaminants in the Great Lakes region of North America (Booty et al., 2004).

Current multimedia mass-balance models provide a "tool box" that can be applied to different environmental problems and form an integrated framework for introducing environmental chemistry concepts to researchers. Many of the assumptions underlying existing multimedia mass-balance models have not changed significantly over the years. An entire discipline dedicated to modeling environmental contaminants in multimedia environments was created owing to the development of the tool box of multimedia models. However, studies on human exposure to PAHs have ignored the health quality data used by the multimedia mass-balance models. To bridge this gap in knowledge, this study established the dynamic multimedia transport (DMT) model, which extends the EQC model developed by Mackay in 1996, models the PAHs in situation of media transmission and flow, and uses the ARCoB model (Chen, 2017; Tseng, 2017) to identify health quality benefits after pollution reduction in the case study. The DMT model provides an alternative way of performing hazard and risk assessments for decision making. The DMT model also provides a tool box for the study of human exposure to PAHs. The simple operation of the DMT model will enable researchers and decision makers to obtain the required output without overly complex operating procedures.

2. Materials and methods

This section is divided into two subsections, and the outline of this study is presented in Fig. 1.

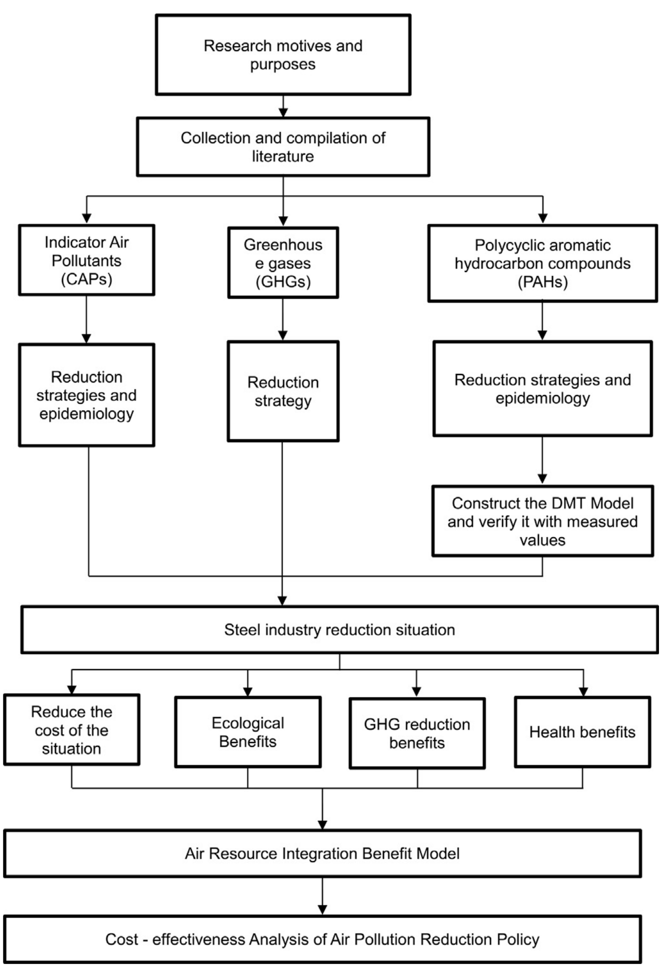

Fig. 1. Study outline.

2.1. Developing and verifying the DMT model of PAHs

The DMT model was developed using the system dynamics software STELLA with reference to the EQC model, which has been widely used to assess or predict the fate, distribution, and transport of chemicals in the environment (MacLeod et al., 2011). The main sources of PAHs in the environment are fossil fuel combustion (Christensen and Bzdusek, 2005; Moon et al., 2006, 2010; Keita et al., 2016; Llamas et al., 2017; Gope et al., 2018), and most PAHs originate from industrial operations (Taichung City Government Environmental Protection Bureau, 2010), e.g., the steel industry contributed to 45% of total PAH emissions. In this study, we simulated the PAHs discharged from the steel industry and their transmission between environmental medium and food medium to assess the level of human exposure. Furthermore, the data and calculation method used in this study refer to the results indicated in the EQC model. Fig. 2 shows the DMT model of PAHs.

Regarding the scenarios in this study, the "Steel Industry Policy Assessment Instructions" indicated by the Industrial Development Bureau of Ministry of Economic Affairs (Industrial Development Bureau of Ministry of Economic Affairs IDB, 2012) was used, and the supply and demand balance was retained. The target year was 2025. The scenarios included crude steel supply and demand gap due to self-production, crude steel supply and demand gap partly due to production and imports, and crude steel supply and demand gap due to imports. In this study, the crude steel supply and demand gap is completely self-produced for the steel industry business as usual (BAU) scenario and was compared with cases I (crude steel supply and demand gap partly due to production and imports) and case II (crude steel supply and demand gap due to imports). Furthermore, the DMT model of PAHs was verified by comparing the DMT results with previous reports (Table 1).

2.2. Human exposure and health benefits of PAHs

According to the literature, approximately 80% of human PAH exposure occurs by ingestion. Human exposure data from the National Environmental Health Research Center (2013) was analyzed, such as national daily feeding habits (vegetables, milk products, beef, pork, chicken, eggs, fish, etc.,), to quantify human PAH exposure. For the formula and parameters for each medium of exposure, this study used the Human Health Risk Assessment Protocol for Hazardous Waste Combustion Facilities (U.S. EPA, 2005) and the health risk assessment draft multimedia transmission model, which is used for the risk assessment of hazardous waste combustion facilities to estimate the risk of individual carcinogenic and noncarcinogenic health effects.

The average lifetime exposure of PAHs was converted to human PAH concentrations inside the body to estimate the carcinogenic risk of PAH exposure. Table 2 presents the comparison of the carcinogenic risks of the three scenarios (BAU, case I, and case II) with previously reported values, the average lifetime exposures for BAU, case I, and case II were 1.04×10^{-5}, 9.9×10^{-6}, and 8.41×10^{-6} mg/kgbw, respectively. In addition, Fig. 3 shows the exposure pattern of PAHs.

In this study, we used the ARCoB model (Chen, 2017; Tseng, 2017) to quantify the implementation of the policy after the reduction of air pollutants (APs), greenhouse gases (GHGs), and PAHs in the environmental combining benefits. The benefits include reduced medical expenses due to decreased pollutant concentration, disease proliferation, and loss of life; ecological benefits due to decreased air pollution, and decreased environmental costs due to GHG reduction. The costs include the investment required to implement the policy scenario. Fig. 4 shows the qualifying health benefit used by the ARCoB model structure.

3. Results and discussion

We used STELLA to establish a dynamic system model of PAHs with reference to the EQC model (Mackay et al., 1996). We then used this