MAKING NANOFABRICATION GREENER: HARNESSING THE POWER OF BOTTOM-UP METHODOLOGIES

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Making Nanofabrication Greener: Harnessing the Power of Bottom-up Methodologies

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Abstract

The interest in nanostructured materials is expanding across many fields of research and technology due to their unique properties, including high surface area, versatile chemical functionalization, and distinct magnetic, electrical, optical, and catalytic characteristics compared to their bulk counterparts. As a result, nanostructured materials find utility in a wide range of fields, including sensing, medicine, and energy storage. However, the fabrication of these nanostructures presents challenges that intersect with the goals of sustainable development. Thus, traditional nanofabrication techniques, often involve hazardous chemicals, high energy consumption, and generate significant waste. Additionally, their scalability is often limited. Addressing these challenges requires the development of greener fabrication processes that minimize environmental harm and energy usage, as well as the integration of sustainable practices throughout the entire lifecycle of nanostructured materials. In this regard, bottom-up approaches, and in particular colloids, biomolecules, and block copolymers, offer promising solutions. These versatile materials can self-assemble into precise nanostructures with minimal energy input, reducing environmental impact. Finally, innovations involving to the usage of bio-based building blocks have put the focus not only on addressing the environmental footprint of nanostructure fabrication but also on promoting the use of renewable resources and enhancing their recycling.

Keywords
Nanofabrication, Bottom-up, Block copolymers, Bio-molecules, Bio-based,

Introduction

Nanoscience, a long history short

Nanomaterials are materials characterized by dimensions within the nanoscale range, typically between 1 and 100 nm in any external dimension, internal structure, or surface feature (ISO n.d.) While nanomaterials and nanotechnology are often perceived as contemporary terms associated with cutting-edge science, it is important to recognize that the synthesis and applications of such materials data back to ancient times. Even though the precise history of the use of nanosized objects by humanity is difficult to elucidate, early examples, such as the use of asbestos nanofibers or carbon nanotubes to reinforce ceramic mixtures, as well as the employment of metallic nanoparticles to create colour effects on pottery or glass surfaces, trace back as far as the thirteenth or fourteenth century A.D. (Caiger-Smith, 1985) In this sense, one of the most renowned examples of the usage of nanomaterials in early times is the Lycurgus Cup, crafted by the Romans in the fourth century A.D. (Heiligtag & Niederberger, 2013) This dichroic cup presents a jade-like appearance under direct light, transitioning into a translucent red colour when light passes through it, showcasing also colour variations depending on incident light angles. During the modern age, painters, artists, and artisans were continuing employing these materials without knowing the cause of these surprising effects (Heiligtag & Niederberger, 2013).

The modern concept of nanotechnology and the study of the unique properties that derive from them was introduced by the American physicist and Nobel Prize Richard Feynman in 1959 during his lecture entitled “There’s Plenty of Room at the Bottom” at the California Institute of Technology (Caltech), in which he described the possibility of directly manipulate individual atoms as a design tool more powerful than conventional chemistry. Two more events remain as stepping stones in the progress of nanoscience, one is the invention of scanning tunnelling and atomic force microscopies in the 1980s, (Anderson et al., 1982; Binnig & Rohrer, 1983)and the other is the development of powerful lithographic tools started in the 1980s-1990s. (Lawson & Robinson, 2016) While the first one allowed for the first time not only to observe but also to manipulate surfaces at the atomic scale, the introduction of lithographic approaches allowed the creation of ordered and controllable structures at the nanoscale over large surface areas. Since then, researchers have directed their efforts toward refining fabrication methodologies for greater efficiency and precision, alongside investigating the distinctive optical, mechanical, electrical, magnetic, and chemical properties arising from the resulting nanostructures.

The several nanofabrication technologies developed during the last decades for the production of structures with sub-100 nm dimensions can be broadly categorized into two groups depending on the direction of structure creation: top-down and bottom-up approaches. In the following section, more details about both approaches will be provided, with a special focus on their advantages and limitations in terms of their sustainability and environmental impact.

