

Nanotechnology meets circular economy

The transition from a linear ‘take-make-dispose’ economy to a circular economy is gaining momentum. Although there are many opportunities for using nanotechnology to enable circularity, the knowledge gaps related to (eco-) toxicological hazards and the presence of nanomaterials in waste streams constitute significant challenges.

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There are more than a hundred definitions of circular economy, most of which focus on reducing, reusing and recycling¹. Increasingly, countries around the world are developing strategies relevant to resource efficiency and circular economy^{2–6}, with the European Union (EU) having among the most elaborate plans when it comes to circular economy and policy integration⁷. In an EU regulatory context, circular economy is defined as “an economic system whereby the value of products, materials and other resources in the economy is maintained for as long as possible, enhancing their efficient use in production and consumption, thereby reducing the environmental impact of their use, minimising waste and the release of hazardous substances at all stages of their life cycle”⁸. Nanotechnology is often — and has from the outset been — mentioned as a fast-moving technology and might thus help reach circularity by, for instance, securing resource efficiency and reducing humanity’s environmental impacts^{9–11}. It is also often stressed that new technologies, which outpace policy and regulation and come with high uncertainty regarding risks, might increase public concern and even hostility towards them¹¹.

In March 2020, the European Commission published a Circular Economy Action Plan that contains, among others, the aims to make sustainable products the norm, ensure less waste generation and specifically halve residual non-recycled municipal waste by 2030¹². The action plan’s objectives are very relevant for nanotechnology because they include initiatives for circular electronics, batteries, textiles, construction and buildings. These are all applications in which nanomaterials are increasingly applied. To deliver on the EU’s Circular Economy Action Plan, the transformation is supported by €95.5 billion from the EU’s new Horizon European research and innovation funding programme that runs until 2027¹³.

The European Commission will also work to minimize the presence of

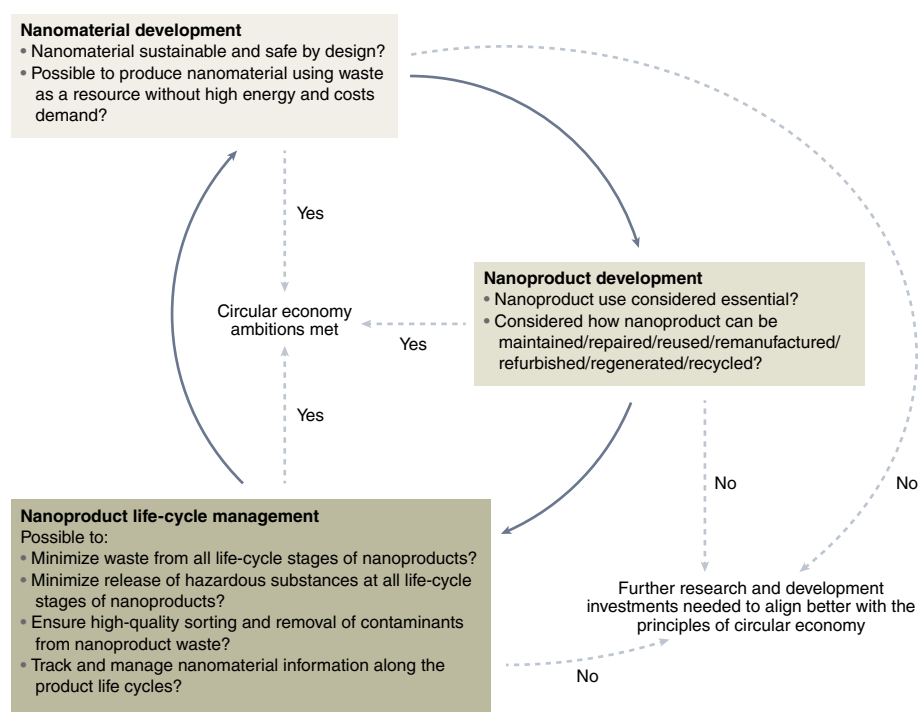


Fig. 1 | Critical questions to be addressed for nanomaterials in a circular economy from development, over nanoproduct development, to nanoproduct life-cycle management. Nanotechnology can only be used to meet the circular economy ambitions if the development of nanomaterials and nanoproducts are sustainable and safe along the life-cycle of the nanoproducts. This includes considerations of whether the use of the nanoproducts are essential, minimizing waste and tracking and managing nanomaterial information. Further research and development might be needed to ensure that the development of nanoproducts are aligned with the principles of circular economy.

