*European Cooperation in Science and Technology (COST) is a funding organization for the creation of research networks, called COST Actions.*

**EsSENce Cost Action CA19118**

*Project Title:*

**"High-performance Carbon-based composites with Smart properties for Advanced Sensing Applications"**

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|---|---|
| **Deliverable No** | D3.2 |
| **Deliverable Title** | Feasibility study and business plan for upscaling the manufacturing technologies of CNM composites |
| **Working Group** | 3 |
| **Originator** | Andreia Araújo, Raquel Santos (INEGI) |

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

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# DISCLAIMER

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# 1 Project Summary

The main goal of the COST ACTION EsSENce is to develop a scientific & technological innovation hub at European and International level, focusing on advanced composite materials reinforced with carbon-based nanomaterials for sensing applications.

The main focus of the scientific community is to combine advances in manufacturing technologies with the development of innovative nano-enabled composite materials for the fabrication of lightweight smart devices with structural performance and improved and/or added new functionalities, including sensing and detection.

The advent of sensors in many different applications, such as environmental monitoring, monitoring constituents in food products, security, gas sensing as well as diagnostics and human health monitoring, has led to the ever-growing modification of existing processing and manufacturing routes by incorporating advanced carbon-based reinforced composites offering multi-functionality. Among the applications of carbon based (nano)materials (CNMs) composites, lightweight and smart sensors, which will provide highly accurate and real-time monitoring functions in different equipment and devices without the cost of structural integration, is the area that is particularly focused on EsSENce.

The deliverable 3.2 (D3.2) entitled Feasibility study and business plan for upscaling the manufacturing technologies of CNM composites, was developed within the WG3 regarding Novel CNMs & new processing routes. The main purpose of this document is to assess the current status of CNMs exploitation on the market and, through a feasibility study, understand what are the motivations behind it, and propose actions to further increase its use and commercialization.

# 2 Introduction

Carbon is one of the basic elements for life on Earth, and it can be found in over 95 % of all known chemical compounds. This element presents extreme versatility: it can not only form bonds with almost every other element, but also with itself, in the form of single, double and triple bonds [1]. The resulting structural diversity of organic compounds and molecules is accompanied by a broad range of chemical and physical properties [2]. Diamond and Graphite are two well-known natural allotropes of carbon (composed exclusively by carbon elements), that provide illustrative examples of the different properties that can be attained [3]. After the discovery of fullerenes, in 1985, a novel group of carbon allotropes in the nanoscale started receiving substantial interest by the scientific community. The still growing nanocarbon family now includes, besides fullerenes, carbon nanotubes (CNTs), carbon nanofibers (CNFs), nanodiamonds, nano-onions, graphene, graphene quantum dots, graphene nanoribbons, among many others [1, 3]. CNTs and graphene are the most studied carbon nanoparticles and have shown great promise in applications ranging from high-performance (nano)composites, to electronic and energy storage devices, to biological materials. CNTs were taken into awareness of the scientific community in 1991 as one-dimensional (1D) nano graphitic materials with cylindrical morphology and extremely high aspect ratio. While the first well-known experimental discovery and investigation of graphene, a planar monolayer of carbon atoms packed into a two-dimensional (2D) honeycomb lattice, dates 2004 [3]. Since then, researchers have continuously found ways to improve the production and properties of these particles and, also made new exciting discoveries.

Nowadays, the question that arises is why are these particles not already widespread on the market?

History tells us that the commercialization of a revolutionary new material can take decades, along with a mix of patience and persistence. The initial hype around a material's discovery stimulates funding and leads to initial technological advances. However, along the way, "commercialization anxiety" starts as: i) the material's quality is not consistent enough; ii) large-scale production has not been established; iii) the material is not affordable (high production costs); and iv) concerns about environmental health and safety. At the same time, materials suppliers hesitate to make the large investments required to address quality, scalability, and affordability issues without clear validation of demand for the material. While early adopters can take several years to become comfortable enough with using the material in their next-generation products. A good example of this process is carbon fibre, which has been described as the macroscopic analogue of CNTs. Its widespread adoption, particularly in the form of epoxy intermediate products and composites, is now considered a commercialization success, but it took more than two decades for this to happen [4].

Therefore, other questions arise: what is the current status of CNMs utilization on the market and what can be done to further increase its use and commercialization?

Looking into the business world, it is fundamental to evaluate the potential for success of a new opportunity before significant investments (cost, time and resources). For that reason, feasibility studies, also known as feasibility assessment or feasibility analysis, are critical tools that can help to determine whether a product idea or opportunity is viable, feasible, and profitable [5]. Determining an optimal solution requires evaluating the level of risk, cost and benefits of alternatives/options based on several feasibility areas. Literature sources do not seem to agree on the number of areas. However, there is some convergence on five generic areas known as TELOS (Figure 1), that were set out by James A. Hall [6] in 2007 [7].

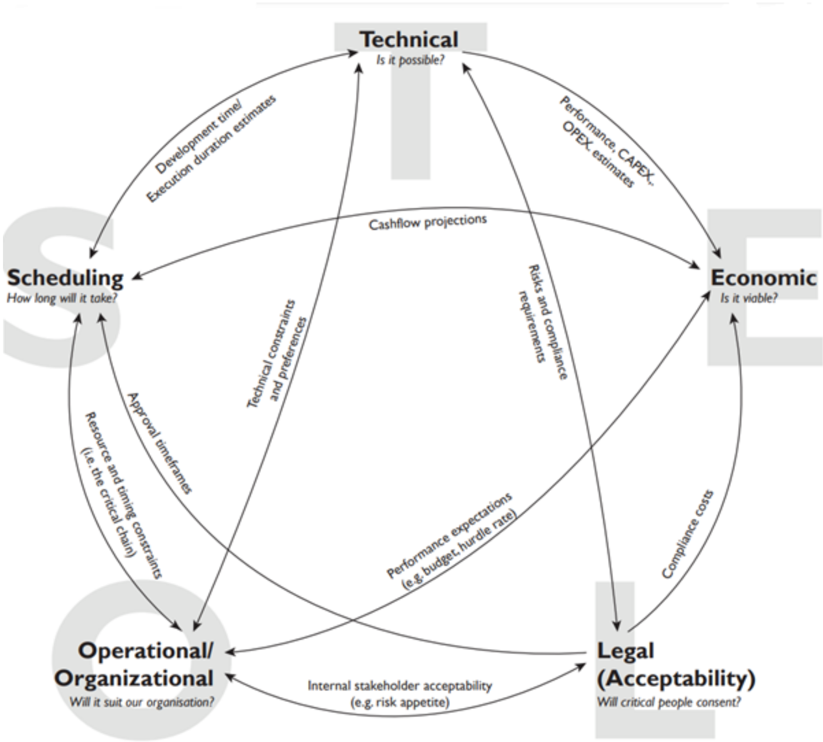



**Figure 1 Representation of the TELOS framework [8].**

As it can be seen in Figure 1, TELOS stands for Technical, Economical, Legal, Operational and Scheduling feasibility. Moreover, Table 1 provides more details on the aspects considered in each area of the TELOS studies [5, 7-9].

**Table 1 Identification of the TELOS assessment areas.**

| | | |
|---|---|---|
| **T** | Technical Feasibility | Focuses on system requirements that are established from the perspective of the technology that will be employed. The suggested system is technically practicable if the development technology is readily available and simple to implement. |
| **E** | Economic Feasibility | Assesses whether the benefits exceed costs using appraisal methods. |
| **L** | Legal Feasibility | Determines the project's ability to surmount various regulatory and ethical requirements, including conflicts either with the national or international legal requirements. |
| **O** | Operational Feasibility | Assesses how well a proposed plan fits within the existing business environment, and if developed, whether current purchasers will use it. Some variables that affect the outcome of this analysis are whether management support, how buyers feel about the current system in place, and if the proposed system will benefit the organization. |
| **S** | Scheduling Feasibility | Assesses whether the proposed project can be completed within desired or mandatory time. |

The aim of this work is to provide a broader perspective on the practical application of carbon nanomaterials on the market, in order to understand the feasibility of its utilization and what are the main constraints it faces at the moment. Since this work does not consider a specific product/project, the TELOS framework was adapted in a broader sense, and for that reason this document is divided into 5 main topics. The Technical Feasibility describes the different types of carbon nanomaterials available and its main properties. The Economic Feasibility is dedicated to the market research and includes not only the potential applications of CNMs but also explores practical examples of products already available on the market. In the Legal Feasibility chapter, regulatory and environmental considerations regarding the utilization of CNMs are assessed. The Operational Feasibility lists different nanoparticles' production methods and its scalability potential, producers/suppliers. Finally, the Scheduling Feasibility identifies potential risks and challenges, along with technical barriers that limits its utilization at this moment.

# 3 Technical Feasibility

The Technical Feasibility study of a project or product being developed typically aims to answer questions regarding the possibility of execution. For instance, in a company, a group of technical experts study the whole project, including the capability to convert the idea into real, check the accessibility to technical resources, the needs for customization, among others. In the case of this work, it is important to start by understanding what are the types of carbon nanomaterials available for the development of new products offering multi-functionalities, and what are their main properties and features.

## 3.1 Types of CNMs

As previously mentioned, the CNM family is vast and still growing, owning to the interest it generates in the scientific community. According to their spatial dimensions, CNM can be roughly divided into zero-dimensional (0D), as for example fullerenes, 1D, such as single-walled, double-walled or multi-walled carbon nanotubes (CNT, SWCNT, DWCNT, MWCNT) and carbon nanofibers (CNF), or 2D, particles from the graphene family like graphene sheets and few layers graphene (Figure 2) [10]. Recently, other particles such as graphene nanoribbons, graphene quantum dots, nano-onions, nanorods, nanowires, among many others, have arisen, along with bio-based nanocarbons (CNM produced from bio-based or biomass sources). More details can be found in the previous deliverable D3.1.

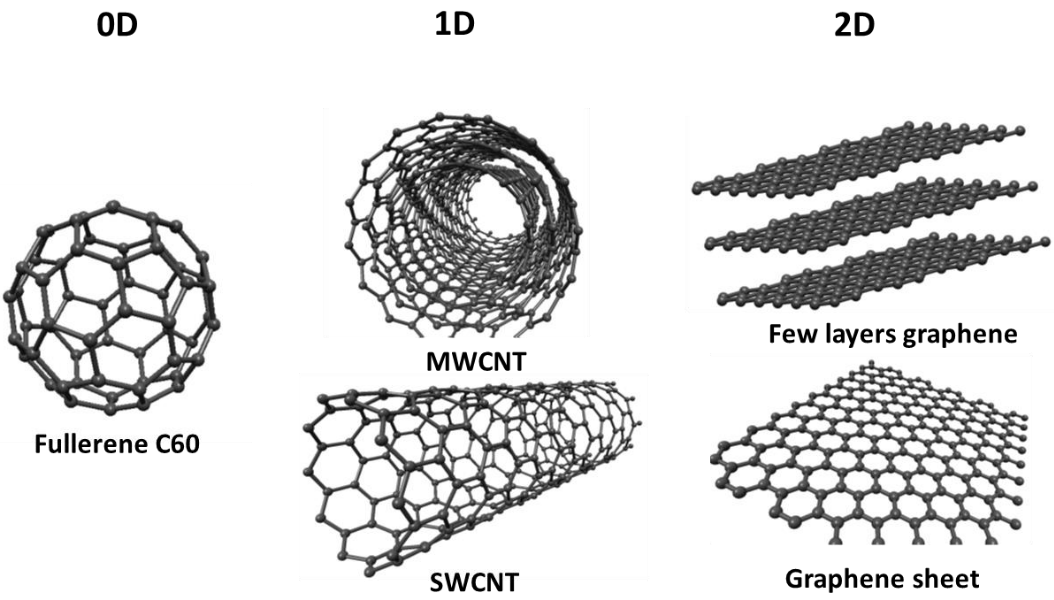



**Figure 2 Different types of carbon-based nanomaterials.**

Excellent mechanical properties, electrical and thermal conductivities, and high specific surface area, are some of the features typically associated to CNMs. In fact, the research of the most common CNM is at a stage where most of the outstanding physical properties have been discovered, but the development of the technology that bridges academic to industrial manufacturing still needs focus.