Top-down: lights and shadows

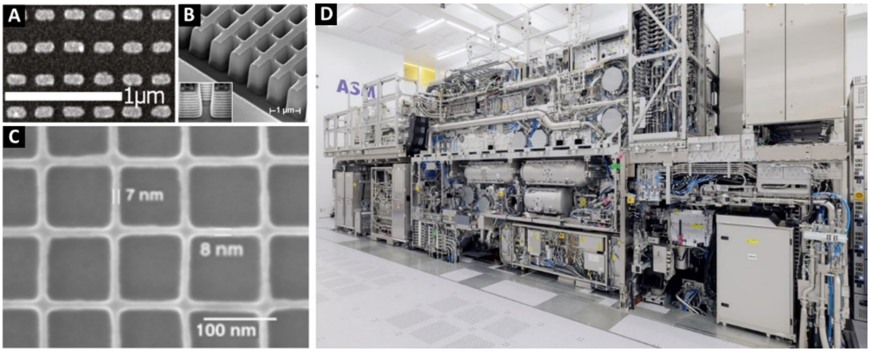
Top-down approaches can be likened to sculpting from a block of stone to obtain the desired shape. In these methodologies, external experimental parameters such as light, electrons, ions, or mechanical forces, among others, are typically employed to pattern materials and create nanostructures through the selective etching or partial removal of material. As previously highlighted, lithography stands as one of the most crucial top-down methodologies in nanofabrication. Lithographic-based techniques involve transferring a pattern from a mask or template onto a substrate through selective exposure to radiation, typically light or electrons. Widely adopted in the semiconductor industry, techniques such as optical lithography, electron-beam lithography, and X-ray lithography enable the fabrication of integrated circuits and intricately defined nanostructures with exceptional precision (see Figure 1A). Another category within lithographic techniques involves scanning probe methods. In this approach, a sharp tip is directly employed to pattern substrates at the nanoscale using techniques like scanning tunnelling microscopy (STM) and atomic force microscopy (AFM). These methods enable the precise manipulation of atoms or molecules, facilitating the creation of highly controllable and adjustable nanostructures. Also part of the lithographic techniques family is nanoimprinting lithography (NIL), which involves pressing a template with predefined patterns into a deformable material, such as a polymer resist, and the subsequent transfer of the pattern. It has attracted growing interest in recent years due to its cost-effectiveness compared to other lithographic methods and its capability for facilitating large-scale pattern creation. Alternative top-down methodologies such as chemical or dry etching have also been successfully applied in the preparation of materials at the nanoscale. The selective removal using chemical reactive solutions (chemical etching) or plasma (dry etching) enables the fabrication of high-precision patterns and features over large surface areas (around cm^2) by the usage of a mask and the etching of the exposed material.

Even though top-down methodologies have historically been pivotal in nanofabrication, various concerns regarding their environmental impact, economic costs, and technical constraints have impeded their further advancement and widespread application across many research fields and industries. Technical restrictions are related to material compatibility, restricting the range of materials that can be used for nanomaterials fabrication, and resolution limitations. Thus, constraints inherent to the top-down fabrication approach such as the diffraction limit, lateral spread during the patterning process, or imperfection at the mask used, have limited the obtention of ultra-small (sub-10 nm scale) using standard top-down fabrication methodologies. These technical problems have been partially solved with the introduction of more complex technologies such as Extreme Ultraviolet Lithography (EUV) but the adoption of these new methodologies has exacerbated the concerns about their environmental and economic impact. Thus, the cost of one of the most advanced EUV machines, fabricated by the Dutch company ASML can be over $380 million (ExtremeTech, 2024). This new machine focused on high numerical-aperture (high-NA) EUV, allows the fabrication of complex nanopatterns down to 4-8 nm. However, the associated high cost, together with the complex technologies involved during the manufacturing and subsequent fabrication process make this technology not accessible to the majority of industries. In addition to this, access to these technologies has been recently used as a weapon in the economic conflict between the USA and China.

