Metallurgical and Materials Data 3, no. 4 (2025): 121-125

Publisher: Association of Metallurgical Engineers of Serbia

Metallurgical and Materials Data

www.metall-mater-data.com

Nanomaterial synthesis methods and the treatment of nanowaste with the possibility of recycling

Rebeka Rudolf[1,2,3,*], Senka Šekularac Ivošević[4], Špiro Ivošević[4], Peter Majerič[1,2,3]

[1] University of Maribor, Faculty of Mechanical Engineering, Smetanova ulica 17, 2000 Maribor, Slovenia
[2] Zlatarna Celje d.o.o., Kersnikova ulica 19, 3000 Celje, Slovenia
[3] Institute Jožef Stefan, Jamova 20, 1000 Ljubljana, Slovenia
[4] University of Montenegro, Faculty of Maritime Studies Kotor, Put I Bokeljske Brigade 44, 85330 Kotor, Montenegro

ARTICLE INFORMATION:

https://doi.org/10.56801/MMD76

Received: 20 November 2025
Accepted: 19 December 2025

Type of paper: Review paper

ABSTRACT

This review article presents different types of nanotechnologies and syn-thesis of nanomaterials. The use of nanomaterials is presented in different sectors. The following discusses the issue of when the post-use phase of nanomaterials occurs and when they become nanowaste. This waste must be handled carefully, so as not to endanger human health and the environment. In this discussion, we therefore present potential approaches that could be used in the future for recy-cling nanomaterials. Namely, the idea is to include nanomaterials in the circular economy, so that the way of organising their synthesis and consumption, which is based on sharing, reuse, repair, renovation and recycling of existing nanomaterials and nanoproducts, would be as long as possible.

Keywords: nanomaterials, use, nanowaste, recycling.

1. Introduction

Nanotechnology is a branch of science and engineering that focuses on the synthesis of materials that have at least one dimension of 100 nm or less. These are nanoparticles (Figure 1), nanotubes, nanopyramids, nanocomposites (Figure 2) etc., and all of them have different properties compared to materials of conventional dimensions. Their modified physicochemical properties originate from the large surface area to volume ratio, which is reflected in their higher surface activity. Nanomaterials have multiple advantages, including high stability, target selectivity and plasticity. Due to these properties, they can be used in various fields, from electronics, chemistry, biotechnology, medicine, and, recently, also in space technology *(Scalia, 2020)*.

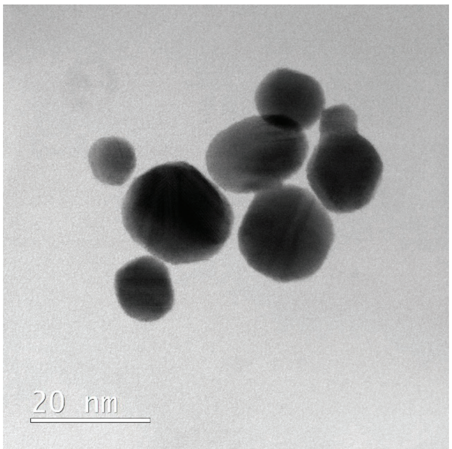

Fig. 1. Au nanoparticles synthesised by Ultrasonic Spray Pyrolysis

* Corresponding author.
E-mail address: rebeka.rudolf@um.si (Rebeka Rudolf).

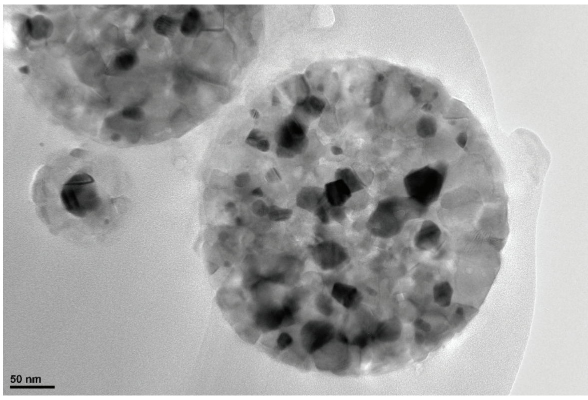

Fig. 2. Ag/TiO2 nanoparticles synthesised by Ultrasonic Spray Pyrolysis

2. Nanomaterial synthesis methods

We know different production technologies or nanomaterial synthesis methods, which are classified into "bottom-up" (from the bottom up) and "top-down" (from the top down). Examples of "bottom-up" methods are sol-gel, chemical vapour deposition - CVD, flame spray synthesis, various pyrolyses and atomic or molecular condensation (Salek, 2022). Examples of top-down methods include laser ablation, nanolithography and high-energy milling (Abid, 2022). The classification of various production technologies is shown in Figure 3.

