Comment

Preparing for tomorrow with materials today

Nam-Joon Cho

School of Materials Science and Engineering, Nanyang Technological University, 50 Nanyang Drive, 637553, Singapore
SyneRx Antiviral Drug Discovery Center (AViDD), Division of Gastroenterology & Hepatology, School of Medicine, Stanford University, Stanford, CA 94305, USA
njcho@ntu.edu.sg

Introduction

Throughout history, new materials have been the foundation of disruptive technologies [1]: from bronze, paper, and ceramics to steel, polymers, and semiconductors, each material enabled far-reaching advances and defined the era [2]. Seventy years ago, the transformation from using bulk quartz sand for construction and waste to synthesizing pure semiconductors [3] from single crystals led to a complete transformation of the electronics industry and sweeping changes in communications, computing, and transportation [4]. Today, inspired by the United Nation's Sustainable Development Goals (SDGs) – a blueprint to achieve a better and more sustainable future for all [5] – new classes of materials are emerging, ones from nature and with the potential to alleviate the environmental burden, provide radically new functions, and challenge our notion of what constitutes a “material” [6]. Such progress has been facilitated by the advent of nanotechnology and our ability to manipulate material structure and properties at the nanoscale [7,8].

These materials, inspired and co-opted from biology, combine (1) hybrid-composite design, integrating disparate building blocks; (2) compartmentalized architecture, encapsulating desirable biomolecules while excluding others; and (3) hierarchical organization [9]. Together, they enable unique and remarkable combinations of properties, including adaptability, plasticity, multifunctionality, and environmental responsiveness – far beyond those achieved by monolithic materials of the synthetic world. Such material innovations emphasize exploring the foundational materials science of natural materials toward developing entirely new classes of materials from inexpensive, readily available, and sustainable sources [6]. However, pursuing materials innovation by itself is insufficient to conquer the sustainability needs of the global society.

As issues of sustainability become paramount, we call attention to another key issue that is critical to realize the true potential of materials innovation, that is, looking beyond material performance alone to incorporating elements of sustainable processing to create what we term “cross-economy” to realize the twin goals of pursuing materials innovation and practically realizing sustainable practices.

Why we need a cross-economy

Traditionally, raw materials are obtained from natural resources and assembled into products by using manufacturing methods. These products are then distributed to consumers who buy and use them before eventually discarding them. In this case, the discarded items are simply considered waste and the main goal of this so-called linear economy is economic profit [10] (Fig. 1**a**). The manufacturing methods are a means to an end and recycling is not considered in this model.

Recognizing the limitations of this approach and the finite resources of the planet, there have also been efforts to create a circular economy, which prioritizes sustainability over profit [11]. In the circular economy, the manufacturing and consumption stages focus on sustainable practices to minimize overuse of materials and to recycle obsolete product materials rather than discard them as waste [12] (Fig. 1**b**). Furthermore, manufacturing processes are ideally developed to minimize energy consumption [13]. However, there are also challenges with the circular economy model, including limitations placed on repeated recyclability and material durability along with continuing overconsumption of materials [14]. While a fraction of materials is recycled, the problem of large-scale waste, especially plastics, persists and a paradigm shift conceptually is needed to overcome these existing challenges [15].