In terms of sustainability (the focus of this work) concerns are common to all the top-down approaches such as high energy consumption or waste generation. Thus, the high complexity of the required setups, which often include powering motors, heating and cooling elements, vacuum pumps, light, x-ray, electron sources, and other components, makes the top-down-based fabrication methodologies energy-intensive. Thus, the energy consumption of a standard EUV machine is estimated at around several tens of megawatts during typical operation, ASML Annual Report (2020) which could be roughly equivalent to the annual energy usage of approximately 2.000 average households in Europe. Another important factor that needs to be considered is also the water consumption of these machines. Top-down methodologies often require cooling systems for the refrigeration of various equipment, including lasers, vacuum pumps, or processing chambers. Thus, for example, cooling water flow for standard immersion double-patterning optical lithography is estimated at 75 L/min which means 39.5 million water litters per year are needed for the correct operation of the machine. With the increase in the complexity of the techniques and required setups, water consumption grows exponentially. Standard EUV machines need around 1600 L of water per minute only to refrigerate all their components ASML Annual Report (2020).

Figure 1.

Scanning Electron Microscopy (SEM) images of different nanostructures recently proposed in the literature fabricated by top-down techniques ***(A-C).*** *Reprinted with permission.(X. Li & Gilchrist, 2016a) Copyright 2016 American Chemical Society. Setup of the high-NA EUV equipment of ASML* ***(D)***



The increase in the complexity of the required machines has also another collateral impact: the weight of the top-down setups is also growing. While a standard optical photolithography system had an average weight of a few hundred kilograms, a typical EUV tool weighs around 180 tons (Figure 1B). With the assembly sites placed often far away from the industrial facilities where the top-dawn machines are going to be used, their transportation has a big impact in terms of CO_2 emissions. To put it in context, according to the International Maritime Organization (IMO), the average emissions from maritime shipping are approximately 13 grams of CO_2 per ton-kilometre (gCO2/ton-km). (*Third IMO GHG Study 2014*, n.d.) Extrapolating these numbers, the transportation of a standard EUV machine with a weight of around 180 tons from Rotterdam (Netherlands) to Shanghai (China), covering roughly 22,000 kilometres, would result in emitting approximately 52 tons of CO_2, equivalent to the annual CO_2 absorption of approximately 2,300 to 2,360 mature trees.

In addition to their energy and water consumption, and related shipping costs, another significant concern regarding the ecological impact of top-down fabrication approaches is their substantial waste production. One of the most significant portions of the generated waste is related to their water consumption, i.e., water used for cleaning, cooling, or even at some chemical processing can be contaminated with chemicals or particles and therefore requires treatment before disposal to avoid environmental harm. Additionally, chemical processes used in top-down fabrication, such as wet etching or photoresist development, generate waste solutions which often contain hazardous or toxic chemicals. Finally, as highlighted in this section, the ongoing advancement and evolution of top-down methodologies underscore the importance of managing end-of-life considerations for fabrication equipment and components. Over time, these components may reach the end of their lifecycle, contributing to electronic waste (e-waste).

For all these reasons intensive research has been developed in the last decades to explore alternative fabrication approaches that allow more sustainable and environmentally friendly nanofabrication methodologies. It is within this context that bottom-up fabrication approaches emerge as a contrasting counterpart to traditional top-down methodologies. In the following section, they will be introduced and their advantages and disadvantages discussed.

Bottom-up: the revolution of the small things

Bottom-up nanofabrication refers to the process of building structures or materials from the bottom or atomic/molecular level up. Contrary to previously mentioned top-down methodologies, here atoms, molecules, or nanoparticles are manipulated and arranged to construct the desired nanostructures or nanomaterials. One of the main advantages of these approaches is their scalability since they do not suffer from the limitations previously mentioned such as the diffraction limit or lateral spread during the patterning process. Moreover, they do not normally require big infrastructures or restrictive environments, making nanofabrication and nanoscience potentially available for many industrial applications and research environments. The main bottom-up methodologies are focused on the usage of colloidal or polymeric species that spontaneously arrange themselves into the desired structure under the right conditions, such as the nature of the solvent, the chemistry of the substrate surface, or the interactions between the molecules or particles used as building blocks. The following sections will be focused on the key bottom-up approaches, highlighting the diverse nanostructures achievable through each technique.