harmful substances in recycled materials and harmonize the classification and management of hazardous waste. Thus, there is a strong link between the circular economy and chemicals management addressed in the Chemicals Strategy for Sustainability (CSS) published in October 2020¹⁴. The CSS is highly pertinent for nanomaterials as these are considered chemical substances in the EU. The CSS introduces three new principles to address the environmental and health concerns of chemicals: (1) safe and sustainable by design, (2) phasing out the most harmful

chemicals for non-essential uses, and (3) ‘one substance–one assessment’, which refers to having one safety assessment for all uses of a given substance instead of having many European agencies assess the same substance for individual uses under their respective legal jurisdictions, such as industrial chemicals, food, toys and cosmetics.

In this Comment, we discuss examples of how nanomaterials can be used to meet the ambitions of the Circular Economy Action Plan and the CSS. As summarized in Fig. 1, we furthermore reflect on the unique challenges that remain if nanomaterials are

to become an integrated part of a future circular economy.

Reuse of nanoproducts

A transition to a circular economy can be supported in different ways, including long-lasting design, maintenance, repair, reuse and remanufacturing¹¹. The common denominator is the aim of closed-loop material flows in the economic system, keeping products, components and materials at their highest utility¹⁵. In the circular economy taxonomy, reuse requires that a product is still in good condition and fulfils its original function for its conceived purpose¹⁶. In such a case, the product is not yet waste¹⁷, and preparation for reuse requires little effort. This has to be considered already in the design phase of products (linking to the 'sustainable by design' of nanomaterials) and is fundamentally different from recycling, which typically — but not always — involves more extensive processing of (waste) materials (Fig. 1).

Most nanomaterials are embedded in a solid product matrix, for example, a polymer¹⁸. Therefore, reusing nanoproducts often implies circular flows of nanomaterials. As for any other product, the precondition for reusing nanoproducts is that the original functionality and properties remain. Although the reuse of nanocomposites has been studied extensively¹⁹ (including different techniques for the regeneration of polymeric nanocomposites and their reuse potential in wastewater treatment and monitoring processes), limited knowledge is available on how the quality and functionality of both individual nanomaterials and composites are affected by reuse. The few studies available indicate that the functionality of the individual nanomaterials, namely zinc oxide nanoparticles or carbon nanotubes, is retained only over a limited number of cycles²⁰. When this functionality is lost, nanoproducts may be discarded as waste and possibly recycled.

Recycling of nanomaterials

If nanomaterials are to be recycled, they first need to be recovered from the waste. Some studies have recovered inorganic nanoparticles from complex liquid mixtures using centrifugation or solvent evaporation, which have high energy and economic costs. Methods using magnetic fields, thermoresponsive materials, molecular antisolvents and nanostructured colloidal solvents are cheaper, faster and less energy intensive²¹. Techniques to recover nanomaterials from solids have also been documented. For example, nanomaterials, such as iron and titanium, can be fully recovered from lithium-ion batteries