Looking into more details to the CNMs, it is of utmost importance to recognize its diversity. For instance, in the case of standard chemicals, the names refer to a singular and specific chemical structure, while for CNMs, this is not applied. A practical example is the basic term “carbon nanotube” that is employed for particles with numerous variations in terms of structure, such as the diameter, wall number, length, chirality, and also functionalization, among others [11]. This is especially true for the different particles that form the graphene family. Graphene is a fully graphenic, single-layer sheet of *sp*$^2$-hybridized carbon. However, when this single-layer sheet contains areas of disrupted aromaticity where carbon atoms are oxidized (including functional groups, such as epoxide, hydroxyl, carbonyl, and carboxyl), this particle is called graphene oxide (GO). Additionally, the exposure of GO to thermal, ultraviolet (UV), biodegradation, and chemical processes, leads to the elimination of oxygen functional groups and allows the restructuring of a greater proportion of graphenic carbon (frequently exhibiting defects), and this particle is called reduced graphene oxide (rGO). Particles composed by more than one layer of graphene, and typically till 5 layers, are named few-layers graphene, and the list goes on. Besides this, all these different types of particles exist with varying defects, sizes, thicknesses, oxidation levels, and surface functionalities [12] [13]. In reality, this is translated in particles with vastly different physical and chemical properties, contributing for its versatility and possible utilization in a wide variety of applications.

## 3.2 Properties of CNMs

Table 2 presents generic properties for different types of CNMs. Nevertheless, it should be noted that there are many other factors influencing the properties of these types of particles, such as the producer and production method, particle dimensions, purity, presence and number of defects, chirality, functionalization, among others [4, 14].

**Table 2 Generic properties of different types of CNM [14].**

| CNM | Dimension | Hybridization | Thermal Conductivity ($Wm^{-1} K^{-1}$) | Electrical Conductivity ($SM^{-1}$) | Tensile strength |
|---|---|---|---|---|---|
| Fullerene | 0 | mostly $sp^2$ | 0.4 | $10^{-8}$ | |
| CNT | 1 | mostly $sp^2$ | ~3500 | Depends on CNT type/structure | |
| Graphene | 2 | $sp^2$ | 4840-5300 | Around $2x10^5$ | Up to 130 GPa |
| Graphene oxide | 2 | $sp^3$ | ~72 | 0.1 | |

In terms of purity, defined as the percentage that corresponds to the product of interest, CNMs are often mixtures with a range of different sizes and can even be “contaminated” with other types of CNMs (for instance SWCNTs may contain a certain amount of MWCNTs), along with non-carbon species from the production process, namely metal catalysts [REF]. The presence of these impurities or dimensions diversity can significantly interfere with the overall performance of the CNMs. Another important aspect, is the presence of defects in the structure of the CNMs, for instance by exhibiting $sp^3$ hybridization instead of the preferred $sp^2$ hybridization, that compromise the electron-transport properties or promote breakage during dispersion processes especially when harsh conditions are applied. In the case of CNTs, for instance, chirality is also an essential factor, since it determines whether a nanotube has metallic or semiconducting properties [4].

Another interesting perspective was studied by Kobashi et *al.* [11], that analysed eight industrially used CNTs from well-known large-scale producers, and the results showed the great variety in terms of dimensions of these selected particles. Note that these CNTs were synthesized by various chemical vapor deposition (CVD) methods, including floating catalyst, fixed bed, and fluidized bed.

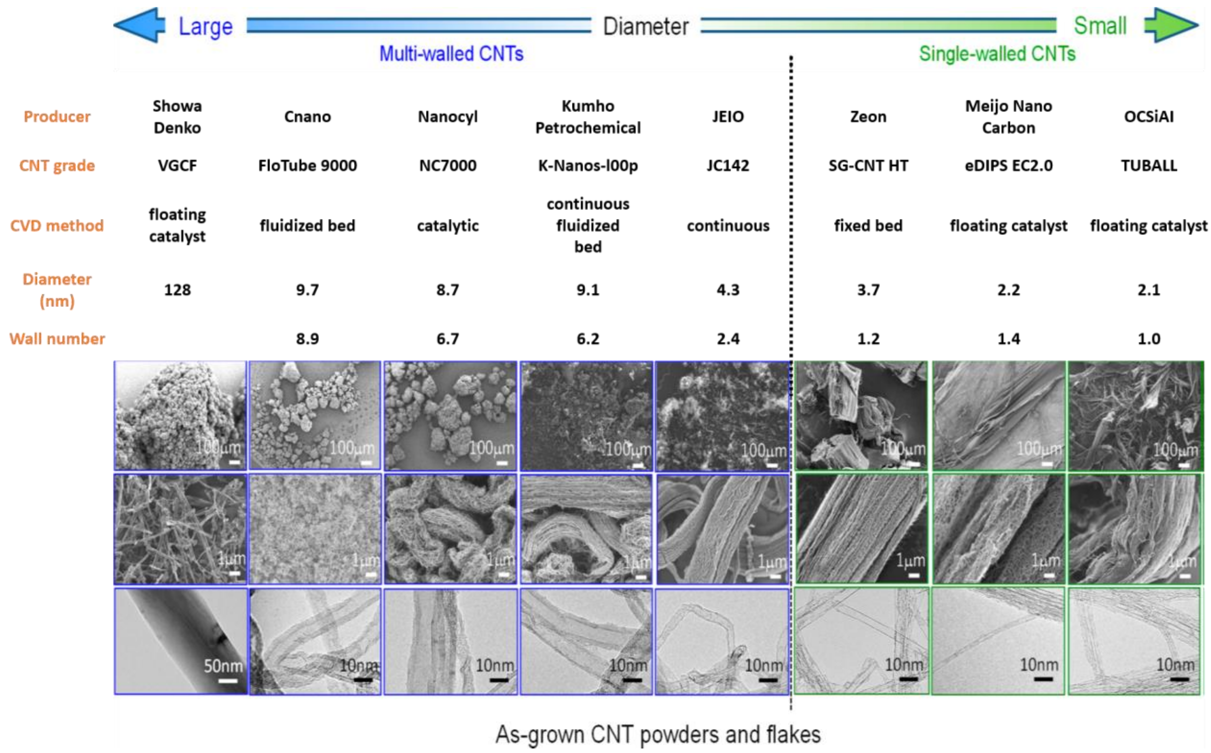



**Figure 3 SEM and TEM images of as-grown, commercialized CNT powders and flakes from well-known worldwide suppliers in order of decreasing diameter (left to right) (adapted from [11]).**

It is possible to observe that for both SWCNTs and MWCNTs, the same name can be applied for particles with different dimensions, which will contribute to particles with different properties. This is actually one of the challenges faced by the industry: how to select the best type of particle and producer for a certain application? Considering that the mass production of CNMs is already well established (meaning that we are taking out of consideration the composition variability and/or presence of impurities in different production batches), it is highly recommended to make an initial research campaign to determine the most promising type and amount of CNMs, along with the optimized dispersion methodology, for the main properties of interest.

# 4 Economic Feasibility – Market Research

The Economic feasibility study is associated to the price and all kind of expenditure related to the scheme before the start of a project. When the so-called project includes launching a new product, factors such as the size of the market, the level of competition and the target audience, must be considered. This evaluation process also forecasts an expected return on investment (ROI), as well as outlines any financial risks, allowing the decision-makers to determine the potential economic benefits to the organization. [9]. In this chapter, the economic feasibility is dedicated to the identification of target market sectors where CNMs can be employed, along with products on the market that already make use of these types of particles.

## 4.1 Market Growth

The market for nanomaterials has been experiencing steady growth, driven by increasing research activities and technological advancements. It is considered highly competitive with the presence of large-scale key players operating in it, including Strem Chemicals, Inc., Sigma Aldrich, Inc., Nanoshell LCC, Nanocyl, Graphenea, and so many others (Section 6.2). The global nanomaterials market was estimated at USD 12,42 billion in 2023 and project to grow at a compound annual growth rate (CAGR) of 15% from 2024 to 2030. This significant growth is promoted by emerging technologies. For example, titanium (Ti) and silver (Ag) nanoparticles play an important role in the nanomaterials market with a share of 31.2%, owing to their usage in medical applications segment, since both exhibit biocompatibility in addition to other notable features. In addition, carbon-based nanomaterials, with special focus on graphene and CNTs, have been playing a pivotal role on the new era of mobility, where lightweight and smart materials are in rising demand. In particular, according to recent studies, the global graphene market was valued at USD 620 million in 2020 and is projected to reach USD 1,479 million by 2025, growing at a CAGR of 19.0 % from 2020 to 2025[1]. While the CNTs market may grow from USD 1.1 billion in 2023 to USD 2.3 billion by 2028, at a CAGR of 14.6 % between 2023 and 2028[2].

## 4.2 Market sectors

The diversity of particles and interesting properties, described in the previous section, allows the utilization of CNMs in several sectors, as it can be seen in Figure 4, for a wide variety of applications, which will be exploited in more detail in the following sub-sections.