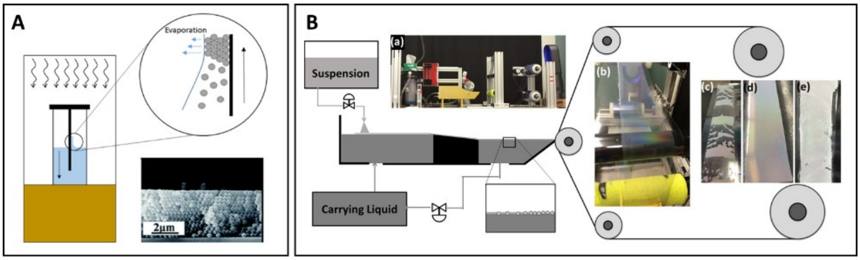
Colloidal self-assembly

Self-assembly of colloidal particles has proven to be an inexpensive method to fabricate nanometric structures, from monolayers to 3D nanomaterials with a wide variety of possible shapes (Galisteo-Lõpez et al., 2011; S. H. Kim et al., 2010, 2011). 3D structures have been mainly produced using the so-called evaporation-induce colloidal self-assembly by vertical, or convective deposition method(Dimitrov & Nagayama, 1996; Jiang et al., 1999). This technique relies on capillary forces to organise colloids during the evaporation of a liquid (Figure 2A), leading to the crystallization of spheres into a multilayered three-dimensional FCC lattice (Kralchevsky & Nagayama, 1994). Colloidal crystals, inverse opals and photonic glasses have been developed using this technique (Bian et al., 2018; Finlayson & Baumberg, 2013; Mishchenko et al., 2012; Wong et al., 2003). Thereby, using this approach, Xiao et al. have recently shown the versatility of bio-inspiring artificial opals, composed of colloidal dielectric spheres, to present specific structural colour responses by tuning the thickness and concentration of the assembled particles (Xiao et al., 2015).

One of the main limitations of colloidal assembly is the difficulty of obtaining larger nanostructured surface areas. To address this, colloidal assembly is frequently complemented by other conventional deposition techniques, including drop-casting,(Hoang et al., 2015) spin-coating, (Brasse et al., 2018; Müller et al., 2014) and Langmuir-Blodgett deposition.(König et al., 2014; Volk et al., 2015) In this sense, Li and coworkers have presented an automated Langmuir−Blodgett deposition design that allows continuous roll-to-roll deposition of particles into well-ordered arrays (Figure 2B) (X. Li & Gilchrist, 2016b). Other limitations inherent to the colloidal assembly are for example the obtention of nanostructures with a high number of defects, due to the spontaneous nature of the assembly. This can be important for applications where long-range order is required such as the microelectronics industry, however, it may be less critical for other high-end applications like optics or sensing, where the emphasis lies more on specific functionalities rather than perfect structural regularity.

Figure 2.

Self-assembly of multi-layer colloidal arrays through the vertical deposition technique and SEM image of the cross-section of SiO2 NPs ***(A).*** *Schematic illustration of experiment setup using an automated Langmuir–Blodgett* ***(B)*** *Reprinted with permission (X. Li & Gilchrist, 2016a). Copyright 2016 American Chemical Society.*



From the environmental perspective, colloidal self-assembly overpasses many of the concerns specified for the top-down methodologies. Thus, since colloidal self-assembly techniques rely on processes driven by thermodynamic or kinetic principles, they typically require minimal energy input compared to the high energy consumption associated with top-down approaches discussed previously. Additionally, concerns regarding the quantity and toxicity of generated waste, as well as water consumption, can often be minimized through the application of colloidal self-assembly techniques. This makes colloidal self-assembly a potentially more environmentally friendly option for nanostructure fabrication.