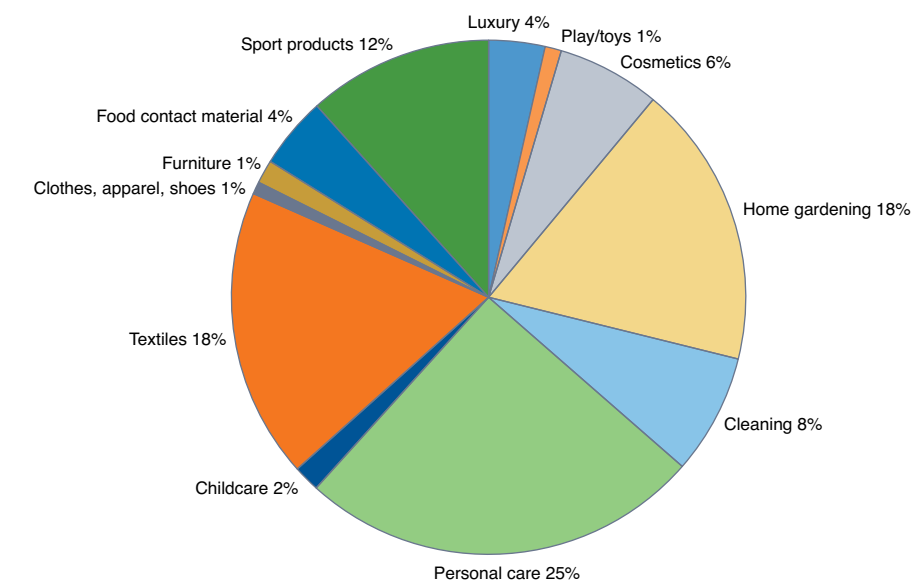


Fig. 2 | Distribution of products in the Nanodatabase according to categories of non-essential uses proposed by ChemSec. Here, 1% is equal to 52 products.

using high-temperature metal recovery²². Furthermore, successful extraction of inorganic metal oxide nanoparticles, multiwalled carbon nanotubes, and nanoclays from polymer nanocomposites has been reported using either calcination or chemical dissolution with concentrated formic acid followed by centrifugation. Calcination provides the highest recovery yields (>95%) for most nanomaterials but causes a loss of surface functionalization groups. Extraction of nanomaterials with chemical dissolution preserves the functional groups better but results in lower recovery yields (40–60%)²³.

Once nanomaterials are recovered from the waste matrix, they can be reused in new nanoproducts. Several studies have indicated that recycling of nanomaterials such as zinc oxide nanoparticles and single-walled carbon nanotubes from batteries is feasible^{24–26}. The performance of the recycled nanomaterials or products will define their further use. Studies have indicated that the functionality of recycled nanomaterials is retained only over a limited number of (re)use cycles, usually ten or less^{20,27}. Efficient recycling requires studies on nanomaterials' intrinsic thermal, mechanical and chemical recyclability properties and how these properties change once nanomaterials are mixed with other materials in secondary nanoproducts.

Nanomaterials as chemical contaminants

The presence of nanomaterials in certain waste streams may be an obstacle to high recycling rates and multiple material cycles.

Current recycling systems are mostly open loops, meaning that secondary materials are recycled into applications that are different from those producing the waste²⁸. In some cases, the presence of nanomaterials in existing products can inadvertently impair the functionality of the new products. An example is nanoclay used as a filler in plastic polymers for food packaging. The presence of nanoclay can make polyethylene plastic more brittle with decreased impact strength²⁹, which could be an issue for the quality and sustainability of the recycled plastics. At the moment, it is unclear for which products or material streams this might represent a problem, nor is it clear how to recover nanomaterials from waste streams³⁰. Lack of traceability is a significant obstacle, and little information is typically available about material properties in open-loop recycling operations³¹, meaning that it may remain unknown whether a recycled material contains nanomaterials³². While examples of recovered nanomaterials exist^{33–35}, the separation of nanomaterials from products may be difficult, owing to technical challenges and high energy requirements. Nanomaterials recovered from end-of-life products may also be of low quality, for example, in low concentrations or with contaminants present.

Waste as a resource

Considering waste as a resource is a crucial element of the circular economy. There are several examples of repurposing conventional waste into nanomaterials to avoid the extraction of primary resources.

