

OPEN
EDITORIAL

Advances in green chemistry and engineering

Jechan Lee^{1✉} & Assunta Marrocchi²

Green chemistry and engineering seek for maximizing efficiency and minimizing negative impacts on the environment and human health in chemical production processes. Driven by advances in the principles of environment protection and sustainability, these fields are expected to greatly contribute to achieving sustainable development goals. To this end, many studies have been conducted to develop new approaches within green chemistry and engineering. The Advances in Green Chemistry and Engineering Collection at *Scientific Reports* aims at gathering the latest research on developing and implementing the principles of green chemistry and engineering.

In the research areas of green chemistry/engineering, green synthesis of chemicals and solvents, waste recycling, and biodegradable polymer synthesis are emerging trends. Developing less hazardous synthesis protocols of chemicals and solvents is necessary to move the industrial landscape in various sectors (organic synthesis, pharmaceuticals, pollutant extraction, etc.) forward to a long-term sustainable reality. Although earlier studies on green synthesis of chemicals/solvents tended to focus on small molecules, medium-sized molecules have recently garnered more attention. The current landscape of waste recycling is to recover value-added fractions (e.g., monomers and functional materials) from complex waste substances characterized by intricate compositions (e.g., composite and unsorted plastics). Synthesized biodegradable polymers have continuously gained attention due to the difficulty in procuring reproducibility when using natural polymeric materials¹. Many recent studies aim to improve the scalability and stability of biodegradable polymers to meet criteria for commercialization.

Article highlights in this collection

Highly-stable low-toxic organogermanium compounds have recently been used as reagents in the synthesis of complex organic molecules^{2,3}. Stachowiak-Dłużyńska et al. reported an efficient protocol for the reactions between alkynylgermanes and silanols or terminal acetylenes using a commercially-available potassium bis(trimethylsilyl)amide (KHMDs) as the catalyst⁴. The KHMDs catalyst allowed a dealkynative coupling to synthesize a variety of organogermanes such as alkynylgermanes and germasiloxanes. The KHMDs-based process offered desirable features such as high chemoselectivity, simple operation, benign reaction conditions, and low cost of the reagents and catalyst, thereby potentially enabling green synthesis of value-added organogermanium compounds.

Natural deep eutectic solvent (NADES), made from non-toxic components derived from natural compounds (e.g., menthol, thymol, organic acids, and salts)⁵, is considered an environmentally friendly solvent. Hunter et al. proposed a method of extracting micro- and nano-plastic particles from water using hydrophobic NADES⁶. Three hydrophobic NADESs were made by combining decanoic acid, menthol, or thymol with different molar ratios. They were used to extract micro- and nano-plastic particles of polystyrene, polyethylene terephthalate, and polylactic acid from fresh water and salt water. The extraction efficiencies ranged between 50 and 93% within 0.2–1.3 h. The extraction efficiency was highly associated with the type and size of plastic particles.

Among various coating methods, thin phosphate-based coating combines crucial material protection potential and environmental benefits by repelling water, decomposing organic and inorganic compounds, and providing anticorrosive properties⁷. Zemajtis et al. investigated the effect of a hydrophobic agent on the transformation from superhydrophilicity to superhydrophobicity of TiO₂-doped zinc phosphate coating systems using high-resolution neutron imaging (HR-NI), confocal laser scanning microscope, scanning electron microscope, and X-ray diffraction techniques⁸. The HR-NI showed that water imbibition is observed for the superhydrophilic coating, while water ingress into porous ceramic substrate is prevented by the superhydrophobic coating. The characteristics of the TiO₂-doped zinc phosphate coating were highly associated with chemical bonding, surface roughness, and photocatalytic reactivity. It was also demonstrated that a two-layer superhydrophobic system

¹Department of Global Smart City & School of Civil, Architectural Engineering, and Landscape Architecture, Sungkyunkwan University, Suwon 16419, South Korea. ²Department of Chemistry, Biology and Biotechnology, University of Perugia, 06123 Perugia, Italy. ✉email: jechanlee@skku.edu

can create effective water barriers on the surface with the contact angle of 153° that is still effective for damaged surface.

Due to rapidly growing demand for wind energy, the generation of wind turbine blade waste have increased. Therefore, decommissioned wind turbine blades need to be carefully recycled⁹. Muzyka et al. proposed a novel concept of end-of-life wind turbine blade recycling process¹⁰. The process is to dissolve thermoset resin fraction (containing ester groups) of wind turbine blade waste and carbon fiber composites via transesterification at < 200 °C in the presence of 1,5,7-triazabicyclo[4.4.0]dec-5-ene, ethylene glycol, and 1-methyl-2-pyrrolidinone (1:1:1 molar ratio), resulting in up to 100% resin degradation yield. Fiber materials could be readily separated from the product stream. The resin degradation yield may depend on waste compositions.