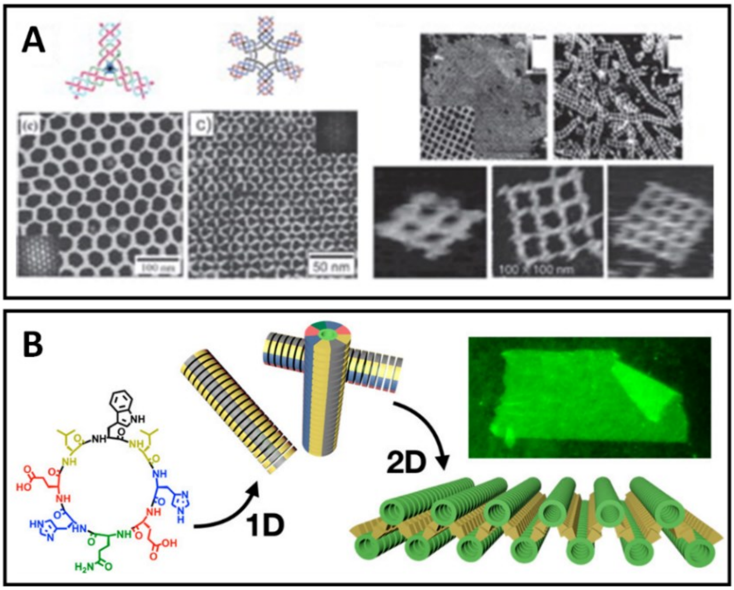
However, several limitations remain unsolved. Even if the colloidal self-assembly process itself does not generate large quantities of hazardous waste, this technique requires the previous synthesis of the colloidal objects. This synthesis normally involves the usage of toxic or hazardous chemicals, which have negative environmental impacts if they are not treated correctly. Additionally, synthesizing monodisperse colloids with uniform size and shape can be challenging, especially for non-spherical or complex structures. Related to this, some of the colloidal synthesis methods presented in the literature are well-suited for lab-scale quantities but may face challenges when scaled up for industrial production. For these reasons, researchers have focused on the development of new bottom-up technologies that involve less hazardous and complex synthetic steps. This strategic shift aims not only to mitigate environmental impacts but also to enhance the applicability of these methodologies.

Biomolecules assembly

Biomolecule-based self-assembly has emerged as a powerful strategy for fabricating nanostructures with precise control over size, shape, and functionality (L. Wang et al., 2019). One of the most prominent biomolecules used for self-assembly is DNA (H. Li et al., 2009). Through techniques such as DNA origami and DNA nanotubes, researchers can program DNA molecules to fold into complex nanostructures with predictable base-pairing interactions (Figure 3A) (Agarwal et al., 2021; He et al., 2005, 2006; Lund et al., 2005). Other biomolecules such as proteins or peptides also offer possibilities for nanofabrication. Thus, while the folding patterns of the proteins have been exploited in the creation of functional nanostructures (Solomonov et al., 2024), the self-assembly of peptides via non-covalent interactions has allowed the creation of structures such as nanofibers, nanotubes, and nanoparticles (Figure 3B) (Levin et al., 2020). Finally, other biomolecules such as lipids and polysaccharides, have been also used in the fabrication of nanostructures such as liposomes, lipid bilayers, or nanofibers respectively (Fan et al., 2021; Mahler et al., 2021).

Figure 3.

Examples of 2D structures fabricated using DNA ***(A).*** *Adapted with permission.(He et al., 2005, 2006; Lund et al., 2005) Copyright 2005-2006 American Chemical Society. Sequential 1D-to-2D self-assembly of cyclic peptides* ***(B)*** *Reprinted with permission.(Insua & Montenegro, 2020) Copyright 2020 American Chemical Society*