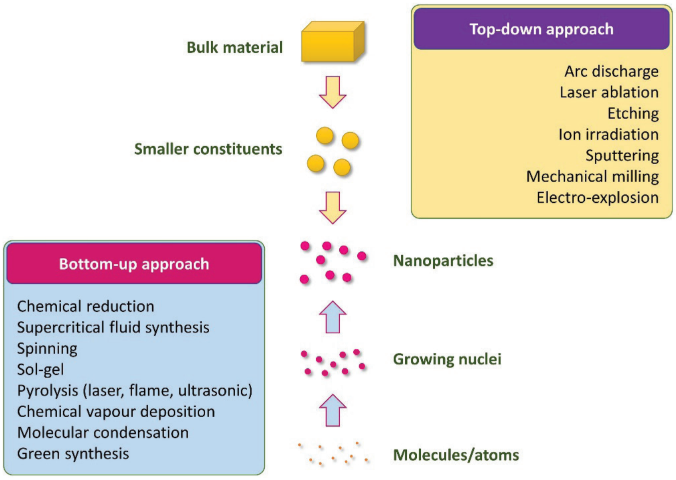

Fig. 3. Top-down and bottom-up production technologies, from (Rudolf, 2025)

Currently, these methods are suitable for producing small quantities of nanoparticles with large variations in size and shape from one batch to another. A bottom-up method called Ultrasonic Spray Pyrolysis (USP) has good potential to overcome these technological problems and achieve more controlled synthesis of nanoparticles *(Majerič, 2020)*. Pyrolysis is generally a process of chemical decomposition of various compounds at elevated temperatures. In the USP method, ultrasound is introduced additionally, which is used to disperse a solution with the desired material into droplets. These droplets are exposed to elevated temperatures, so that the material from the droplet is decomposed chemically by pyrolysis, thus obtaining nanoparticles of pure elements. The advantages of the USP method are: simple placement of individual elements and changing their configuration, continuous synthesis of nanoparticles and the possibility of synthesising high-purity nanoparticles from various materials. The disadvantage of the method is the low efficiency of USP devices (currently around 50%) due to losses of dissolved material on individual structural elements of the USP device.

The use of nanomaterials is known today in many sectors, and some examples are presented below:

Electronics: Nanomaterials can be used in electronic devices such as smartphones, laptops and televisions, to improve performance and reduce energy consumption. They can create high-resolution displays, improve storage capacity, and improve the efficiency of rechargeable batteries, among other things (*Salaudeen, 2024*).

Biotechnology: Nanomaterials in biotechnology can improve the efficiency of a variety of techniques dramatically, including drug delivery, water and soil remediation and enzymatic processes. In this review, the techniques that benefit most from nano-biotechnological approaches are grouped into four main areas: medical, industrial, agricultural and environmental (Shahcheraghi, 2022).

Medicine: Nanomaterials can be used in medical applications such as imaging, diagnosis and treatment. Nanoscale drug delivery systems can improve the efficacy and target specificity of drugs significantly (*Damodharan, 2021*).

Space technology: Nanomaterials and nanostructures have a broad impact on space missions and programmes (e.g., launchers, planetary science and exploration). Their main benefits are related to reduced vehicle mass, the improved functionality and durability of space systems and increased propulsion performance (*Scalia, 2020*).

Environmental remediation: Cleaning up pollutants and contaminants using nanoparticle-based catalysts and nanofilters that can clean polluted water, air and soil by removing pollutants and pathogens (*Roy,2021*).

Food and Agriculture: Improving the quality, safety and shelf life of food and agricultural products by using nanomaterials, which improves the efficiency and effectiveness of various toxic compounds while reducing their impact on the environment, and improving the efficiency and effectiveness of irrigation systems, leading to reduced water use and better crop growth (*Jain, 2017*).

3. Nanomaterials and environmental impact

Nanomaterials may pose certain risks to human health and the environment, including toxicity, reactivity, and the release of particles into the air, water and soil. Long-term exposure to nanoparticles may cause chronic health problems, such as respiratory problems, cardiovascular disease and reproductive problems *(Rakesh , 2024)*.

There are also concerns about the impact of nanomaterials on ecosystems and wildlife, and their persistence in the environment (*Bakshi, 2020*). In addition, the unique properties of nanomaterials may pose safety concerns during synthesis, handling and application. Further scientific research is needed to understand these risks fully.