[1] Graphene Market, Markets and Markets, March 2021
[2] Carbon Nanotubes Market, Markets and Markets, July 2023

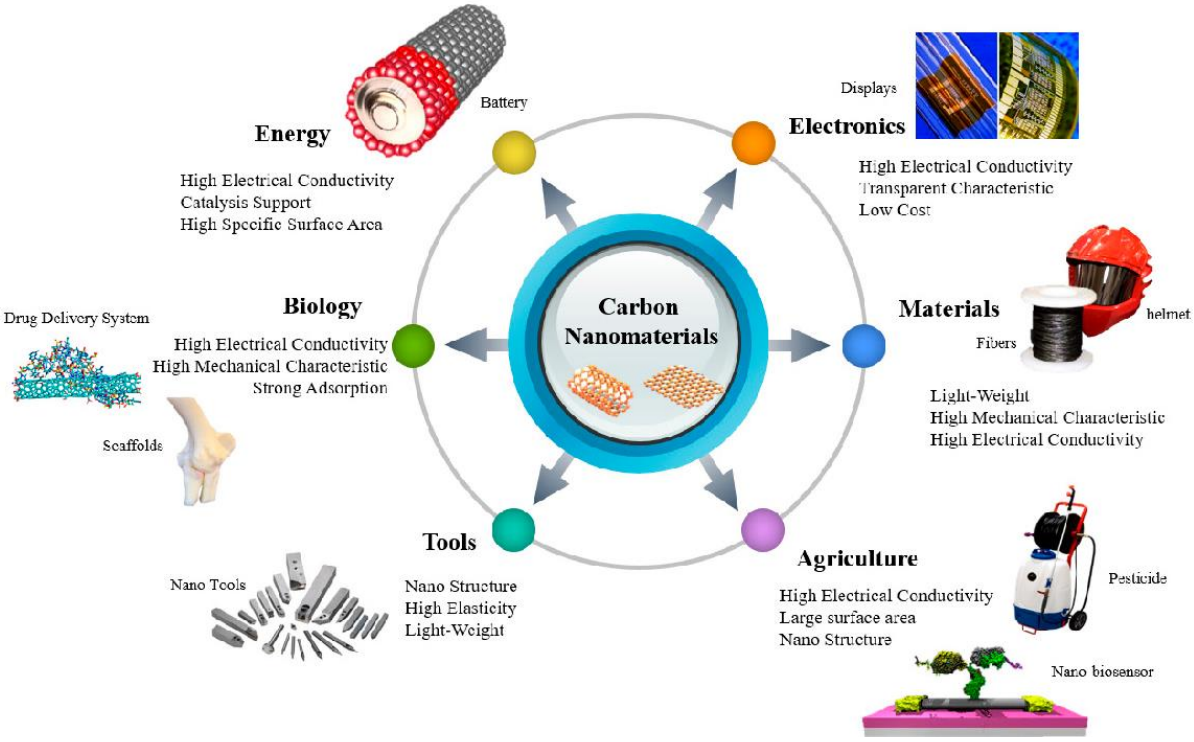



**Figure 4 An overview of the different applications of CNMs [15].**

### *4.2.1 Electronics and energy storage*

Recently, major efforts have been made to explore the properties of materials with nanometer size in order to utilize in diverse nanoelectronics and nanotechnologies. 5 depicts a schematic illustration of advanced electronic applications based on CNMs, such as solar cell, light-emitting diode (LED), flexible/wearable electronics, battery, transistor, and supercapacitor [16].

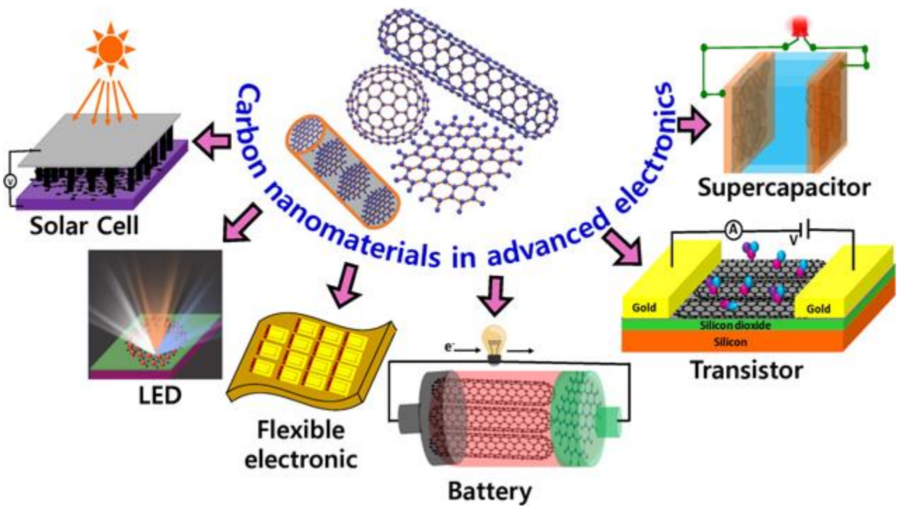



**Figure 5 Schematic illustration of advanced electronic applications based on carbon nanomaterials such as fullerene, CNT, graphene, and CNF [16].**

Fullerene derivatives are extensively used to augment the activity of methanol electro-oxidation in the anode of direct methanol fuel cells (DMFCs), and play a major role in enhancing the overall efficiency of photovoltaics, as it can be seen in Figure 6 [17] [18].

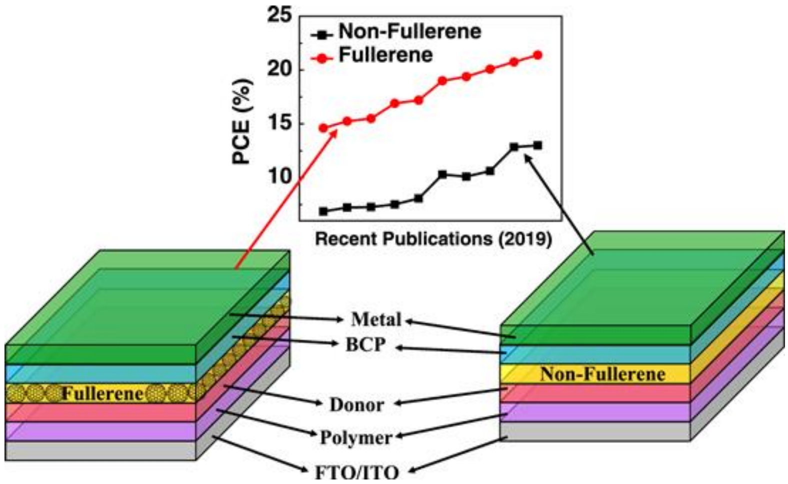



**Figure 6 Enhanced performance of fullerene-based photovoltaics as compared to non-fullerene photovoltaics [16].**

Semiconducting CNTs allow the construction of smaller transistors for all kinds of electronic devices, owing to their band–gap, which is inversely proportional to its diameter. In particular, flexible thin-film transistors are being proposed for use on flexible digital circuits, artificial skins, and radio frequency devices, due to their outstanding electrical properties and intrinsic mechanical strengths [16]. These nanomaterials can also be incorporated into different types of flexible batteries, for instance for wearable devices like the one represented in Figure 7 [17, 19]. CNTs are used as the polarizer in liquid crystal displays (LCDs), the field emitter in field emission devices (FEDs), and the transparent electrode in organic light-emitting devices (OLEDs). CNTs are also employed in some new types of displays, such as thermochromic displays, flexible fibre displays, and incandescence displays [17].

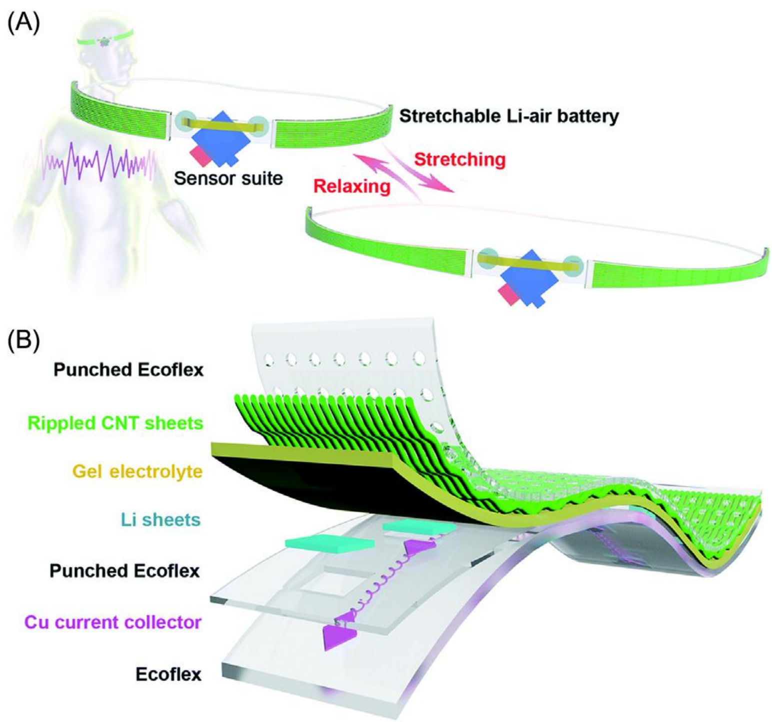



**Figure 7 (A) Potential application of stretchable Li-air batteries as elastic "energetic straps" to power a sensor suite for wearable physiological monitoring. (B) Multilayered structure of the stretchable Li-air battery** [17].

In contrast, the high carrier mobility and optical transparency of graphene make it a leading candidate for radio frequency analogue circuits and transparent conductors. Graphene, in the form of transparent and conductive film, is a potential candidate to replace indium tin oxide in touchscreens [17].

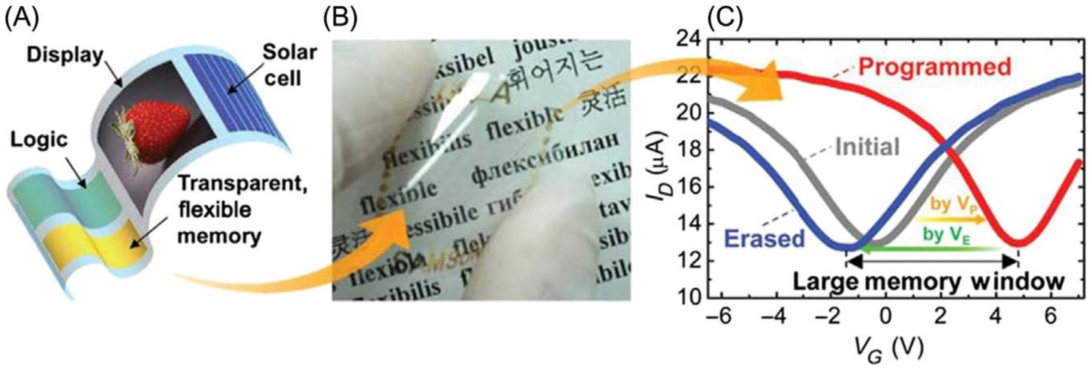
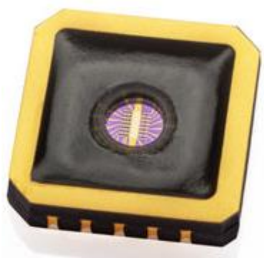



**Figure 8 (A) Flexible transparent memory can be utilized for transparent and flexible electronics. (B) Photograph of the large-scale transparent, flexible memory array. (C) Memory characteristics of the flexible transparent memory [17].**

**Table 3 Commertial application of CNMs in Electronics and energy storage.**

| Product | Company | Details | Image |
|---|---|---|---|
| **Huawei Mate 20 X smartphone** | The Sixth Element (Changzhou) Materials Technology Co Ltd. and Jiangsu Warwick Century Electronics Group Co Ltd | Graphene-based thermal conductive film for improved thermal management. |  https://www.c6th.com |
| **Graphene field-effect transistors (GFETs)** | Graphenea | Graphenea offers graphene transducers for a variety of sensing applications. |  https://www.graphenea.com/ |

## 4.2.2 Healthcare and medical devices

Carbon nanomaterials have been used as multifunctional potent platforms for a number of different biological and biomedical applications, which includes not only i) drug delivery, cancer and other therapies; ii) diagnostic medicine and bioimaging; iii) biosensors, as it is listed in Figure 9; but also iv) scaffolds, orthopedic implants and medical equipment.