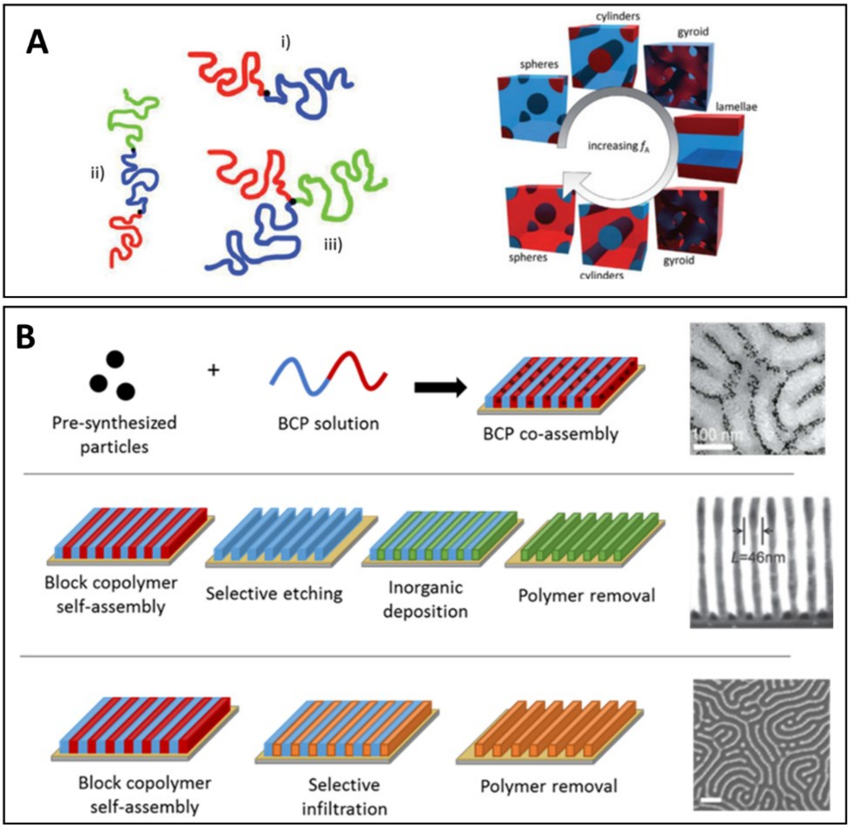


From the environmental point of view, the self-assembly of biomolecules offers a more sustainable approach when compared not only with top-down but also with bottom-up alternative fabrication methods. Thus, by the usage of renewable biomaterials as building blocks, such as proteins, peptides, and DNA, biomolecules self-assembly offers a powerful environmentally friendly fabrication alternative to previously introduced manufacturing methods that rely on non-renewable resources and often lead to the generation of harmful by-products. Moreover, the natural character of the biomolecules makes the generated nanomaterials biodegradable, which can significantly reduce waste accumulation and improve the sustainability of nanoscience. However, despite the remarkable progress in biomolecule-based self-assembly, several challenges remain. These include achieving scalable production methods, ensuring reproducibility of nanostructures, and understanding the interactions between biomolecules and their environments, making necessary the search for new bottom-up nanofabrication methods.

Block copolymers

A block copolymer (BCP) is a macromolecule composed of two or more chemically incompatible polymer segments, known as blocks, which are covalently bonded together. Depending on the arrangement of these blocks, different macromolecular architectures can be formed, including diblock, triblock, star, or graft copolymers (Figure 4A). The self-assembly of these macromolecules gives rise to a diverse range of nanostructured materials over large surface areas. Therefore, BCP self-assembly solves some of the problems previously mentioned for the other bottom-up fabrication technologies focused on their reproducibility, the possibility of obtaining complex nanostructures and scaling up the fabrication process among others.

Figure 4.
Schematics of the different strategies followed to create inorganic architectures using BCP films as a template: ***(A)*** *BCP co-assembly,* ***(B)*** *selective infiltration, and* ***(C)*** *Inorganic deposition. Reproduced with permission (Alvarez-Fernandez et al., 2019; Alvarez-Fernandez et al., 2021; Hong et al., 2010; Q. Li et al., 2008). Copyright 2008, 2021 Wiley-VCH; 2019 Royal Society of Chemistry; and 2009 American Chemical Society.*