Finding alternatives to non-biodegradable plastics has raised concerns worldwide as plastic waste harms the environment. Microalgae are considered as a renewable source for bioplastic production¹¹. Chalermthai et al. conducted techno-economic assessment (TEA) of co-production of food packaging bioplastic and food supplement from edible microalgae, *Arthrospira* spp. (Spirulina)¹². In their study, the production scale was assumed to meet 1% of the local plastic demand in Thailand (≈1200 MT per year) and 1% of the global Spirulina demand as food supplement (≈1000 MT per year). The TEA results indicated that the co-production of the Spirulina-based bioplastic and food supplement powder is an attractive approach with the annual revenue of up to USD 55.6 million, a payback time of ≈2.6 y, and a return on investment of ≈38.5% despite high capital and operating costs. In the large-scale process, the selling price of bioplastic and the split ratio of biomass used for bioplastic and food supplement were found to be the most sensitive parameters affecting its profitability.

This Collection provides a group of articles offering new insights into the approaches to synthesize less hazardous functional chemicals and solvents for different applications (e.g., organic synthesis, microplastic extraction, and coatings), suggesting new routes to develop composite waste recycling method, and evaluating the techno-economic potential of algal biorefinery for producing both bioplastic and food supplement.

Published online: 07 March 2024

References

- Panchal, S. S. & Vasava, D. V. Biodegradable polymeric materials: Synthetic approach. *ACS Omega* **5**, 4370–4379 (2020).
- Dahiya, A. & Schoenebeck, F. Orthogonal and modular arylation of alkynylgermanes. *ACS Catal.* **12**, 8048–8054 (2022).
- Xu, Q.-H. & Xiao, B. Organogermanium (IV) compounds in photo-induced radical reactions. *Org. Chem. Front.* **9**, 7016–7027 (2022).
- Stachowiak-Dłużyńska, H. *et al.* Access to germasiloxanes and alkynylgermanes mediated by earth-abundant species. *Sci. Rep.* **13**, 5618 (2023).
- van Osch, D. J. G. P., Dietz, C. H. J. T., van Spronsen, J., Kroon, M. C., Gallucci, F., van Sint Annaland, M. and Tuinier, R. A Search for Natural Hydrophobic Deep Eutectic Solvents Based on Natural Components, *ACS Sustain. Chem. Eng.*, **7**, 2933–2942 (2019).
- Hunter, J. R. *et al.* *Sci. Rep.* **13**, 10585 (2023).
- Hasan, M. S., Zemajtis, F., Nosonovsky, M., and Sobolev, K. Synthesis of ZnO/TiO₂-Based Hydrophobic Antimicrobial Coatings for Steel and Their Roughness, Wetting, and Tribological Characterization *J. Tribol.*, **144**, (2022)
- Zemajtis, F. *et al.* From superhydrophilicity to superhydrophobicity: High-resolution neutron imaging and modeling of water imbibition through porous surfaces treated with engineered nano-coatings. *Sci. Rep.* **13**, 11176 (2023).
- Yang, W., Kim, K.-H. & Lee, J. Upcycling of decommissioned wind turbine blades through pyrolysis: A review. *J. Clean. Prod.* **376**, 134292 (2022).
- Muzyka, R., Sobek, S., Korytkowska-Wałach, A., Drewniak, Ł & Sajdak, M. Recycling of both resin and fibre from wind turbine blade waste via small molecule-assisted dissolution. *Sci. Rep.* **13**, 9270 (2023).
- Park, Y.-K. & Lee, J. Achievements in the production of bioplastics from microalgae. *Phytochem. Rev.* **22**, 1147–1165 (2023).
- Chalermthai, B., Charoensuppanimit, P., Nootong, K., Olsen, B. D. & Assabumrungrat, S. Techno-economic assessment of co-production of edible bioplastic and food supplements from Spirulina. *Sci. Rep.* **13**, 10190 (2023).

Acknowledgements

The guest editors express their gratitude to all colleagues for submitting their cutting-edge contributions. Our gratitude is also due to all peer reviewers who donated their valuable time to assess and help improve these contributions.

Author contributions

J.L. wrote the editorial. A.M. gave feedback on writing the editorial.

Competing interests

The authors declare no competing interests.

Correspondence and requests for materials should be addressed to J.L.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2024