Examples include producing carbon dots from plastic bags³⁶ and polyethylene bottles³⁷, carbon nanomaterials from solid waste³⁸, and different metal nanoparticles from battery waste³⁹ and e-waste such as compact disks⁴⁰ and old computer printed circuit boards⁴¹. Nanomaterials can also be added to improve the quality of secondary materials and achieve the desired functionality. Examples include concrete⁴² and different types of plastic⁴³, paper⁴⁴, composite⁴⁵ and alloy materials⁴⁶.

Finally, nanotechnology holds the potential to support a circular economy by recovery and substitution of rare elements⁴⁷. For instance, carbon-based nanomaterials (graphene, nanotubes and fullerenes) could potentially substitute 14 rare metals, such as indium in transparent electrodes⁴⁸. While the replacement is possible, it remains to be investigated whether this substitution increases the circularity of the products in which the nanomaterials could be used and whether this substitution is sustainable in the long run.

Safe and sustainable by design

The (eco)toxicological hazard profiles of many nanomaterials are challenging to establish. Recently, the European Commission revised the information requirements that manufacturers and importers must provide for nanomaterials under the EU's chemical legislation. The minimum characterization information includes particle number size distribution, surface functionalization, shape, aspect ratio, specific surface area and exposure estimates for all life-cycle stages. While this will help manufacturers, importers and downstream users to document appropriate risk management, it remains uncertain whether and to what extent the interactions between particle characteristics (for example, particle size distribution, surface chemistry and volume specific surface area) affect the overall hazard of a given nanomaterial⁴⁹. Similar to other chemical contaminants, tracking the fate of nanomaterial properties throughout the life cycle of secondary materials is not straightforward owing to the lack of suitable direct characterization techniques. Therefore, such techniques are required to ensure safety along the entire life cycle. Future discovery of nanomaterials may be driven by the use of machine learning and artificial intelligence, and safety considerations ought to be built into the machine learning algorithms⁵⁰. For this to be possible, considerable amounts of standardized high-quality data are needed in open-access databases that have yet to become available⁵¹.

There has been considerable progress in establishing 'safety by design' approaches for nanomaterials and nanoproducts in the past decade⁵². However, the tendency to treat safety as an inherent material property in its own right is problematic, as safety also depends on, for example, how materials are used⁵³. Consequently, complete and absolute nanomaterial safety will be difficult to guarantee in a future circular economy setting.

A final challenge for nanotechnology in a circular economy relates to the intention of the CSS to phase out harmful chemicals for non-essential uses. Obviously, what constitutes non-essential uses is a matter of opinion and subject to intense discussions. As an example, the Swedish non-governmental organization, ChemSec, was one of the first stakeholders to propose a step-wise approach that distinguishes between essential uses and two categories of non-essential uses. Categories of non-essential uses are: (1) products or uses that do not fulfil any basic human need or are not essential for the functioning of our society; and (2) products that are ubiquitous in our everyday life. In addition, medical products and devices, products for military operations, energy production and storage, transportation and communication, and alike are considered essential only if the product or process itself is considered essential for the overall functioning of society and if there are no alternative chemicals or other ways to achieve a similar end function at the product level⁵⁴. Independently of whether some nanomaterials can be argued to be harmful or not, it is noteworthy that almost all products (99%) currently listed in the Nanodatabase (www.nanodb.dk) fall into the two categories that ChemSec classifies as non-essential uses (Fig. 2). This Nanodatabase is an online inventory containing more than 5,200 products listed according to their manufacturers or other stakeholders⁵⁵. The only products that might be considered essential are 30 products that fall into the product category 'communication'.

Outlook

The introduction of a circular economy means that a set of key questions must be considered as early in the commercialization process as possible by researchers and developers of nanomaterials and nanomaterial-containing consumer products (Fig. 1). Some of these questions focus on the nanomaterial itself, including whether the nanomaterial is sustainable and safe by design, and whether it can be produced using waste as a resource without

a high energy and cost demand. Another set of questions is related to nanomaterial application and includes whether the envisioned use in certain products can be considered essential and how the value of the nanoproducts can be upheld for as long as possible. It also includes how nanoproducts can be maintained, repaired, reused, remanufactured, refurbished, regenerated and recycled. Finally, there is a set of questions related to the broader life-cycle management of nanoproducts. For instance, can waste generated during the life cycle of a nanoproduct be minimized? Can the release of hazardous substances at all stages of the life cycle be minimized? Can high-quality sorting and removal of contaminants from nanomaterial waste be ensured? Have the intrinsic thermal, mechanical and chemical recyclability properties of nanomaterials changed once these are mixed with other materials during recycling? Can the properties of the nanomaterials be regenerated if lost during processing? And can information about the nanomaterial be tracked and managed along the product life cycles?