In the future, the increased use of nanomaterials may also lead to an increase in the risk of toxicity and chemical reactivity towards the ecosystem. This will need to be monitored. The effects of many purpose-made nanomaterials on human health and the environment are not yet explained well scientifically, and it is also important to note that not all nanomaterials have hazardous properties. A review of the literature shows that studies conducted on the same type of nanomaterials are inconsistent; some studies indicate the biocompatibility of nanomaterials *(Eyube, 2024)*, while others demonstrate a potentially hazardous nature (e.g. carbon nanotubes) *(Koiranen , 2017)*. The potential risks of these materials thus depend on their size, shape and degree of agglomeration and solubility in media, as well as on other physicochemical properties. The removal of nanomaterials from products containing nanomaterials must be carried out with particular care, to ensure that the nanomaterials are harmless to the health of the people who handle them and that they are not released into the environment. Nanomaterials need to be neutralised that are potentially hazardous, toxic or chemically reactive.

The impact of nanomaterials in the environment may also depend on their physicochemical properties and their interactions with other pollutants *(Kabir, 2018)*. Nanomaterials that are found in the environment naturally are the product of various natural phenomena such as volcanic eruptions, soil erosion, forest and other fires, dust storms, etc., or they originate from intentional/unintentional human activities (e.g. burning fossil fuels, mining/demolition of buildings, automobile and air traffic, etc.).

The environmental impacts of nanomaterials vary according to their size, shape, composition and the amounts released. Proper treatment and disposal of nanoparticle waste is crucial for preventing ecological damage, as many conventional waste management systems are not designed to process nanoparticles effectively. When disposed of improperly, by depositing on a landfill or by incineration, nanomaterials can be released into the environment with negative consequences *(Aswathi, 2022)*.

4. Nanowaste

The general definition of waste is that it is a substance or object that the holder discards, intends to discard, or is required to discard. Waste can be divided into types and streams according to the source of generation, according to the properties of the waste into hazardous and non-hazardous, and according to individual waste streams with the same or similar properties and requirements for their management.

Nanowaste can be the result or by-product of industrial or commercial processes that use them. Due to the different types of nanomaterials, such as their chemical composition, size, shape and use, a single recycling process will not be sufficient for all classes of nanomaterials.

Handling nanowaste will require developed safety measures for its handling, and only then would it be possible to envisage the possible degradation or recycling of nanomaterials. The broader scientific community and decision-makers will need to develop assessments, regulations and monitoring measures for manufacturers involved in nanotechnology. Extensive environmental and health impact studies will need to be carried out before nanomaterials are placed on the market; these will need to include studies on the toxicity and chemical reactivity of new nanomaterials. Only then can safe disposal and potential recycling procedures be established. Manufacturers of nanomaterials (or independent bodies) will also need to determine whether these substances or production techniques could pose a risk to public health or the environment. Products will only be allowed to be marketed if there is no risk, or if the risk can be controlled by protective measures *(Rudolf, 2020)*. Concentrated industrial nanowaste will need to be diluted and deactivated after use. In addition, companies producing nanomaterials and companies using them, where nanowaste is generated as a by-product of their industrial activities, will need to demonstrate that they do not pose a risk to the environment or human health. We believe that newly developed nanomaterials should not be placed on the market without appropriate collection protocols and possible recycling. As part of the collection, appropriate storage procedures will also need to be developed, which will need to be reviewed and approved by government agencies on the basis of indisputable evidence. To provide sufficient evidence, the manufacturers will be able to conduct their own tests, or, in individual cases, they will be able to refer to existing scientific procedures and findings from nanowaste research.

When nanomaterials are released into the environment they enter the nanowaste phase, and then pass through various pathways to environmental systems. The lack of regulatory requirements, standard methodologies for proper characterisation, and the continuous production of new nanomaterials make it difficult to evaluate the resulting nanowaste. Such a lack of data on nanowaste increases the level of uncertainty in risk assessment and leads to poor risk management and public communication. It will therefore be necessary to develop guidelines that will introduce a new perspective in the risk assessment of nanowaste, in order to address its risks in a more systematic and precise manner.

At present, nanowaste is regulated primarily under the existing conventional waste management frameworks, despite fundamental differences in the transport behaviour, chemical reactivity and exposure pathways. Regulatory approaches at the European and international levels largely treat nanomaterials indirectly, resulting in a regulatory gap for nanowaste-specific risk assessment, monitoring and recycling. The development of harmonised guidelines, standardised classification schemes and life-cycle-based regulatory approaches will be necessary, to ensure the safe handling, disposal and potential recycling of nanomaterials.