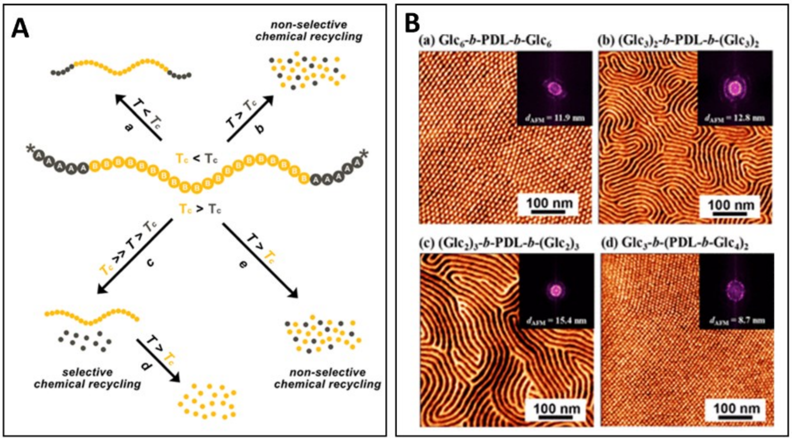
As previously mentioned, the chemical incompatibility between the BCP blocks triggers the formation of microphase-separated structures, offering a versatile platform for thin-film applications. Thus, by precise control over the molecular architecture of the blocks, BCP thin films can adopt various geometries such as spherical, cylindrical, gyroidal, and lamellar configurations with feature sizes and periods typically ranging from 10 to 50 nm. These geometries are largely based on parameters such as the volume fractions of each block (*f*), the number of repeating units (*N*), the interaction parameter between the repeating units, referred to as the Flory–Huggins parameter (χ), as well as the thin film process conditions (i.e., thickness and annealing) (Bates & Fredrickson, 1999; Feng et al., 2017; B. H. Kim et al., 2013), While BCPs predominantly consist of organic-based blocks, selective modification of individual blocks allows for the creation of inorganic nanofeatures through techniques such as sequential infiltration synthesis (SIS), aqueous metal reduction (AMR), electrochemical deposition or via the introduction of inorganic nanoparticles into the BCP domains (Figure 4B). Following these methodologies highly ordered and tuneable inorganic replicas have been created, with important applications in optics (Alvarez-Fernandez et al., 2021; X. Wang et al., 2017), energy (C. Li et al., 2020) or sensing (Chung et al., 2011; Suthar et al., 2023), among others.

From an environmental point of view, the impact of the synthesis and usage of block copolymers depends on various factors such as their production methods, chemical composition, or end-of-life disposal. Thus, the synthesis of the most common block copolymers used until now, such as poly(styrene)-block-poly(vinyl pyridine) (PS-b-PVP); poly(styrene)-block-poly(methyl methacrylate) (PS-b-PMMA); poly(styrene)-block-poly(ethylene oxide) (PS-b-PEO) involves the use of petrochemical-derived monomers, making the overall process of fabrication and obtention of the monomers resource intensive and non-renewable. Additionally, block copolymers obtained using these types of monomers are normally not biodegradable, contributing to plastic pollution and ecosystem disruption if waste is not correctly managed.

In response, researchers have developed different methods to reduce the synthetic effort necessary for the obtention of block copolymers with different macromolecular characteristics (e.g., molecular weight, obtained morphology). Thus, methodologies such as supramolecular assembly (Álvarez-Fernández et al., 2018; Alvarez-Fernandez et al., 2019; Reid et al., 2019; Sarkar et al., 2019), solvent vapour annealing, (Alvarez-Fernandez et al., 2022) or size exclusion chromatography (Alvarez-Fernandez et al., 2020; Park et al., 2002), have allowed the fabrication of tuneable nanostructures without the necessity of synthesising a specific block copolymer for each application. Even if following these methodologies, the environmental impact of the usage of block copolymers can be reduced, concerns related to waste production, the non-renewable nature of the monomer production, and the non-biodegradable characteristics of the synthesised block copolymers are still hindering the adoption of block copolymers in industrial environments. Two different strategies focused on two different aspects of the problem have been recently introduced to overcome these challenges. The first one is related to the possibility of recycling and reusing the block copolymers, while the second one verse around the usage of natural molecules as monomers for the synthesis of bio-based block copolymers.