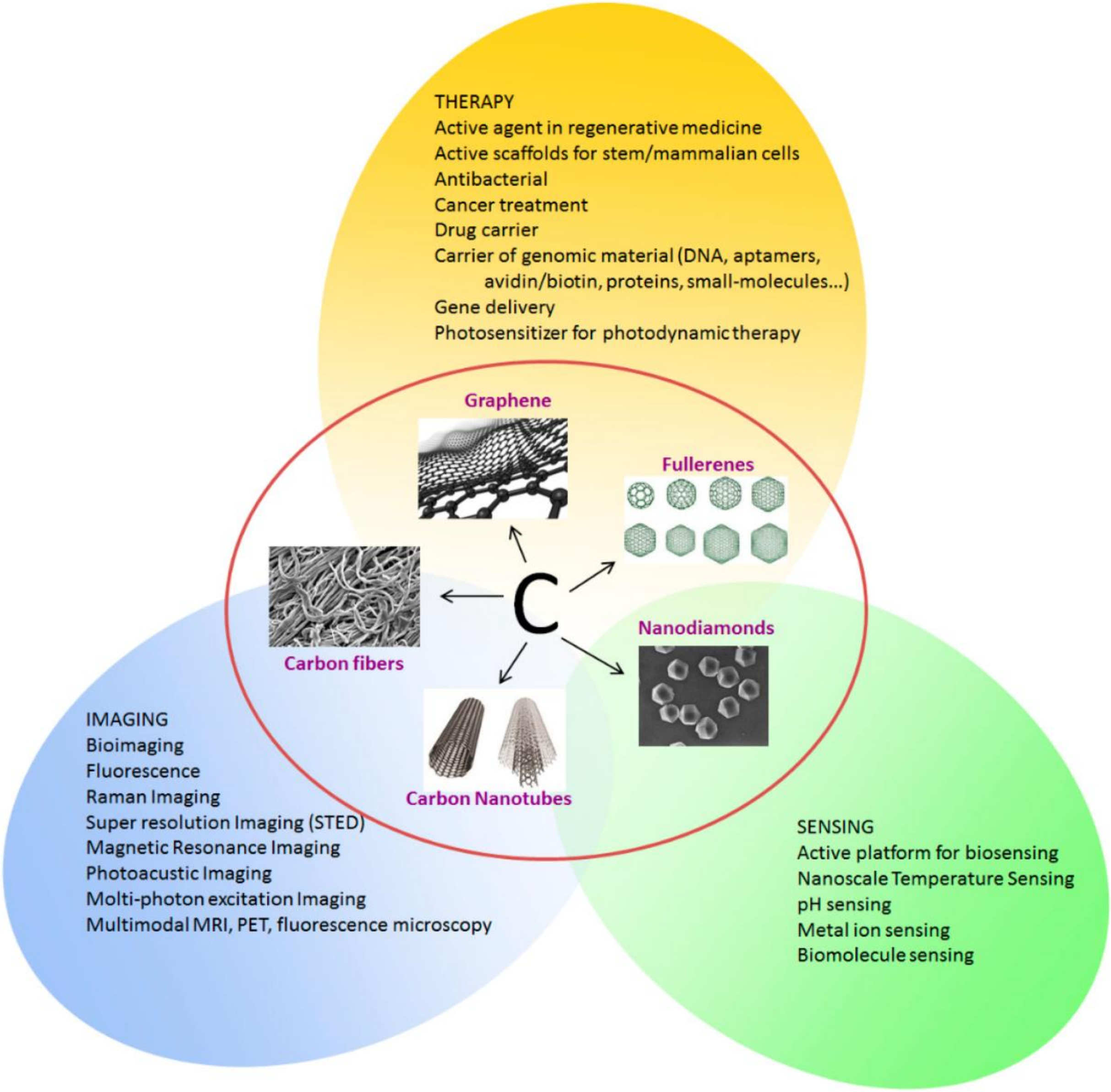



**Figure 9 Application of CNMs in biomedicine [20].**

Drug delivery, cancer and other therapies

The efficacy of a drug delivery system is strongly influenced by the biodistribution, pharmacokinetics, and excretion properties of the compound. CNMs are attractive candidates for drug delivery systems since their dimensions are close to those of viruses and other biological structures. CNMs may linger inside biological structures with poor drainage (e.g., tumours), whereas they may not linger inside healthy cells with normal drainage. The possibility to functionalize CNMs through straightforward methodologies, further increases their potential, as they may be conjugated with chemotherapeutic agents, antibodies, antitumor drugs, and other therapeutic agents. Figure 10 illustrates the possible cellular fate of CNMs: i) cell internalization by endocytosis or simple cell penetration through lipid bilayers; ii) entrapped CNMs could reach the cytoplasm after endosomal release or they could be directed to the lysosome site and the related enzymatic degradation process; iii) cargo release could occur in many organelles, including the nucleus, or it can be designed to occur in the cytoplasm; and iv) the exocytosis and excretion of intact or degraded nanoparticles is possible [20-22].

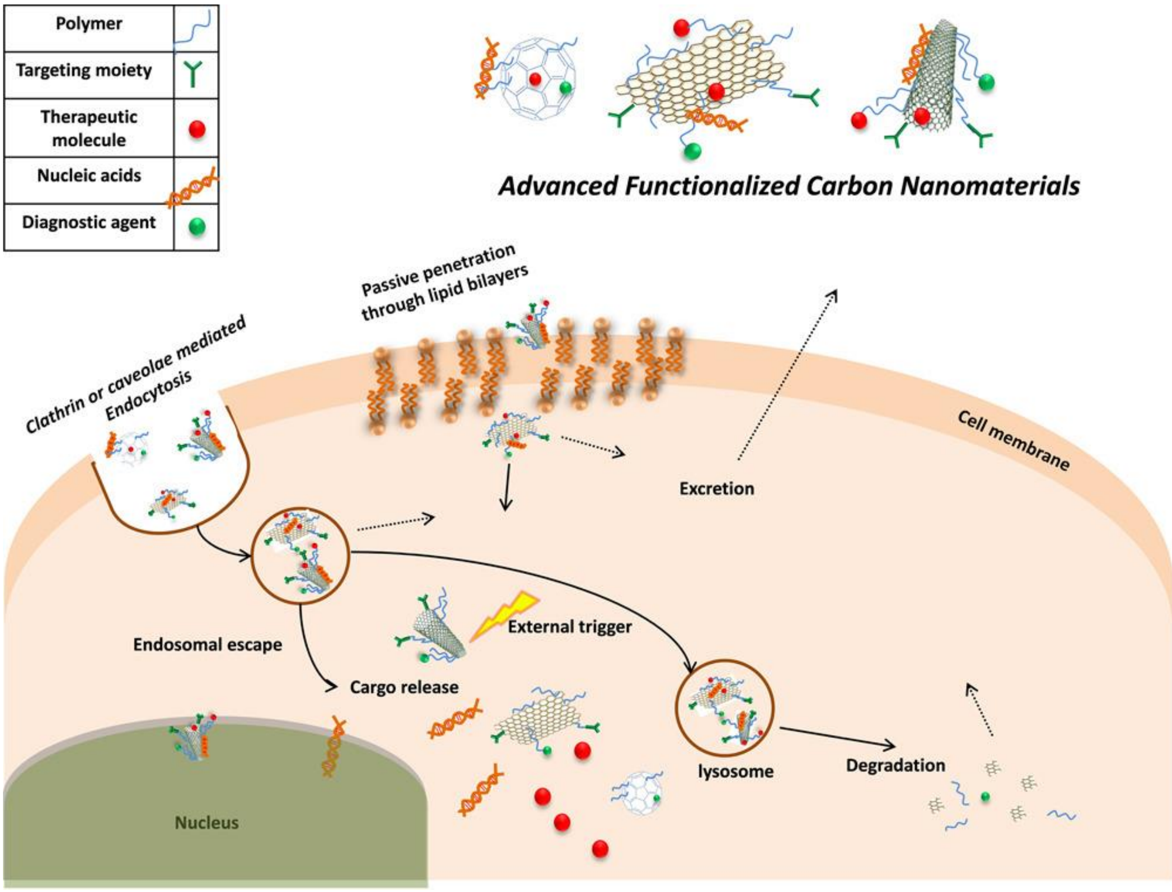



**Figure 10 Schematic cartoon illustrating the cellular fate of functionalized CNMs [21].**

Diagnostic medicine/ Bioimaging

Bioimaging is an extraordinary tool to aid in the study of the function of a particular organ, while not interfering with organ functions, such as respiration, movement, among others. CNMs are suitable for both *in vivo* and *in vitro* biological imaging due to their intrinsic optical features, which include a broad absorption spectrum in the visible and near-infrared (NIR) regions, photoluminescence in the NIR range, significant resonance Raman scattering (distinctive Raman bands) [21] [23]. These particles can also be used as magnetic resonance imaging (MRI) contrast agents with improved sensitivity.

Tissue engineering scaffolds

Biomedical scaffolds are engineered materials designed specifically for interacting with the cellular environment, resulting in the formation of new tissues that are beneficial for medical purposes. Many scaffolds or implants, typically made up of chemically inert, very strong, fatigue-resistant, cheap, and corrosion-resistant metals and their alloys, are used to deliver medication, monitor body functions, and provide support to organs and tissues. CNMs have been used for improving the strength of orthopedic implants: i) CNTs and graphene have been added to bone cement composites to improve longevity of the implant; ii) CNTs mixed with polymethyl methacrylate (PMMA) have been found to offer more advantageous physical characteristics, which allow growth and support the adhesion of newly formed tissue throughout the implant; and iii) CNTs have been used combined to chitosan for the production of scaffolds with microchannel porous structures suitable for tissue-engineering [21] [23].

Biosensors

Biosensors are designed and built to accurately sense and detect biomolecules that play critical roles in all life processes. Generally, biosensors are constructed from two structural parts: a receptor (usually a bioactive molecule which recognizes one or a group of analytes), and a transducer (transfers the chemical information from the recognition event to a readable signal. The unique properties of CNMs make them outstanding materials for biosensors due to: i) high surface-to-volume ratio facilitates the attachments of molecules or particles to enhance a biosensor's sensitivity; ii) quick electron mobility and electrical conductivity can provide the device lower Johnson and 1/f noises; iii) easy functionalization can be used to further enhance the response current; and iv) strong mechanical properties give the biosensors stability, flexibility and even portability [20, 23]. Table 4 provides an example of commercially available products utilizing CNMs for the healthcare sector.

**Table 4 Examples of commercial application of CNMs in the medical sector.**

| Product | Company | Details | Images |
|---|---|---|---|
| Bio-based PLA (Polylactic Acid) filament enhanced with CNMs suitable for 3D printing (Grafylon® G+®) | Directa Plus | - Printed scaffolds (by Università degli Studi di Padova and Synbio) demonstrated the materials promote cell fusion during cell reconstruction tissue, and stem-to neuronal differentiation.<br>- 3D printed plasters customized according to the patients' needs (by Playcast) |  <br>**https://www.directa-plus.com/application/3d-printing/** |

## 4.2.3 Sports Equipment

The degree of competitiveness in sports has been remarkably impacted by nanotechnology like any other innovative idea in materials science. Within the niche of sport equipment, nanotechnology offers a number of advantages and huge potential to improve sporting equipment making athletes safer, comfortable and more agile than ever. Nanomaterials in different sport sections have brought many benefits to the sport equipment.