There are currently no data on the amount of nanowaste generated *(Zahra, 2022),* but the fact is that the large increase in the synthesis of nanomaterials and nanoproducts has led to an increased release of nanopollutants into the environment.

Despite the significant increase in scientific interest in nanowaste, several critical knowledge gaps remain. Quantitative data on nanowaste generation rates are largely unavailable, and standardised methodologies for characterising nanowaste are still lacking. Furthermore, techno-economic assessments of nanomaterial recycling pathways are still scarce, limiting industrial applications. Addressing these gaps is essential for moving nanomaterial management from laboratory-scale concepts to viable industrial and regulatory frameworks.

5. Tehnological pathways and constraints for nanomaterials` recycling

5.1 Classification of nanomaterials from a recycling perspective

The recycling of nanomaterials represents a technologically complex challenge, that differs fundamentally from conventional material recycling due to the nanoscale dimensions, high surface reactivity, and frequent incorporation of nanomaterials into complex matrices. Consequently, recycling strategies must be tailored to the nanomaterial class, application and post-use condition. This section therefore distinguishes major technological pathways for nanomaterial recycling, while highlighting their practical limitations and constraints.

From a recycling standpoint, nanomaterials can be classified broadly according to their composition, structural stability and potential for chemical transformation (see Table 1.). Metallic nanoparticles generally offer higher recycling potential, due to the possibility of conversion into ionic form and subsequent re-synthesis. In contrast, carbon-based nanomaterials and hybrid nanocomposites often exhibit limited recyclability and may require stabilisation or neutralisation rather than recovery.

Table 1. Nanomaterial types and recycling feasibility

Nanomaterial class	Typical applications	Recycling difficulty	Preferred recycling strategy
Noble metal nanoparticles (Au, Ag)	Electronics, catalysis, medicine	Low–moderate	Chemical dissolution → re-synthesis
Metal oxide nanoparticles (TiO_2, ZnO)	Photocatalysis, coatings	Moderate	Thermal/chemical transformation
Carbon nanotubes / graphene	Composites, electronics	High	Stabilisation, containment
Hybrid nanocomposites	Structural materials, coatings	Very high	Matrix degradation or disposal

In the field of nanotechnology the goal is to use recycling processes for worn and discarded nanomaterials wherever possible. All the processes will have to be based on a good knowledge of scientific issues and professional practices, taking into account the existing legislation. The degradation processes will have to ensure that the nanowaste is stable and free of hazardous properties at a later time after use. On this basis, it will be necessary to examine different types of processing of nanomaterials, from thermal, chemical or physical, with the introduction of new, innovative technological solutions for decomposition.

5.2. Recycling pathways for nanomaterials

The potential recycling routes for nanomaterials include physical separation, chemical dissolution, thermal transformation and re-synthesis via bottom-up approaches. Table 2. shows the recycling pathways and their limitations. Physical methods such as filtration or sedimentation are generally insufficient as standalone solutions, due to particle aggregation and incomplete separation. Chemical conversion into ionic or molecular precursors represents one of the most promising routes, enabling subsequent re-synthesis of the nanomaterials using established bottom-up methods such as sol-gel processing, or ultrasonic spray pyrolysis. However, the efficiency of such approaches depends strongly on the precursor purity and contamination control.

Recycling metal nanomaterials will not be easy (*Sharma, 2022*). First, the metal nanomaterial must be collected and sorted properly, and then an appropriate recycling process must be selected. Nanomaterials are found in paints, cosmetics, textiles, pharmaceuticals, metal coatings, electronics, construction, automobiles, pharmaceutical delivery and energy production. The nanometre size makes the treatment of nanowaste very difficult, and allows them to interact strongly with biological structures, therefore they pose a potential risk to human health and the environment. The nanometre size also poses a problem in the separation, processing and reuse of nanoparticles. Recycling can be carried out using incineration, nanofiltration or nanosedimentation, which are preliminary methods of pre-treatment for the recycling of nanowaste. These methods release the degraded material directly into the environment, so an alternative type of treatment is needed to protect living organisms and the environment. One of the variants is the possibility of converting metal nanomaterials into ionic or some other form, which could be processed in the next production stage into a new recyclate. It is known that it is possible to re-synthesise different types of nanomaterials from the ionic state using various "bottom-up" approaches. The key here is the purity of the prepared solution with the dissolved ions, which will affect the final properties of the synthesised new nano-recyclate during synthesis significantly.