From the perspective of the recycling of block copolymers, researchers have been focused on the design of novel polymers that enable chemical recycling to monomer (CRM) or chemical recycling via upcycling methodologies. In this objective, polymers produced through innovative research approaches such as ring-opening polymerization (ROP) are highly promising due to the equilibrium nature of this polymerization method. This characteristic offers an inherent pathway for recycling through reverse ring-closing depolymerization (Figure 5A) (Cederholm et al., 2023). Other strategies rely for example on the Selective Solvent Extraction strategy.(Y. B. Zhao et al., 2018) This methodology consists of the usage of a solvent that selectively dissolves one block while leaving the other intact. This allows for separation and subsequent recycling of the individual polymer blocks. Parallel to this stands the employ of chemical methods e.g.; amido- or alcohol-lysis or thermal and catalytic methodologies for the cleavage of the polymeric chains at specific sites or bonds, enabling the recovery of the original monomers or shorter polymer segments (oligomers) (Si et al., 2023; Y. Zhao et al., 2023).

Figure 5.
(A) *Chemical recycling via reverse ring-closing depolymerization of an A–B–A block copolymer and how the available recycling scenarios depend on the relationship between the T_c of monomer A (grey solid circle) and monomer B (yellow solid circle).* ***(B)*** *AFM phase images of several self-assembled carbohydrates bio-based BCP. Reproduced with permission. (Cederholm et al., 2023; Isono et al., 2020) Copyright 2023 The authors; and 2020 American Chemical Society.*



On the other hand, researchers have also focused on the development of bio-based block copolymers, enabling greener synthetic procedures and avoiding the necessity of petrochemical-derived monomers (Gandini & Lacerda, 2015). One interesting example is the fabrication of the poly(3-hydroxybutyrate)-block-poly(ethylene glycol) (PHB-b-PEG). In this case, the PHB block can be produced by bacteria (such as *Pseudohalocynthiibacter aestuariivivens* P96) from renewable carbon sources (Bonartsev et al., 2013; Esposito et al., 2023; Rai et al., 2011). PHB-b-PEG copolymers have potential applications in drug delivery, tissue engineering, and wound healing due to their biocompatibility and controlled release properties (Bonartsev et al., 2013). Another interesting type of bio BCP, and with important implications in the fabrication of nanostructured surfaces is carbohydrates-based BCP. Thus, for example, maltooligosaccharides such as maltose, maltotriose, maltotetraose, or maltohexaose, and other blocks like poly(δ-decanolactone) have been successfully synthesised and employed in the fabrication of highly ordered and defined nanostructures, with similar results than standard petrochemical-derived BCP like PS-b-PMMA or PS-b-PVP (Figure 5B) (Isono et al., 2020). As previously introduced, the thrive for miniaturization in the microelectronic industry has promoted the search for advanced techniques that allow for a decrease in the feature size obtained. In this objective, bio-based BCP has shown important application with systems achieving sub-10 nm dimensions while keeping a high long-range order and homogeneity (Isono et al., 2013; Otsuka et al., 2012).

Conclusions

The future of nanoscience holds tremendous promise with the advancement of bottom-up nanofabrication methodologies, offering greener and more sustainable approaches to material synthesis and device fabrication. By harnessing the principles of self-assembly and molecular manipulation, we have seen here how bottom-up techniques enable precise control over the design and assembly of nanoscale structures, with minimal material waste and environmental impact. One key aspect of bottom-up nanofabrication is the utilization of bio-inspired and bio-derived materials, such as DNA, proteins, and biopolymers. These materials not only offer inherent biocompatibility but also provide renewable and sustainable alternatives to traditional synthetic polymers and inorganic materials. By mimicking nature's ability to assemble complex structures from simple building blocks, bottom-up approaches can facilitate the development of novel, greener, cheaper, and more advanced nanomaterials.

We have seen here how bottom-up nanofabrication techniques require less energy and fewer harsh chemicals compared to top-down methods, contributing to reduced carbon footprint, environmental pollution, and waste generation. Additionally, the scalability and versatility of bottom-up approaches continue improving, making them already suitable for potential large-scale production. As research in bottom-up nanofabrication continues to evolve, interdisciplinary collaborations between materials scientists, chemists, biologists, and engineers will be essential to explore new design principles, optimize fabrication processes, and unlock the full potential of bottom-up nanotechnology.

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