Composite materials are used in various sporting goods, such as golf clubs, skis, and snowboards. Tennis rackets with enhanced stiffness and strength can be developed through the addition of carbon nanoparticles, while bicycle frames and components with improved lightweight and high-performance properties can be also achieved. Some examples of commercial application of CNMs in Sports equipment are described in Table 5.

**Table 5 Examples of commercial application of CNMs in Sports equipment.**

| Product | Company | Details | Image |
|---|---|---|---|
| Tennis Rackets | HEAD Racquet Sports | HEAD's Graphene 360 technology incorporates graphene into tennis rackets, enhancing the strength, stability, and power of the racket. | <br>**www.head.com** |

| | | | |
|---|---|---|---|
| Graphene-Infused Golf Clubs | Callaway Golf | Callaway Golf uses graphene to enhance the performance and durability of golf club heads. graphene is dispersed in the rubber core matrix and significantly reinforces the inner structure of the golf ball, allowing to enhance launch dynamics, optimize distance and increase and decrease spin where required. |   **https://eu.callawaygolf.com** |
| Bicycle parts | BMC Cycling | Use of modified resin with CNTs to produce carbon fibre reinforced parts with minimal weight and excellent stiffness and strength characteristics. |  **https://www.azonano.com/** |

### 4.2.4 Automotive, aerospace and marine components

The interest for lightweight, smart and advanced materials, in several demanding applications, lead to the increasing use of fibre reinforced polymer (FRP) composite materials. The further introduction of CNMs allows carbon fibre reinforced polymers (CFRPs) not only to achieve superior mechanical properties, but also to acquire new and smart functionalities. At the moment, lightweight automotive components, such as body in white, panels and chassis parts, are produced by using FRP composites, for improved resources efficiency and reduced environmental impact, in luxury or premium class vehicles (as for example, BMW Project i) Other prominent examples lend evidence to this trend gaining momentum: the Boeing 787 Dreamliner is constructed largely of CFRP composites instead of the traditional aluminium (Al) body structure, as well as the horizontal tail of Airbus A340, among others. In fact, lightweight materials share is highest in aviation sector with almost 80 %, although a massive growth is predicted in the automotive industry, where CFRP composites are the materials with the highest weight-savings potential. In addition, conductive FRP composites are widely used in electromagnetic interference (EMI) shielding and interior component applications, having improved fire resistance and mechanical properties. The concept of lightweight materials and design has been also important for boating and marine structures [24], and Table 6 presents few examples of commercial materials with CNMs in its composition for those industries.

**Table 6 Examples of commercial application of CNMs in automotive, aerospace and marine components.**

| Product | Company | Details |
|---|---|---|
| Ford F-150 and Mustang[3] | Ford and XG Sciences | Composite materials modified with graphene. |
| Composite Materials for Aircraft Structures | Hexcel Corporation | Hexcel develops carbon fiber-reinforced composites for aircraft components, utilizing advanced materials including carbon nanotubes. |

[3] https://www.rdworldonline.com/ford-xg-sciences-go-under-the-hood-with-graphene/

| | | |
|---|---|---|
| Prepreg reinforced with carbon nanotubes and graphene - Arovex® - for automotive, aerospace and marine applications [4] | Zyvex technologies | Materials made with modified resin with CNMs that enable the production of fibre reinforced materials with above 200% fracture toughness increase. |
| Carbon Nanotube-Reinforced Boat Hulls | Zyvex technologies | Zyvex Marine developed carbon nanotube-reinforced composite materials for lightweight and strong boat hulls. |

### 4.2.5 Construction Materials

The construction sector is highly demanding in terms of energy and resources. This sector has exhibited a strong interest towards integrating advanced and sustainable materials characterised by lightweight, high strength and stiffness, among others. The combination of composite with CNMs is particularly beneficial for building facades and bridges, where reducing weight without compromising strength can lead to significant improvements in structural performance and safety. The high tensile strength of CNTs and graphene enables the construction of thinner, lighter components that can bear heavy loads, thereby reducing the overall material usage and costs. For instance, CNT-reinforced concrete and composites are being used in bridge construction to enhance load-bearing capacity, and resistance to environmental stresses. Some examples of materials used in construction sector are described in Table 7.

**Table 7 Examples of commercial application of CNMs in construction materials.**

| Product | Company | Details |
|---|---|---|
| **Cementene™[5]** | Versarien | Versarien's graphene-based aqueous admixtures for cement offers improved strength, durability, and thermal properties for construction applications. |
| **Ductal®[6]** | LafargeHolcim | Ductal® is an ultra-high-performance concrete that incorporates carbon nanotubes to significantly enhance its mechanical properties. It is used in constructing bridges, building facades, and complex architectural shapes. |
| **PureGRAPH®[7]** | First Graphene | PureGRAPH® is used in concrete for water management infrastructure, providing enhanced resistance to wear and tear, and extending the lifespan of the structures. |

[4] https://www.zyvextech.com/products/arovex
[5] https://versarienconstruction.co.uk/cementene
[6] https://www.holcim.us/ductal
[7] https://firstgraphene.net/puregraph-products/

### 4.2.6 Other potential environmental and agriculture applications

Beside the examples listed above, CNMs also have numerous potential applications in the environmental and agricultural sectors, summarized in Figure 11.

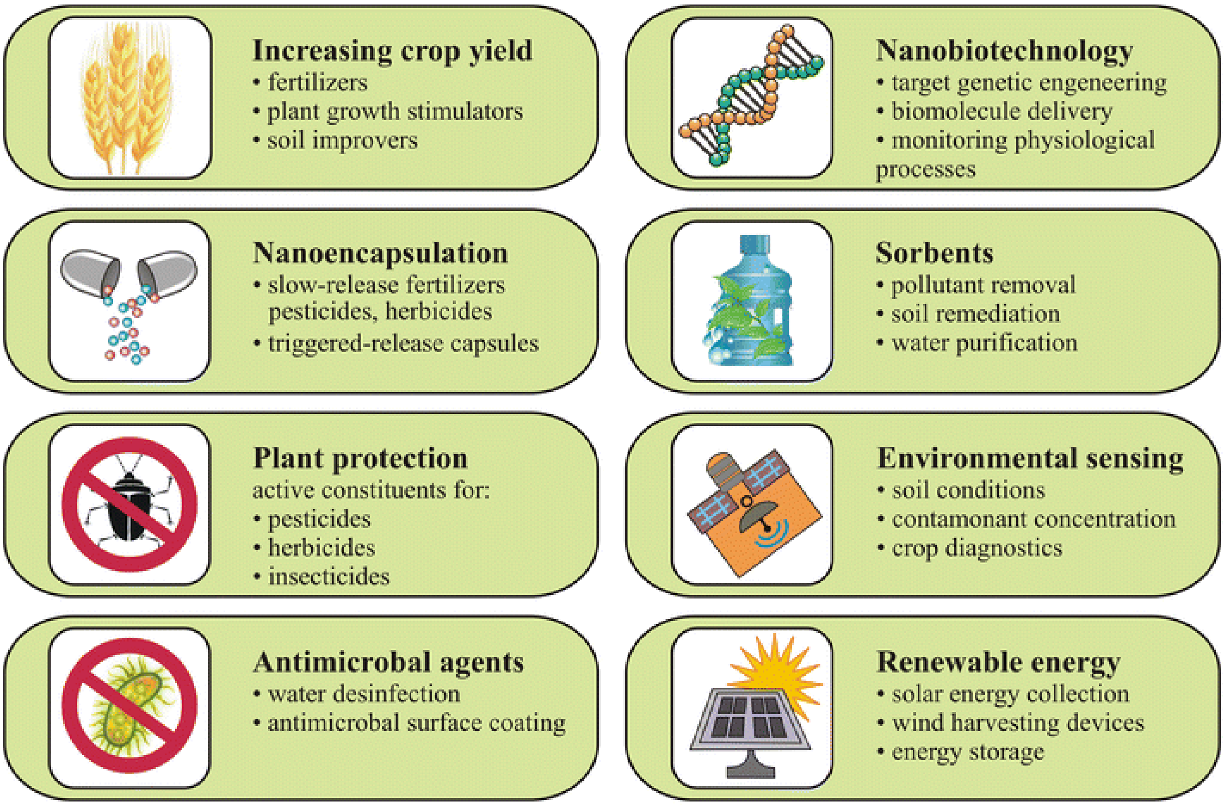



**Figure 11 Potential applications of carbon-based nanomaterials in environmental and agricultural sectors [25].**

Environmental pollution is one of the major global challenges since pollutants of different nature contaminate urban and agricultural areas. In this context, CNMs have a promising potential to improve wastewater filtration systems. For instance, there are several studies reporting the absorption capacity of CNTs towards microcystins (cyanobacterial toxins), lead and copper (III), antibiotics, herbicides or nitrogen and phosphorus, while both fullerenes and CNTs exhibit a mobilization potential for various organic pollutants, such as lindane (agricultural insecticide) and persistent polychlorinated biphenyls. Moreover, contaminants can be desorbed from CNMs, and therefore, filters based on CNMs can be recycled. Carbon-based nanomaterials also possess antimicrobial properties, although the mode of action is still under investigation. Some studies suggest possible applications of CNTs for disinfection purposes or antimicrobial surface coatings. Additionally, not only removal of pollutants from different environmental compartments, but also monitoring of contamination levels has considerable importance [25].

Increasing and optimizing agricultural production on limited areas of arable land sustainably with a minimum negative impact on the environment are major challenges in a future with a continuously increasing world population. Potential contributions of modern nanotechnology in this context comprise [25]:

1. Increase of crop productivity by use of plant growth promoters and new fertilizers based on nanomaterials. For instance, different CNMs have been reported to enhance seed germination.

2. Application of nanomaterial-based plant protection products, including pesticides and herbicides, due to the antifungal properties of CNMs.

3. A general reduction of applied agrochemicals using nanoencapsulated plant protection products and slow-release fertilizers. Example: fungicides, encapsulated in functionalized MWCNTs with citric acid, had a higher toxicity against *Alternaria alternata* fungi compared to the not encapsulated bulk pesticide.

4. Nanotechnologies for optimization of agricultural practices by introducing precision farming, in particular as sensor to detect numerous contaminants.

# 5 Legal Feasibility – Regulatory and Environmental Considerations

Legal feasibility study is used to conclude whether the proposed plan or system conflicts with national or international legal requirements. Before beginning a project, legal feasibility checks to ensure that all parts of the proposed project adhere to legal rules and requirements in that specific geographic area. Zoning laws, social media laws and many others need to be examined because the law must permit all aspects of the project for an organization to get consent to begin [9]. In this Legal Feasibility chapter, health, environmental and regulatory considerations regarding the utilization of CNMs are assessed.

