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Editorial

Life Cycle Thinking and Green Nanotechnology

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Nanotechnology is said to revolutionize many aspects of our lives, in a way traditional science and technology could not deliver. To realise the revolution, it is necessary to take the outcomes of laboratory research to the hands of general public [1]. This process requires careful consideration in two aspects; production scalability [2] and sustainability [3]. In particular, sustainability is receiving more and more recognition as an important aspect of new technologies.

In recent years, growing environmental awareness has led to increased pressure on manufacturers and users of materials to consider the environmental impact of material products. Nanotechnology is no exception. Life cycle assessment (LCA) has recently emerged as a powerful holistic tool for the assessment of the environmental impacts of nanotechnology [3]. Application of LCA to nanotechnology highlights both the positive and negative impacts of nanotechnology on the environment throughout the whole life cycle of nano-products. The life cycle includes all aspects of activities during the life of a product 'from the cradle to the grave', such as the extraction of raw materials and resources, production processes and facilities, the usage of products, and post-use management of the product including recycling and disposal. LCA helps to identify the potential risks associated with nanomaterials and nano-enables products in advance. LCA can also clarify the risk-benefit balance during the entire life cycle of the nano-products. However, the LCA of nanotechnology is still in its infancy. The slow progress in the LCA of nanomaterials is due to the many challenges it faces. The major obstacles include the uncertainty arising from the immature nature of the technology and markets, lack of risk-associated information, a high number of nano-specific properties to be considered, and the fast development pace of technology commercialization.

Although it may take a while to accumulate sufficient data to perform complete LCA of nanotechnology, there is still something we researchers can do today; it is to apply "life cycle thinking (LCT)" [4] to the development of nanotechnology. Without waiting for the opportunity to conduct LCA of already-developed nanomaterials, the development of new nanomaterials can be carried out with sustainability in mind.

The change is already happening. There is a strong trend emerging among the nanotechnology community to develop cleaner or greener methods during the whole life cycle of nanomaterials. Increasing research efforts have been made recently to develop the methods to synthesise nanomaterials without using raw materials containing scarce natural resources and hazardous substances, or the production methods that require low energy and low material consumption [5,6]. The concept of green nanotechnology applies not only to the manufacturing stage but also to the usage stage, in particular, in environmental applications [7]. Caution is required so as not to consider the technology as 'green', only based on the fact that applications are in the environmental and renewable-energy sectors. The potential environmental burden of the applications during manufacturing and disposal stages should be taken into account [3]. LCT helps in guiding the nanotechnology development towards true eco-friendliness, through the assessment of the *overall* risk-benefit balance during the production, usage and disposal stages of nano-products [6]. Nanotechnology is by nature a multidisciplinary research field, but the LCT of nanotechnology calls for strong collaborations from the wider research community beyond physics, chemistry, medicine and biology.

Will the raw materials depend on fossil fuels or deplete scarce resources? Will the synthesis techniques require too much energy, or generate substantial green-house gas and other types of pollutants? Will the use of nanomaterials or nano-enabled products necessitate additional resources that deteriorate environment? Will the applications lead to the generation of nano-waste that causes biological risks? Will the nano-products recyclable or disposable without much energy and environmental costs? Irrespective of the types of nanomaterials and areas of nano-applications, these questions pose great challenges to nanotechnologists and, at the same time, open up great opportunities to realise nano-invention in our lives.

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