The main advantage of recycling is that, by reusing recycled nanomaterials, the impact on environmental pollution would be reduced significantly by reducing the waste, energy consumption, and, indirectly, the share of greenhouse gas emissions, which is one of the goals of the circular economy. Reusing and recycling nanomaterials will slow down the consumption of natural resources, reduce the encroachment on landscapes and habitats, and help limit the loss of biodiversity. Designing more efficient and sustainable products would help reduce energy and resource consumption, as estimates show that more of a product's environmental impact is determined at the design stage. Moving to more reliable nanoproducts that can be reused, upgraded and repaired would reduce nanowaste.

5.3 Technological and safety constraints

Significant constraints currently limit large-scale nanomaterial recycling, including difficulties in nanoscale separation, energy demands, occupational exposure risks and the lack of standardised recycling protocols. In many cases, the existing waste treatment methods act primarily as degradation or containment strategies rather than true recycling solutions. Addressing these limitations will require the integration of material design, process engineering and risk management already at the nanomaterial development stage, as is shown clearly in Table 3.

6. Conclusions

The use of the term recycling of nanomaterials has a higher meaning, as it does not only include the consideration of possible technologies that could be used to obtain a new nano-recyclate. Based on this is shown a possible conceptual life-cycle illustrating the transition from nanomaterial synthesis, through product integration and use, to nanowaste generation and potential recycling pathways (Figure 4). In the future, it will also be necessary to focus on the risk part, taking into account the life cycle of synthesised nanomaterials, which includes understanding the synthesis processes and properties of the nanomaterials that result in interactions with humans or the environment between its synthesis and its useful life. It will also be necessary to focus on appropriate characterisation techniques, that identify their properties and help in understanding how to recycle nanomaterials successfully. From a risk management perspective, it will be necessary to identify systematically those critical issues that will need to be studied in more detail scientifically.

Table 2. Recycling pathways and their limitations

Recycling pathway	Principle	Advantages	Key limitations
Physical separation	Filtration, sedimentation	Simple, low cost	Inefficient at the nanoscale
Chemical dissolution	Conversion to ionic species	Enables re-synthesis	Purity control required
Thermal treatment	Incineration, pyrolysis	Volume reduction	Environmental release risk
Bottom-up re-synthesis	Sol-gel, USP, CVD	High material quality	Energy and process control

Table 3. Classification of nanowaste according to origin and properties

Nanowaste category	Source	Key characteristics	Management challenge
Production nanowaste	Synthesis processes	High concentration, controlled composition	Occupational exposure
Product-embedded nanowaste	Consumer & industrial products	Low concentration, complex matrices	Separation difficulty
Accidental release	Spills, wear, abrasion	Uncontrolled dispersion	Environmental exposure
End-of-life nanowaste	Disposal of products	Mixed material streams	Lack of protocols

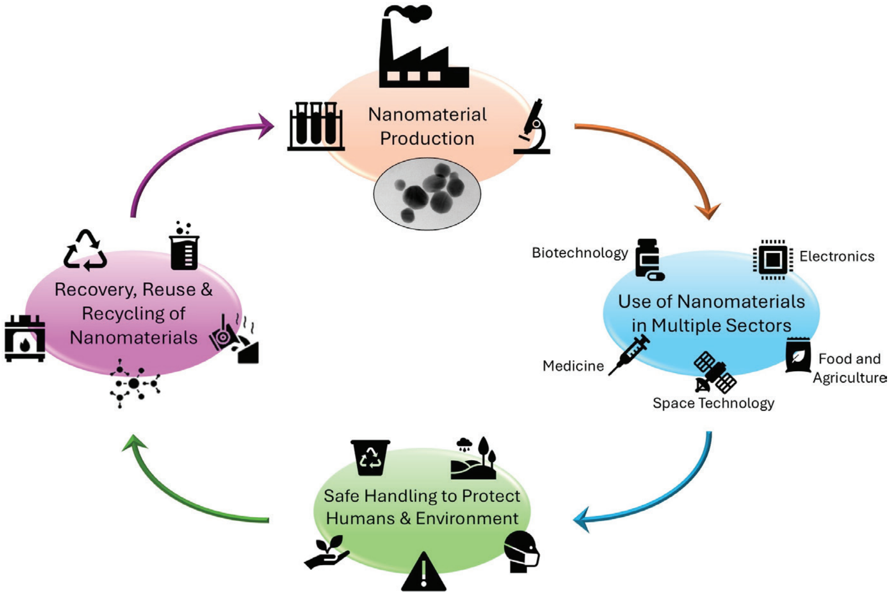

Fig. 4. Schematic presentation of nanomaterials conceptual life-cycle

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgment: This research was funded by the Slovenian Research Agency ARIS: P2-0120 Research Programme and BI-ME/25-27/014 Bilateral project.

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