If the answer to one or more of the above questions is negative for a certain nanomaterial or nanoproduct, further research and development investments should be put into aligning it better with the principles of circular economy. Considering the increasingly prominent position of the circular economy vision, those nanomaterials and nanoproducts will probably meet consumer backlash, negative media attention and extensive regulatory scrutiny. However, if the answers to these questions are positive, it is likely that nanotechnology can live up to the expectations of being the fast-moving technology that helps us reach the goal of increased circularity in society. □

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References

- Kirchherr, J. et al. *Resour. Conserv. Recycl.* **127**, 221–232 (2017).
- Towards a More Resource-efficient and Circular Economy: The Role of the G20 (OECD, 2021); <https://go.nature.com/3Gw5Q6h>
- Circular Economy and Material Value Chains (World Economic Forum, 2022); <https://go.nature.com/3x1151g>

4. *Summary for Policymakers: The Economic, Social, and Environmental Benefits of a Circular Economy in Indonesia* (Indonesia Circular Economy Forum, 2022); <https://indonesiacef.id/en/report/summary-for-policymakers-the-economic-social-and-environmental-benefits-of-a-circular-economy-in-indonesia/>
5. *A Circular Economy Roadmap for Plastics, Tyres, Glass and Paper in Australia* (CSIRO, 2022); https://www.csiro.au/-/media/News-releases/2021/circular-economy/20-00205_LW_CircularEconomyReport_WEB_210121.pdf
6. *Circulating and Ecological Economy* (Japan Ministry of the Environment, 2019); <https://go.nature.com/3t6orAe>
7. *Which Country is Leading the Circular Economy Shift?* (Ellen MacArthur Foundation, 2021); <https://go.nature.com/3wZNs2d>
8. *Regulation (EU) 2020/852 Art. 2(9)* (EU, 2020); <https://go.nature.com/3t7XpZb>
9. *Closing the Loop: An EU Action Plan for the Circular Economy* (European Commission, 2015); <https://go.nature.com/3LVY8s>
10. Pokrajac, L. et al. *ACS Nano* **15**, 18608–18623 (2021).
11. *The European Environment: State and Outlook 2015* (EEA, 2015); <https://go.nature.com/3PTV9i8>
12. *A New Circular Economy Action Plan for a Cleaner and more Competitive Europe* (European Commission, 2020); <https://go.nature.com/3t8fjkZ>
13. Horizon Europe. *European Commission* <https://go.nature.com/2ZdlPne> (2022).
14. *Chemicals Strategy for Sustainability Towards a Toxic-Free Environment* (European Commission, 2020); <https://go.nature.com/38RhVXn>
15. Geissdoerfer, M. et al. *J. Clean. Prod.* **143**, 757–768 (2017).
16. *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives* (European Parliament, 2008); <https://doi.org/10.5040/9781782258674.0028>
17. *Categorisation System for the Circular Economy: A Sector-agnostic Approach for Activities Contributing to the Circular Economy* (European Commission, 2020); <https://doi.org/10.2777/172128>
18. Hansen, S. F., Larsen, B. H., Olsen, S. I. & Baun, A. *Nanotoxicology* **1**, 243–250 (2007).