## 5.1 Health, safety and environmental concerns

### 5.1.1 Health and safety

Nanomaterials present unique physicochemical properties that have been rising health and safety concerns associated to their handling and use. In general, humans are likely to be exposed to nanoparticles mainly by dermal contact and/or inhalation, in particular due to open-air handling that can promote the material loss to the atmosphere and result in potentially harmful exposure. Furthermore, nanoengineered materials can also release CNMs to the environment by several mechanisms, including wear and abrasion of the final product, which may lead to the ingestion of these particles [26]. However, it is hard to determine the consequences of the exposure to CNMs on humans. For this reason, *in vivo* tests, first using cell lines and then relying on animal trials, are indispensable to acquire knowledge on toxicity for risk evaluation [27]. Figure 12 presents the characteristics of CNMs able to influence toxicity, along with possible toxicity types, mechanisms, and routes [28].

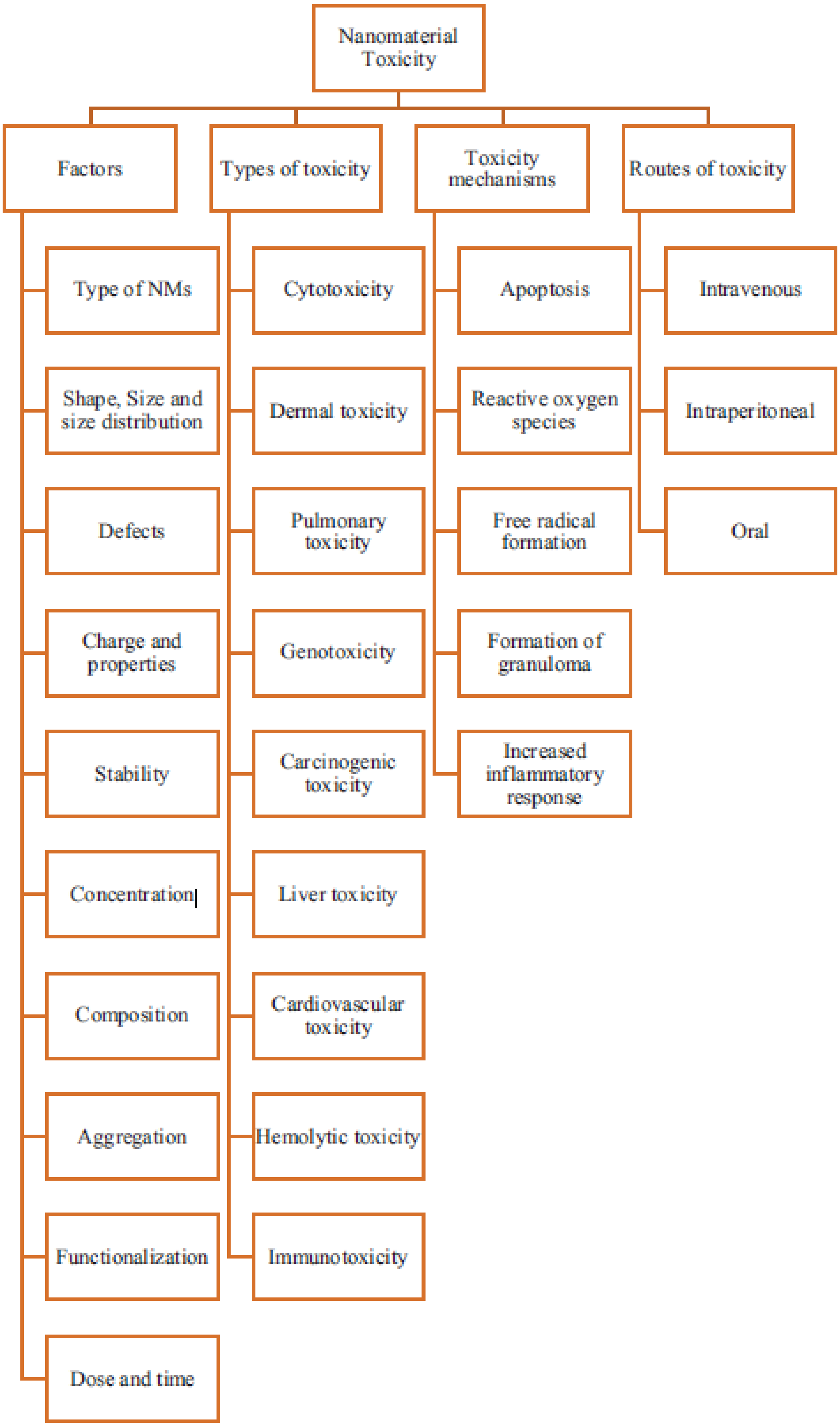



**Figure 12 Possible toxicity of nanomaterials, their factors, mechanisms and routes [28].**

Although there has been rigorous research performed in this direction and considerable experimental reports and data allied to CNMs toxicity at the cellular, molecular and animal levels are available, the conclusions do not align and often conflict. There are also studies reporting that certain types of CNMs are safe for nanomedicine. For instance, Yang et *al.* [29] demonstrated that after intravascular injection of pristine SWCNTs, mice did not show stress or symptoms of abnormality, such as lethargy, anorexia, or changes in body weight.

### 5.1.2 Environment

Nanomaterials can be released into open environments and waterbodies through different sources and routes, throughout their life cycle. However, its detection and quantification in complex environmental media and polymer composites is very limited. In polymer/CNM nanocomposites research, this inability to detect and quantify sufficiently small quantities of CNMs has hindered the development of mechanistic and mathematical models to describe how various environmental parameters impact the release rates [30]. Overall, the ecological effects of CNMs in soils and sediments appear to be very limited even at unrealistically high concentrations (i.e., g/kg). Nevertheless, it is possible that more sensitive organisms may be identified in future research, and that biomarkers may be found that are sensitive to and indicative of CNM contamination [31]. New technologies and more studies are needed to determine the effects of CNMs on aquatic and terrestrial organisms.

## 5.2 Waste Management

Nanomaterials being on the full attention of researchers, industries, and governments, unfortunately, have attracted less on their recycling and waste management strategies. A limited number of studies exist on the fate of nanomaterials after the end-of-life (EoL) stage of "nano-products", meaning that it may end up in a recycling system, incinerated or landfilled, with CNMs being released into the air, water, and soil. Some of the challenges related to EoL nanoproducts include the following factors: i) limited information on the amount of nanoproducts produced and traded on the market, along with their traceability; ii) prediction of the life span of products containing CNMs; iii) amount of CNMs in the EoL products [32].

At the moment, due to a lack of cost-effective and technically competent recycling design, research for the recovery of value CNM products has yet to be turned into applicable technology [33]. Nevertheless, it is urgent to establish proper disposal and recycling methods these types of products.

## 5.3 Regulatory requirements and relevant standards

The regulatory challenge is therefore to ensure that society can benefit from novel applications of nanotechnology, whilst a high level of protection of health, safety and the environment is maintained. Legislation relevant for health, safety and environment aspects of nanomaterials can be grouped under chemicals, worker protection, products and environmental protection, simultaneously applicable. Overall, it can be concluded that current legislation covers to a large extent risk in relation to nanomaterials and that risks can be dealt with under the current legislative framework. However, current legislation may have to be modified in the light of new information becoming available, for example as regards thresholds used in some legislation. Implementation of legislation and use of regulatory instruments created by legislation remains a particular challenge.

- Chemicals: REACH (Registration, Evaluation, and Authorization of Chemicals) provides an over-arching legislation applying to the manufacture, placing on the market and use of substances on their own, in preparations or in articles. REACH is based on the principle that manufacturers, importers and downstream users have to ensure that they manufacture, place on the market or use such substances that do not adversely affect human health or the environment. Its provisions are underpinned by the precautionary principle. There are no provisions in REACH referring explicitly to nanomaterials. However, nanomaterials are covered by the "substance" definition in REACH.

- Worker Protection: Framework Directive 89/391/EEC places a number of obligations on employers to take measures necessary for the safety and health protection of workers. It applies to all substances and work activities including manufacturing and use of chemicals at all levels of the production process, regardless of the number of workers involved and quantities of materials produced or technologies used. This Directive fully applies to nanomaterials. Employers, therefore, must carry out a risk assessment and, where a risk is identified, take measures to eliminate this risk.
- Products: Product legislation lays down requirements regarding specific products, such as medicinal products, plant protection products (PPP), cosmetics, food and feed additives, etc. Consumer products that are not governed by specific legislation have to meet the requirements of the General Product Safety Directive. Virtually all product legislation imposes a risk assessment and the adoption of risk management measures. Nanomaterials are not excluded from this obligation.
- Environmental protection: Environmental regulation relevant in this context relates in particular to integrated pollution prevention and control (IPPC), the control of major accident hazards involving dangerous substances (Seveso II), the water framework directive and a number of waste directives.
    - The IPPC Directive covers approximately 52,000 industrial installations across the EU and requires installations falling under its scope to operate in accordance with permits including emission limit values based on the application of best available techniques (BAT). In principle, the IPPC Directive could be used to control environmental impacts of nanomaterials and nanomaterials issues at IPPC installations through the inclusion of such considerations into the Commission's BAT Reference Document (BREFs) process should the need arise.
    - The Seveso II Directive applies to establishments where named dangerous substances (or substances falling within certain classification categories) are present above specific quantities (or thresholds). It imposes a general obligation on operators to take all measures necessary to prevent major accidents and to limit their consequences for man and the environment. If certain nanomaterials are found to demonstrate a major accident hazard, they may be categorised, together with appropriate thresholds, in the context of the Directive.
    - The Water Framework Directive (2000/60) sets common principles and an overall framework for action to improve the aquatic environment and to progressively reduce the pollution from priority substances and phasing out emissions, discharges and losses of priority hazardous substances to water. A list of 33 priority substances has been established in 2001. Nanomaterials could be included among the Priority Substances depending on their hazardous properties.
    - Directive 2006/12/EC on waste sets the general framework and imposes an obligation on Member States to ensure that waste treatment does not adversely affect health and the environment. The hazardous waste Directive defines which wastes are hazardous and lays down stricter provisions regarding such waste. Hazardous waste must display certain properties set out in an Annex to the Directive and feature on the European Waste List as hazardous. Wastes containing nanomaterials could be classified as hazardous, if the nanomaterial displays relevant properties which render the waste hazardous.

Scientists, regulatory agencies, and governments are taking several measures to institute standard guidelines for handling of nanomaterials around the world. Because of inadequate toxicological/ecotoxicological data of carbon nanomaterials as well as qualitative and quantitative characterization data, public authorities and regulatory agencies face difficulties in framing new laws or adapting incremental approaches to handling the risk management of carbon nanomaterials. The Commission of the European Community has adopted the incremental approach, which emphasizes existing laws and amends them to regulate nanotechnology and nanomaterials. The Commission also acknowledged that if a prevalent material that is already present on the market as an existing entity and is reintroduced in the nano form, that is, less than 100 nm in diameter (nanomaterial), the data sheet of the material shall be updated. The supplementary information, including classification of the nanomaterial, risk assessment, and management techniques must be incorporated in the registration profile and shall be communicated to the buyers. Both the Commission (2008) and the Scientific Committee on Emerging and Newly Identified Health Risks also recommended that existing assessment guidelines for evaluating risks are not suitable for assessing risks associated with nanomaterials.