 https://doi.org/10.1016/j.mattod.2022.11.006

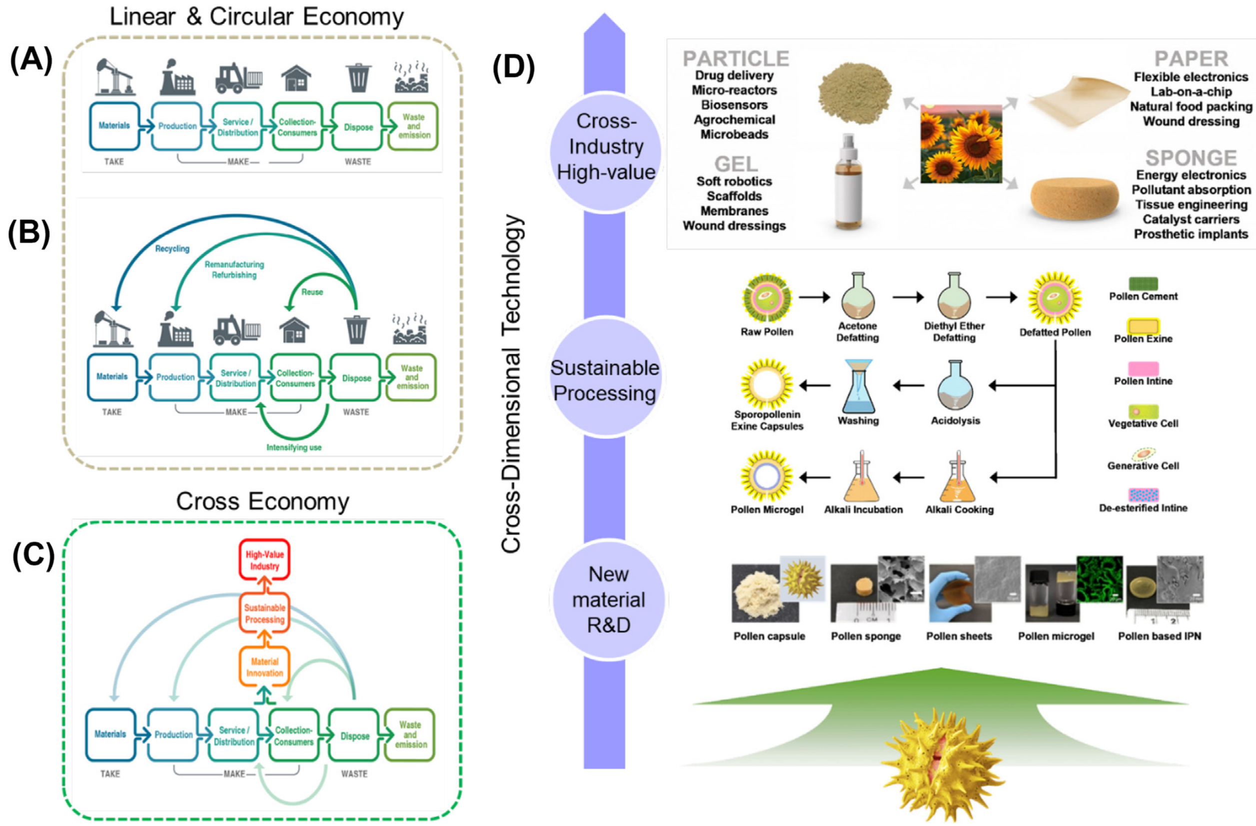

FIGURE 1

Conceptual overview of cross-economy model and cross-dimensional technology. (a) Traditional linear economy and (b) emerging circular economy models. The linear economy model prioritizes industrial output while the circular economy model considers sustainability and aims to reuse, recycle, and remanufacture used materials in a circular fashion. (c) The cross-economy model is grounded in materials science and engineering and sustainable processing to create innovative, high-value products from "waste" by applying a cross-dimensional technology perspective. (d) The cross-dimensional technology concept applied to natural plant pollen.

The cross-economy concept presents a sustainability-driven approach to support materials innovation by reimagining what is possible to achieve with so-called "waste" material as there is no technology enabling viewpoint to commercialize their potential beyond the original application of the starting material (Fig. 1**c**). Rather than recycling waste materials as in the circular economy, the cross-economy approach focuses on transforming waste into high-value materials through a combination of materials innovation and sustainable processing. The approach is grounded in utilizing fundamental engineering principles based on material innovation and sustainable processing to construct more harmonious ecosystems and networks.

A cross-dimensional perspective

Central to the cross-economy is the idea of cross-dimensional technology whereby raw materials, including waste and discarded items, are transformed using sustainable processes into high-value products with high economic value. Such items are not just inputs to be put back into the original manufacturing process but provide the basis for creating new innovative materials. The basic principle of utilizing raw materials to create higher-value products gains inspiration from agricultural innovation efforts such as the Sixth Industrialization Plan [16]. Aside from natural material production and extraction as the exclusive revenue source, economic diversification can be realized by expanding into sectors such as sustainable processing to create high-value products [17].

An exciting example of a material to which the cross-dimensional technology concept can be applied is natural plant pollen, a discrete mesoscale compartment, which encapsulates, protects, and transports male genetic material in flowering plants to enable the biological imperative of reproduction (Fig. 1**d**). To ensure reproductive success, plants produce enormous quantities of pollen—most of which ends up as "bio-waste" and it is very affordable to obtain in large quantities. There is thus enormous untapped potential to transform pollen into a valuable commodity to produce pollen-based materials innovation as a sustainable solution.