19. Akhrame, M. O. et al. *Polym. Bull.* **76**, 647–681 (2019).
20. Reijnders, L. in *Health and Environmental Safety of Nanomaterials: Polymer Nanocomposites and Other Materials Cotton Nanoparticles* (eds Njuguna, J. & Pielichowski, K.) 222–250 (Woodhead Publishing, 2014).
21. Myakontkaya, O., Hu, Z., Nazar, M. F. & Eastoe, J. *Chem. Eur. J.* **16**, 11784–11790 (2010).
22. Olapiriyakul, S. & Cuadhill, R. J. *Environ. Sci. Technol.* **43**, 8140–8146 (2009).
23. Busquets-Fité, M. J. *Phys. Conf. Series* **429**, 012048 (2013).
24. Deep, A. et al. *Environ. Sci. Technol.* **45**, 10551–10556 (2011).
25. Deep, A. et al. *Waste Manage* **51**, 190–195 (2016).
26. Schauerma, C. M. et al. *J. Mater. Chem.* **22**, 12008–12015 (2012).
27. Živković, D. et al. *Recycl. Sustain. Devel* **7**, 1–8 (2014).
28. *Study on the Product Lifecycles, Waste Recycling and the Circular Economy for Nanomaterials* (EUON ECHA); <https://go.nature.com/3POR3Yp>, 2021
29. Avazverdi, E. et al. *Prog. Rubber Plast. Recycl. Technol.* **32**, 99–110 (2016).
30. Recycling of waste containing nanomaterials. In *Nanomaterials in Waste Streams: Current Knowledge on Risks and Impacts* (OECD, 2016); <https://doi.org/10.1787/9789264249752-5-en>
31. Pivnenko, K. & Astrup, T. F. *Waste Manage* **56**, 1–2 (2016).
32. Heggelund, L. R. et al. *Waste Manage* **56**, 584–592 (2016).
33. Tiwary, C. S. et al. *Mater. Today* **20**, 67–73 (2017).
34. Dutta, T. et al. *Renew. Sustain. Energy Rev.* **82**, 3694–3704 (2016).
35. Singh, J. & Lee, B.-K. *Waste Manage* **48**, 353–365 (2016).
36. Yaoping, H. et al. *RSC Adv.* **4**, 47169–47176 (2014).
37. Ghosh, A. & Das, G. *New J. Chem.* **45**, 8747–8754 (2021).
38. Tatrari, G. et al. *Mater. Adv.* **2**, 1454–1484 (2021).
39. Samaddar, P. et al. *J. Clean. Prod.* **197**, 1190–1209 (2018).
40. Rajarao, R. et al. *Mater. Lett.* **120**, 65–68 (2014).
41. Shokri, A. et al. *J. Clean Prod.* **142**, 2586–2592 (2017).
42. Vishwakarma, V. & Ramachandran, D. *Constr. Build. Mater.* **162**, 96–103 (2018).
43. Distaso, M. *Acta Innov.* **37**, 57–66 (2020).
44. Sabazoodkhiz, R. et al. *Cellulose* **24**, 3433–3444 (2017).
45. Irez, A. B. et al. *Composites B* **148**, 1–13 (2018).
46. Yawer, A. K. et al. *Mater. Today Proc.* **42**, 2095–2101 (2021).
47. Rahman, M. M. et al. *Sep. Purif. Technol.* **253**, 117515 (2020).
48. Arvidsson, R. & Sandén, B. A. *J. Clean. Prod.* **156**, 253–261 (2017).
49. Clausen, L. P. W. & Hansen, S. F. *Nat. Nanotechnol.* **13**, 766–768 (2018).
50. Jia, Y. et al. *ACS Sustain. Chem. Eng.* **9**, 6130–6147 (2021).
51. Winkler, D. A. *Small* **16**, 2001883 (2020).
52. Morose, G. *J. Clean. Prod.* **18**, 285–289 (2010).
53. Hjorth, R. et al. *Nanotoxicology* **11**, 305–312 (2017).
54. When is it justified to use very hazardous chemicals? *ChemSec* <https://go.nature.com/3N1Rj4D> (2021).
55. Hansen, S. F. et al. *Nat. Nanotechnol.* **15**, 964–965 (2020).

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