Previously, carbon and graphite materials were spared from registration under REACH (Registration, Evaluation, and Authorization of Chemicals) in European countries. However, this exemption stand-off after the safety issue of this material surfaced by the scientist. Currently, the company has to register under REACH if they are producing these nanomaterials in quantities above one ton per year. Furthermore, the Chemical Safety Assessment must be produced if the production is more than 10 tons per year. If the material falls under PBT (Persistent, Bioaccumulative, and Toxic) or vPvB (very Persistent and very Accumulative), the company must develop an exposure scenario and risk assessment procedure to ensure the safety of these engineered nanomaterials [27].

# 6 Operational Feasibility - Supply Chain and Production

Operational Feasibility may employ the responsibility to examine and also decide whether the proposed methods fulfil all kind of business requirements. Its actions forecast all possible schemes to recognized and resolves troubles. These studies may also examine and verify how the project planned guarantee the method development is feasible or not. Operational feasibility assesses how well a proposed plan fits within the existing business environment, and if developed, whether current purchasers will use it. Some variables that affect the outcome of this analysis are whether management support, how buyers feel about the current system in place and if the proposed system will benefit the organization [9]. In this work, the Operational Feasibility lists different nanoparticles' production methods and its scalability along with the main CNMs producers and suppliers.

## 6.1 Industrial synthesis of carbon-based nanomaterials

Nanomaterials can be synthesized through various methods such as vacuum deposition and vacuum vaporization, solution synthesis, chemical vapor deposition (CVD) as well as chemical vapor condensation, gas condensation, combustion synthesis, physical vapor deposition, mechanical attrition, self-propagating high-temperature synthesis, chemical precipitation, sol-gel techniques, and electrodeposition, among others [28]. Even though the list of available CNMs is very extensive, this chapter will look into more detail into the synthesis and production of the family of CNTs and Graphene.

### 6.1.1 CNTs

As briefly mentioned in Chapter 3, the properties of CNTs are tremendously influenced by its features, such as diameter, wall number, length, chirality and purity. Therefore, delicate control of atomic arrangement is required to achieve predictable definite properties. The most commonly used methods for synthesizing CNTs are arc-discharge, laser ablation and CVD. The first two are well-established methods for producing high-quality and almost perfect nanotube structures (little structural defects). However, these methods produce a large amount of by-products, require solid-state carbon precursors and high temperatures for carbon vaporization (higher than 1000 °C) [34].

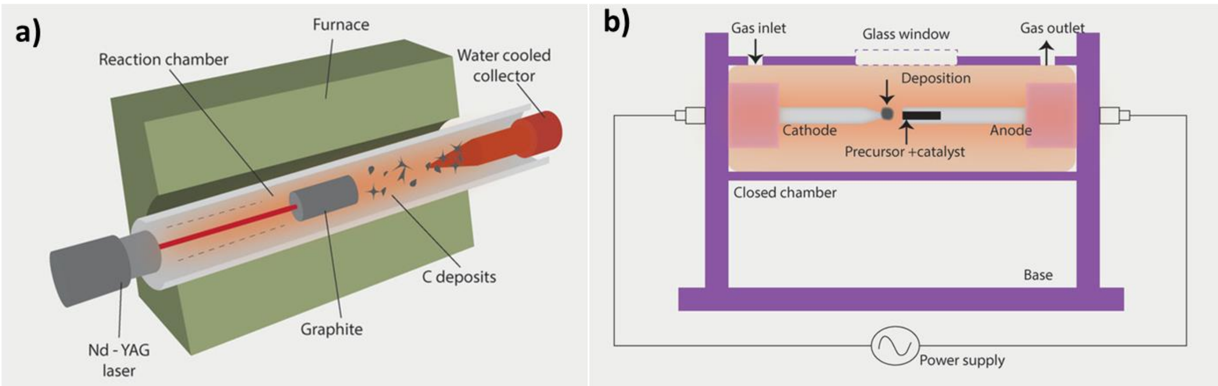



**Figure 13 Schematic representation of methods used for CNT synthesis a) laser ablation and b) arc discharge. Adapted from [34].**

In contrast, CVD synthesis requires simpler equipment and milder conditions in terms of temperature and pressure, making it more suitable for the large-scale production. CVD synthesis is based on decomposition of hydrocarbons to carbon, and subsequent synthesis of carbon nanostructures on various substrates containing catalysts on which the nanotubes are growing. Metal-based (such as nickel, cobalt or iron) nanoparticles are frequently used as catalysts and their size strongly correlates with the diameter of nanotubes synthesized on it (0.5 – 5 nm for SWCNTs, 8 – 100 nm for MWCNTs synthesis) [25, 34]. Figure 14 presents a schematic representation of the CVD process, denoting the formation of carbon from de thermal decomposition of hydrocarbons and the growth of CNTs on top of the catalysts present in the substrate [25].

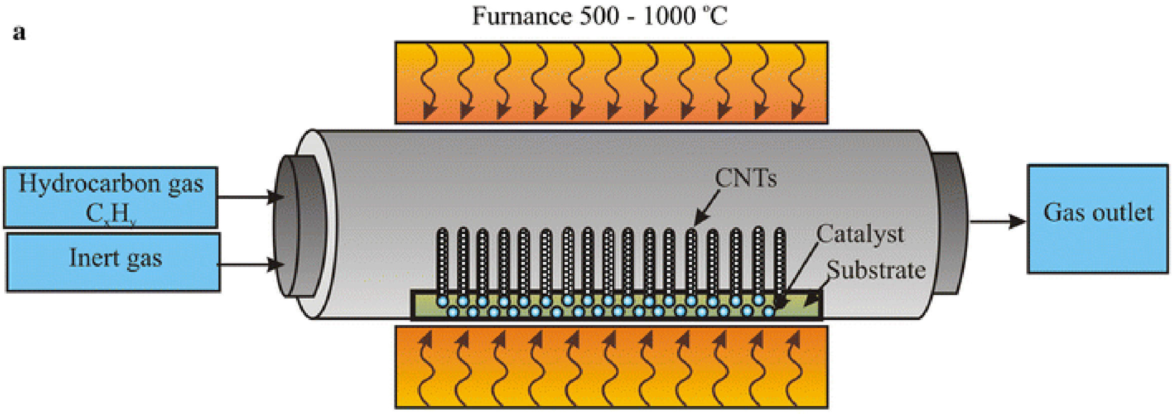



**Figure 14 Schematic representation of chemical vapor deposition process. Adapted from [25].**

Table 8 shows a comparative study of the different methods used for CNTs production, including the yield rate, the type of CNTs able to be produced along with advantages and disadvantages of each process.

**Table 8 Comparative study of different types of methods used in the synthesis of CNTs [14, 15].**

| Method | Yield Rate | (SWCNT) or (MWCNT) | Advantages | Disadvantages |
|---|---|---|---|---|
| **Electric arc discharge** | < 75 % | Both SWCNT and MWCNT | Can create nanotubes with little structural defects due to the high temperature used.<br>Simple and inexpensive process.<br>Can produce large amounts of CNTs. | The chirality of CNTs cannot be controlled.<br>The created nanotubes need to be purified if metal catalysts are used.<br>High temperature required for this method. |
| **Laser ablation** | < 75 % | Only SWCNT | High purity of SWCNT is able to be achieved.<br>The structure of SWCNT produced is better graphitized. | Unable to produce nanotubes on a large scale.<br>High energy is needed for laser usage. |
| **Chemical vapor deposition (CVD)** | > 75 % | Both SWCNT and MWCNT | The highest yield out of the four synthesis methods.<br>High purity nanotubes are produced.<br>Fit for large-scale production.<br>Able to create nanotubes in many forms and structures. | This method mainly favours the growth of MWCNT. |

Industrial applications of CNTs require homogeneous materials with specific properties. However, shifting from well-controlled laboratory conditions to large-scale production frequently results in heterogeneous products, containing impurities of amorphous carbon, carbon fibre, catalyst residues and other nanoparticles. Therefore, CNT production frequently requires further purification and separation steps, substantially increasing the production costs [25]. Establishing convenient methods for sorting nanotubes according to their characteristics (diameter, chirality) and eliminating various undesired impurities will significantly contribute to the developmental progress towards improved applications [25].

Lower cost and mass production can be obtained using the flame synthesis of CNTs. This method is capable of a controlled production of CNTs on the selected substrates by using the appropriate catalyst, the correct temperature and the adequate source of carbon. In the flame process, the catalyst is introduced in the flame where it condenses in spherical nanoparticles. Ni, Co, stainless steel and Fe are generally utilized as catalyst in the flame process [35].

Recently, a new more sustainable take on the production of CNMs has been explored through the use of agriculture or industrial waste as carbon source. In these cases, the previously mentioned production methods have been modified and/or adapted to produce high quality CNTs, in particular by selecting the appropriate substrate and catalyst. The success of the results obtained differs significantly depending on the author and type of waste/biomass used. Nevertheless, it might be possible in the near future to find scalable solutions [33].

### 6.1.2 Graphene

Similarly to CNTs, the synthesis of the particles from the graphene family includes different methods resulting in materials possessing different properties, such as: layer number, lateral dimension, chemical residues, surface charge and surface functional groups. In general, the synthesis methods that have been used to produce graphene can be categorized into bottom-up and top-down approaches, as summarized in Figure 15 [25, 35, 36]. In bottom-up approaches, graphene is built from atom levels, enabling the production of high quality and defect-free graphene which is highly preferred for electronic applications. However, these methods are not very popular for large-scale production due to their low yield, complex processing, and associated higher cost [34]. The top-down production of graphene most often involves the exfoliation and/or oxidation of powdered graphite [35].