Ongoing efforts to transform hard pollen grains into soft matter microgel blocks using environmentally friendly processing methods have led to the development of pollen-based gels, sheets, and sponges. Of note, sustainable processing has been exemplified through the transformation of pollen grains into paper [18]. Compared to conventional processing methods for paper production (*i.e.*, from a wood source) that involve multiple energy intensive processes, the process of transforming pollen grains to paper follows a simple four-step solution-based approach, with zero energy input and zero emission. More importantly, the raw material (*i.e.*, plant pollen) is naturally abundant and its acquisition is non-destructive unlike wood that is obtained from logging, which is environmentally destructive and non-sustainable.

Taken together, new pollen-based materials have demonstrated compelling advantages for applications such as humidity actuators, sensing platforms, oil absorbents, and anti-counterfeiting paper, and there is a bright future as such promising innovations shift from the lab to real-world applications. Simply put, from one simple material previously regarded as biological waste, a wide range of new material innovations have emerged and have the potential to solve some of the biggest environmental challenges such as identifying suitable pollen-based substitutes to replace plastic. Imagine the future that lies ahead for not only pollen but the wide range of natural materials – the so-called waste of conventional production processes – that can support the cross-economy approach and help our world become more innovative and sustainable.

Outlook

Over the past two centuries, the rapid pace of industrial progress has catalyzed societal advances that have improved numerous facets of the human experience, but these improvements have come at the expense of creating a wide range of physical harms on all scales of life from individual cells and organisms to ecosystems and the planet. If current practices continue, then life on Earth will be damaged irreparably while there is a fleeting opportunity to transform how we interact with the environment and other forms of life in order to foster new heights of sustainability and diversity on this planet. We, as stewards of the planet, must strive to realize a brighter future for Earth where technological innovation is viewed not only through the lens of industrial progress but also sustainability. Through adoption of a cross-dimensional technology perspective grounded in science and engineering, the cross-economy model described here can help to create forward-looking solutions that enhance sustainability while also harnessing scientific knowledge and technological innovation to achieve continued industrial progress in more harmonious ways. To implement this vision, a solid government support for research in sustainability is essential, along with strong partnerships between the research and development and industrial sectors. This will facilitate the development and adoption of sustainable processing methods in the industry before policies to incentivize their adoption can be introduced towards fully realizing the cross-economy model.

Data availability

No data was used for the research described in the article.

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.

Acknowledgment

This conceptual work was developed during the COVID-19 pandemic and was refined through discussions with world-leading experts in sustainability within the materials science and engineering community, including Prof. Kookheon Char of Seoul National University, Prof. Curtis W. Frank of Stanford University, Prof. Atul Parikh of UC Davis, and Professor Joshua A. Jackman of Sungkyunkwan University. The cross-economy concept was originally discussed and conceived together with Dr. Yuhyun Park of the DQ Institute. The author wishes to thank the aforementioned experts for their valuable insights and suggestions.

References

[1] S. Jong, Nat. Biotechnol. 29 (8) (2011) 685–688.
[2] R. Hummel, Understanding Materials Science: History, Properties, Applications (2005).
[3] D. McWhan, Sand and Silicon: Science that Changed the World, OUP Oxford, 2012.
[4] S.E. Thompson, S. Parthasarathy, Mater. Today 9 (6) (2006) 20–25.
[5] D. Griggs et al., Nature 495 (7441) (2013) 305–307.
[6] S.H. Ali, Nat. Mater. 17 (12) (2018) 1052–1053.
[7] R. Feynman, There's plenty of room at the bottom, in: Feynman and computation, CRC Press, 2018, pp. 63–76.
[8] K. Ariga, Nanoscale Horiz. 6 (5) (2021) 364–378.
[9] G.M. Whitesides, Interface Focus 5 (4) (2015) 10.
[10] G. Michelini et al., Proc. CIRP 64 (2017) 2–6.
[11] W.R. Stahel, Nature 531 (7595) (2016) 435–438.
[12] M. Geissdoerfer et al., J. Clean. Prod. 143 (2017) 757–768.
[13] M. Lieder, A. Rashid, J. Clean. Prod. 115 (2016) 36–51.
[14] S.F. Hansen et al., Nat. Nanotechnol. (2022).
[15] W.Y. Lau Winnie et al., Science 369 (6510) (2020) 1455–1461.
[16] K.-C. Kim et al., J. Korean Soc. Rural Planning 21 (2) (2015) 149–162.
[17] C.G. Machado et al., Int. J. Prod. Res. 58 (5) (2020) 1462–1484.
[18] Z. Zhao et al., Adv. Mater. 34 (19) (2022) 2109367.