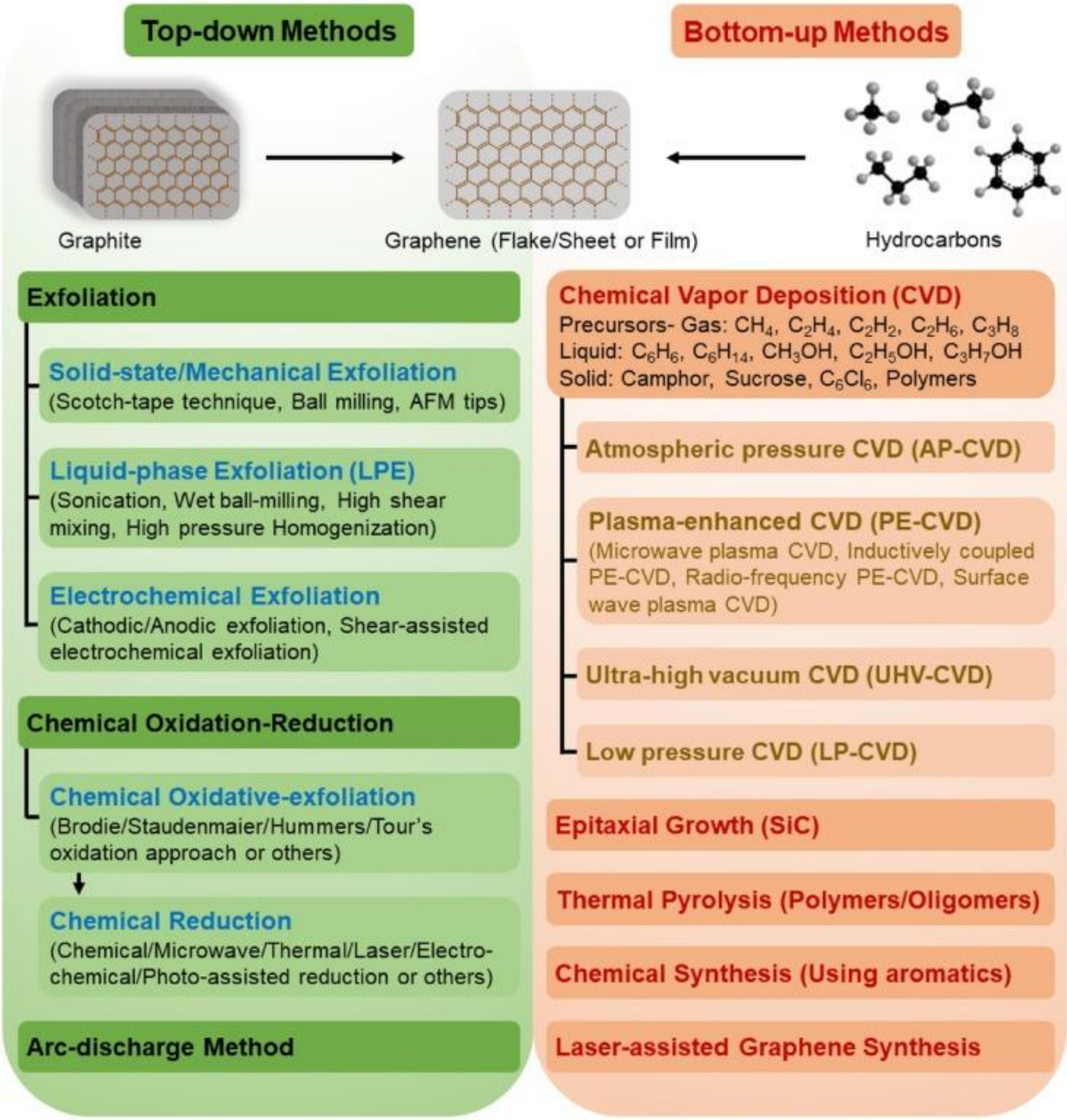



**Figure 15 Summary of different graphene synthesis approaches using top-down and bottom-up methods [37].**

The graphite oxidation and exfoliation route is currently the most popular wet chemical method to produce graphene materials, namely graphene oxide (GO) and reduced graphene oxide (rGO), due to its production cost, scalability, reproducibility and processability. In the past years, several methods have been explored in order to improve the quality of the graphene particles produced, which can be denoted from Figure 16 [38].

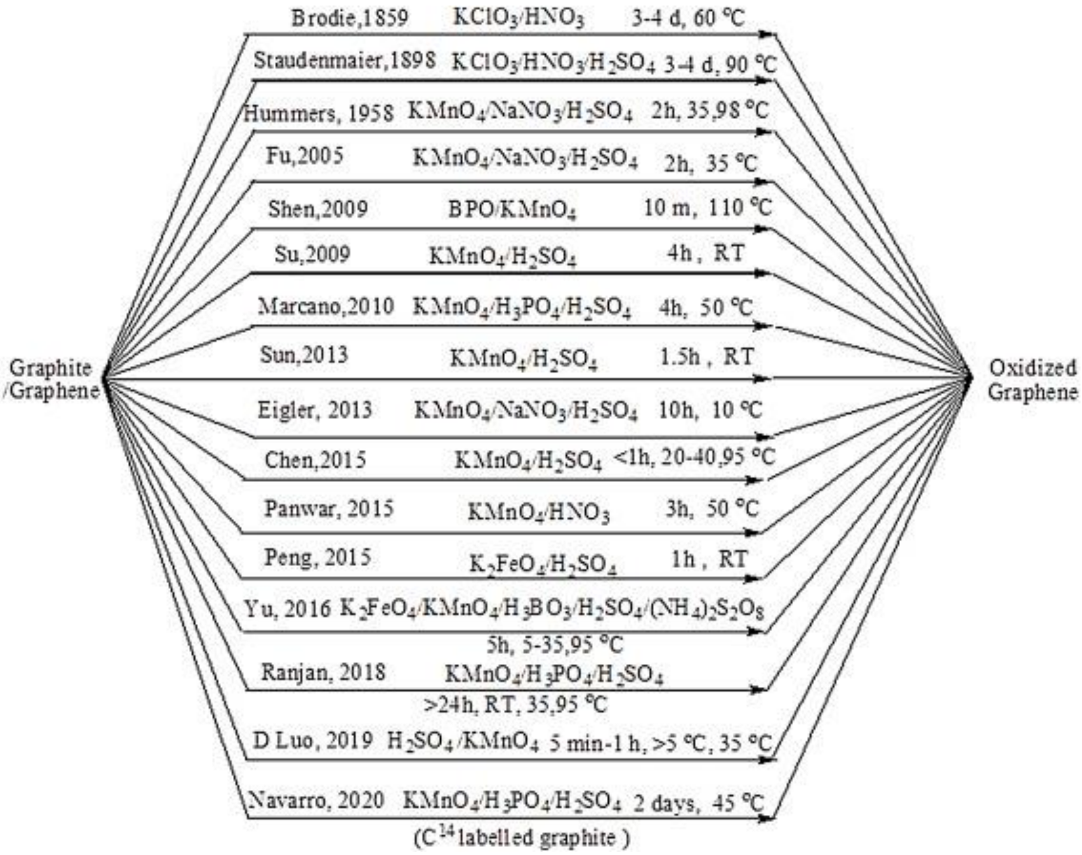



**Figure 16 Conversion of graphite into oxidized graphene through various extraction methods [38].**

Nowadays, the different methods are able to provide graphene or reduced graphene oxide sheets of different qualities, depending on the requirements of the corresponding applications. Graphene of moderate quality for structural applications can be obtained in large quantities with relatively low production costs. High quality graphene for electronic devices can produced in smaller quantities and at higher cost. [25].

## 6.2 CNMs producers

Leading producers of CNMs:

- Mitsui Chemicals (Japan) SWCNTs
- OCSiAl (Russia) MWCNTs
- Cnano Technology (China) CNTs
- Showa Denko (Japan) CNTs
- Nanocyl (Belgium) CNTs.
- Toray Industries (Japan) CNTs
- Arkema (France) CNTs
- NanoXplore Inc (Canada) graphene
- Graphenea (Spain) graphene
- Avanzare (Spain) graphene
- Directa Plus (Italy) graphene
- First Graphene Ltd (Australia) graphene
- XG Sciences, Inc (USA) graphene

# 7 Scheduling Feasibility - Risk Assessment

A very significant part of a feasibility study is Scheduling Feasibility, which plays an important role to complete the project in its schedule time. For instance, a good project sometimes may be unsuccessful if it is not finished in its bounded time frame. Here we may predict the time requirement to complete various task of the entire project. All invested groups should recognize and agree that the project is to be finished within an agreed-upon timeframe for the proposed plan to be successful [9]. For this project, the Scheduling Feasibility identifies potential risks and challenges that limit the larger utilization of CNMs at this moment.

Based on the information from previous chapters, the following challenges can be referred as the most important for the broader commercialization of products containing CNMs:

**1. Production Costs and Scalability**

- **High Costs**: One of the primary challenges in the widespread adoption of CNMs is their high production cost. The processes for synthesizing high-quality CNTs and graphene, such as CVD, can be expensive and complex [39], or even present low yields.

- **Scalability Issues**: Producing these materials on a large scale while maintaining consistent quality is a significant hurdle. Achieving industrial-scale production that can meet commercial demands without compromising on the properties that make these materials desirable is still a challenge [39].

**2. Quality and Consistency**

- **Material Variability**: Carbon nanomaterials often exhibit significant variability in terms of size, purity, and structure, which can affect their performance in applications. Ensuring uniformity and reproducibility in production is difficult, leading to inconsistencies in material properties.

- **Characterization Challenges**: The complexity of these nanomaterials makes it challenging to characterize them accurately and consistently. Advanced techniques are required to analyse their properties, adding to the complexity and cost.

**3. Dispersion and Integration into Matrices**

- **Dispersion Issues**: Incorporating carbon nanomaterials into other materials (such as polymers) often requires them to be well-dispersed to achieve the desired properties. However, CNTs and graphene have a tendency to agglomerate due to van der Waals forces, which can lead to weak points in the material.

- **Integration Techniques**: Developing effective methods to integrate these nanomaterials into existing manufacturing processes without degrading their properties is a challenge. This includes finding suitable binders and ensuring strong interfacial bonding with matrix materials.

**4. Health and Environmental Concerns**

- **Toxicity and Safety**: There are ongoing concerns about the potential health risks associated with the inhalation and exposure to carbon nanomaterials. Studies on the toxicity of CNTs and graphene are still emerging, and there is a need for comprehensive assessments to ensure safe handling and use.

- **Environmental Impact**: The environmental impact of producing and disposing of carbon nanomaterials is not fully understood. Ensuring sustainable practices and assessing the long-term ecological effects are crucial for broader adoption.

**5. Regulatory and Standardization Issues**

- **Lack of Standards**: There is a lack of standardized testing and quality control measures for carbon nanomaterials, making it difficult for industries to adopt these materials confidently. Developing global standards for their characterization, testing, and use is essential.

- **Regulatory Challenges**: Navigating the regulatory landscape for new materials can be complex. Manufacturers must comply with a range of regulations regarding safety, environmental impact, and consumer protection, which can vary significantly across different regions.

**6. Market Acceptance and Awareness**

- **Industry Reluctance**: Industries may be hesitant to adopt new materials without proven long-term benefits and reliable supply chains. The novelty of carbon nanomaterials means that many industries lack the experience or confidence to integrate them into their products.

- **Awareness and Education**: There is a need for greater awareness and understanding of the potential benefits and challenges associated with carbon nanomaterials. Educating stakeholders about the capabilities and safe handling of these materials can facilitate broader adoption.

As it can be observed, part of the risks described already have possible solutions, as demonstrated in the previous chapters. Nevertheless, more efforts need to be put in practice to achieve higher usage of CNMs-based products.

# 8 Conclusion

The potential for CNMs in revolutionizing various industries is immense. However, their widespread application is hindered by several challenges that must be addressed to facilitate greater utilization. These challenges underscore the need for continued research and development to optimize production methods, improve material consistency, and address safety concerns, which are critical steps toward integrating carbon nanomaterials more fully into industrial applications.

Since a good part of fundamental research is typically explored in the academia, it is of utmost importance to include industrial partners in these investigations, which can better provide requirements, key performance indicator (KPI) and problems to be solved. At the same time, the academic entrepreneur also plays a pivotal role in overcoming challenges and advancing to the commercialization of innovative materials. Researchers with strong entrepreneurial competencies and the ability to capitalize on commercially-based research play a crucial role in accelerating techno-creative innovation. This can only be achieved with the support of universities, that should provide a supportive entrepreneurial environment and infrastructure, including robust intellectual property (IP) management systems and efficient technology transfer offices (TTOs), to empower academic entrepreneurs to produce innovations that are both technologically viable and commercially feasible [40].

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